Accelerated Insertion of Materials – Composites (AIM-C)

Methodology

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FOREWORD

The Accelerated Insertion of Materials – Composites (AIM-C) Methodology was jointly accomplished by Boeing and the U.S. Government under the guidance of NAVAIR, agent to the Defense Advanced Research Projects Agency (DARPA). Materials and Processes provide the foundation from which all Department of Defense (DoD) systems are built. New materials and designs are continuously being developed that have potential to provide significant improvement in system performance. However, due to the long and difficult process of maturing a material to the state where the designer's knowledge base is ready for use, few materials ever get transitioned. The Accelerated Insertion of Materials (AIM) program seeks to develop and validate new approaches for materials development and characterization that will accelerate the insertion of materials into hardware. Currently, the development of a designer knowledge base (which incorporates design allowables, reliability, manufacturing, reproducibility, and other essential information about materials) is a time consuming and costly endeavor, requiring thousands of tests and millions of dollars. Consequently, new material insertion into hardware is extremely difficult, typically taking 15-20 years if successful at all. Emerging efforts in materials modeling are leading to incremental improvements in specific areas, e.g., materials processing and mechanical behavior. The time between development of a new material and its implementation into production can be significantly shortened through a radical change in materials development methodologies. Introducing change with credibility to the users and certifiers is the exact mark of Accelerated Insertion of Materials – Composites (AIM-C).

Dr. Leo Christodoulou, the DARPA Program Manager, and Dr. Ray Meilunas, NAVAIR technical agent for the program, led integration of the effort. The AIM-C technical team was led by Gail Hahn, Dr. Karl M. Nelson, and Charles Saff of Boeing.

The objective of the Accelerated Insertion of Materials – Composites program was to demonstrate concepts, approaches, and tools that can accelerate the insertion of new materials into Department of Defense systems. The AIM-C concept involves the use of existing knowledge, analysis techniques, tests, and demonstration articles to develop a designer knowledge base (technical and production readiness information) from the outset, rather than the more traditional approach of sequential, unlinked research and development, sometimes locally optimized without a production-readiness transition path.

The objective of the AIM-C Methodology document is to provide a disciplined framework that captures the insertion problem statement, communicates the problem with the AIM-C system to the Integrated Technology/Product Team, and provides a suite of knowledge bases, analytical tools, and test/validation approaches for the team to use with confidence levels, risks/drivers, risk mitigation options, and links to further detail. The methodology follows a building block approach to achieve material insertion from material basic material characterization to certification in field applications. The methodology is intended to provide guidance at all levels of the certification process. This methodology can also be used without the AIM-C system.

The attachments to this volume were provided by American Optimal Decisions under the direction of Dr. Stanislav Uryasev.

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1. Introduction

The objective of the Accelerated Insertion of Materials Program is to provide the concepts, approach, and tools that can accelerate the insertion of composite materials onto Department of Defense (DoD) systems. The primary concepts used to enable accelerated insertion of materials include: the definition of an integrated product team (IPT) made up of both the technology and application development members; the use of a disciplined, coordinated maturation plan developed by this IPT; the combination of this maturation plan with existing knowledge, analysis tools, and test techniques, that enable accelerated development of a design knowledge base (DKB) from which maturity of the material system is determined; and the incorporation of an early key features fabrication and test article to focus the insertion, qualification, and certification efforts.

This document describes the approach taken to combine these concepts into a cohesive plan to accelerate maturation for successful insertion. During the development of this methodology, several analytical and test tools were developed to aid the IPT in developing their plan and in predicting and assessing the capabilities of the material system being introduced. The alpha version of the software system used to make these tools available is described in a Users' Manual provided as Appendix E to this report.

1.1. Purpose – The purpose of this volume is to present the methodology developed during the AIM-C program that can accelerate development of the design knowledge base (DKB) required for insertion of new materials into DoD systems. To accomplish this purpose, this report presents the key elements of the methodology, their content, how they are applied, and how they each contribute to the acceleration of insertion defined by the process. Before summarizing these key elements of the methodology there are some important concepts and relationships that must be defined.

1.2. Qualification and Certification Definitions – Throughout this document, the words qualification and certification will be used frequently. In general, unless the context provides a different interpretation, qualification will be used to mean the knowledge base developed on a material system, under particular process conditions, that demonstrates ability for meet a specific set of materials and process specifications. Certification will be used to refer to that knowledge base for a material system, fabrication process, and assembly procedure that meets the design requirements for a given component of a DoD system. In this definition set, qualification refers to the general acceptability and limitations of a material and process and certification refers to the ability of the material and process to perform as required in a specific application. These definitions are depicted in Figure 1.1 to show that the DKB developed by the AIM-C methodology consists of both data sets and while there is much shared between these datasets, specific applications often do require more data focused toward that application than is contained in the qualification dataset.

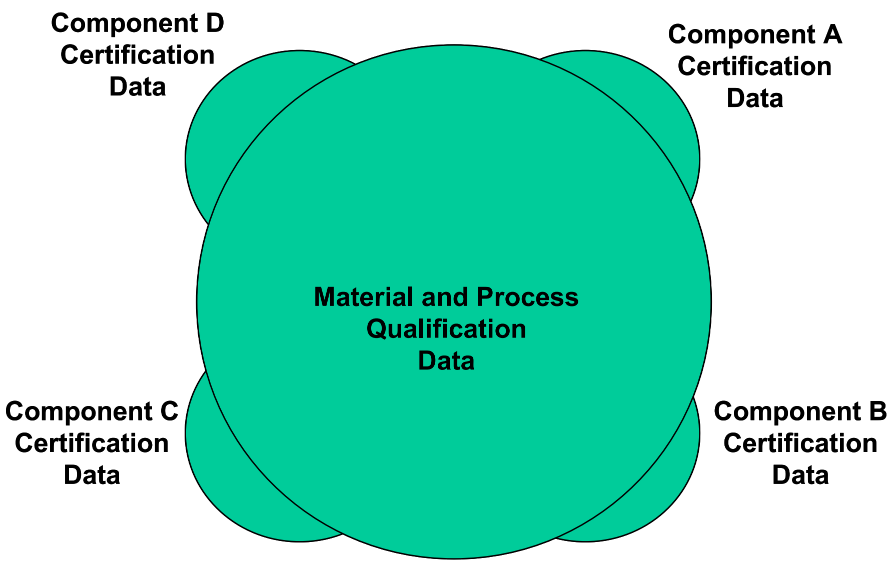


Figure 1.1 – The Design Knowledge Base Includes Both Qualification And Certification Data

The design knowledge base developed by the AIM-C system includes both qualification data and certification data for a specific application. This was intentionally done because accelerated qualification does not necessarily ensure accelerated insertion. The development of the DKB must go beyond qualification data to the certification data for the given application in order to ensure insertion.

1.3. Definition of Designer Knowledge Base

– The Design Knowledge Base as defined in Figure 1.2 includes both the qualification data for a given material and process as well as the additional testing (or analysis or existing knowledge) required to demonstrate that the use of this configuration, material, process, and assembly technique meet the design requirements for the application. As the material system is applied to additional components within even a given system the design knowledge base grows

The Design Knowledge Base (DKB) for AIM-C is defined as that knowledge that qualifies the materials for use and certifies the material for use in specific components of the aerospace system being to which it is applied. In general terms the elements of a design knowledge base for aerospace systems was defined by a set of experienced leaders of integrated product development teams as shown in Figure 1.2. This figure identifies everything that the IPT desired in the DKB, a portion of which was the focus of the AIM-C Phase 1 effort.

Figure 1.2 Integrated Product Team's View of the Design Knowledge Base

It should be noticed that while the AIM-C team focused on the materials and processing, manufacturing, and structural aspects of this DKB, we did address some elements of the Supportability and Miscellaneous categories. In general, the methodology in AIM-C was developed at high levels for the majority of the categories shown in Figure 1.2 and in depth for only a few of the elements shown. This allowed us to address the broad issues surrounding accelerated insertion, while still allowing us to focus on a few for more complete development. Those few that are more fully developed will pave the way toward the understanding required to extend the methodology to those elements that were addressed at only the higher levels.

1.4. Approach Overview

- The AIM-C approach is a multi-faceted plan to achieve safe, reliable, and rapid insertion of a material system into a DoD application with minimum risk of failure as the application approaches certification. The approach consists of assembling an integrated product team of the technology and application development members, assessing the readiness of the material for insertion, determining the requirements for the application, determining how the IPT will determine conformance with those requirements, gathering the knowledge by existing knowledge, test, and analysis to fulfill the requirements, assessing the conformance to requirements to determine if the knowledge gathered can be committed to the design knowledge base, or whether there are elements of the knowledge that require a different approach to ensure robustness.

There are gates at each step denoted by technology readiness level throughout the maturation process; however, there are two primary gates which are impacted most by AIM-C methodology. The first is the technology readiness review (TRL= 0) in which the IPT reaches the consensus that the material, its support materials, and its processes can be obtained with sufficient reproducibly that materials evaluated can be obtained using rudimentary requirements sheets to achieve the same pedigree. Another key review (TRL= 3) is at the time of the decision to proceed with the key features fabrication and test article(s). The materials, processes, and fabrication techniques must be capable of producing full-scale parts consistent with the designs for this application. Moreover, the key features article should demonstrate predictable geometry, response, strength, failure modes, and repair capabilities so that parts subsequently fabricated are not outside of tooling, processing, analysis, and repair capabilities.

As the AIM-C methodology is expressed in this report, please note that it is also applicable to the insertion of other technologies.

1.4.1 Baseline Best Practices – There were a number of Best Practices that were used in the development of the AIM-C methodology. These Boeing Best Practices include: Integrated Product Teams, Quality Function Deployment, Technology Readiness Levels, and ISO 9000. These practices and methods are defined here and their use within the AIM-C System is examined so that as the methodology is presented the use of these practices will be evident.

First, Integrated Product Teams are multi-disciplinary teams used throughout much of industry so that the knowledge base resident within each discipline can be brought to bear on the solution of a problem. Design solutions are a known compromise among affected disciplines and must not result in a design having a weakness overlooked by a discipline that is not represented. IPTs have been so successfully applied to design, build, and test of high performance products that they are now being introduced into manufacturing and most recently into technology development to reap similar gains to those achieved in design. The benefit of a multi-functional team to develop a DKB is the rapid assessment of the requirements imposed by affected disciplines in the development and evaluation of a new materials system even before it is ready for evaluation in trade studies.

One of the key points encountered during the course of the AIM-C Program was that IPTs doing technology development are usually separate from those doing product development. If these teams are going to successfully and rapidly insert a new material into an application, these two teams must become one team throughout the course of the insertion process. There are some very good arguments for maintaining the tie between the groups even after this point in the maturation process, but the key is that the applications team must know what the technology development team knows about the material and processes that are proposed and the technology team must know what the requirements, environments, and expectations of the materials will be in the proposed application. Neither team can be successful without the information from the other team. They must be made into one team.

Quality Functional Deployment, via a House of Quality concept is used in the AIM-C Program to simply document the relationship of requirements from the systems level to the component and technology levels. Insertion cannot be successful without meeting the requirements. Unsuccessful insertions have most often been stopped, not by a lack of knowledge about potential show stoppers, but because people did not carefully document and share the requirements for the component or material or manufacturing process or did not address the issues they knew existed. Without documentation these issues can be ignored to the peril of the insertion. An example of Quality Function Deployment is shown in Figure 1.3.

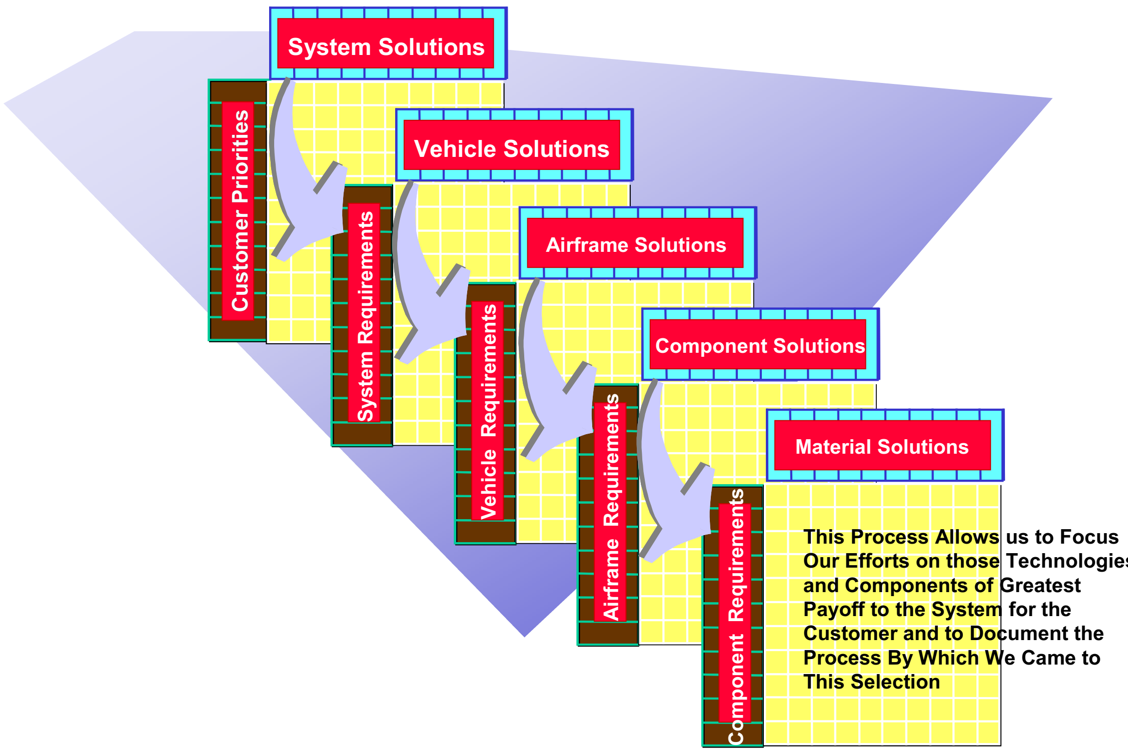


Figure 1-3 Quality Function Deployment Is Used in AIM-C to Document the Linkage of System Level Requirements and Technology Requirements

Evaluations of the applicability of a material or process to a specific component are best performed at the component level. But often it is difficult to interpret component level performance or benefit at the systems level. The house of quality process offers a tie between systems level requirements and payoffs to component level requirements and payoffs. But the relationship is not one to one. There are often component level requirements that limit how a material can perform or what processes can be used that impact the application of the material to the component. These are often requirements not defined at the systems level, but are part of the disciplinary knowledge base that comes through the IPT. Documenting these requirements is just as important as documenting the system level requirements and priorities.

The AIM-C Methodology used Technology Readiness Levels to track the maturation of the technology (material) through the insertion process. It did not take long as we formulated IPTs under the AIM-C Program to realize that although various disciplines used Technology Readiness Levels (TRLs) to track technology maturity, they did not interpret their TRLs consistently. Technology developers tended to start their TRLs with the discovery and documentation of a new capability. Application developers tended to start their TRLs at the stage when the technology was reproducible and when they could receive a specified product using an initial definition or specification. As shown in Figure 1.4, these TRL definitions are out of phase with one another.

Technology Readiness Levels													
Technology Development	1	2	3	4	5	6	7	8	9				
Application Development				1	2	3	4	5	6	7	8	9	10

Figure 1.4 The Discrepancy Between Technology Based TRLs And Application Based TRLs

This discrepancy in definition between these two TRL definitions, led to confusion between the technology development teams and the application development teams. This discrepancy was not unique to AIM-C but has existed since the formation of the Readiness Level definitions. The Air Force has always focused on a more applications oriented set of TRLs fostered by Dr. Jack Lincoln the specialist in airframe certification for so many years. At the same time NASA used a set of TRLs that was more closely aligned with the technology development TRLs, since they were so often looking at embryonic technologies at the research level.

Once the discrepancy was realized, a single set of Technology Readiness Levels was determined focused on the application as shown in Figure 1.5. Technology Readiness Level 0 was defined to encompass all the development work from discovery to the development of a reproducible process at the laboratory or pilot plant scale. At TRL of 0, an IPT between the technology development team and the application development team is formed and a Technology Readiness Review is held to determine that its properties and projected costs are attractive, that the technology (or material) is reproducible, and that the system ready to begin the AIM-C insertion process. If that review is positive for the material, then that team continues to work toward maturation of the system to insertion. While the process works through all TRL levels, it is really most focused on levels 0-4 for the AIM-C program because that is where most of the risk reduction is done that eliminates the showstoppers and risks for insertion to the application. Levels 5-8 deal with design certification and readiness for production. While levels 9-10 deal with production and support for the product.

Technology Readiness Levels													
Technology Development	0.25	0.50	0.75	1	2	3	4	5	6				
				One Team									
Application Development			0	1	2	3	4	5	6	7	8	9	10

Figure 1.5 The Common TRL Numbering Scheme Adopted by AIM-C

Once a common definition for the meaning of each TRL was defined, then the progress of the entire IPT could be tracked according to a single TRL-based chart. This chart is shown in Figure 1.6, but its use is described in greater detail in later sections of this report. This chart became the IPT's primary means of assessing the maturation of a material, or technology, through insertion.

TRL	0	1	2	3	4	5	6	7	8	9	10
Application/ Design											
Certification											
Assembly/ Quality											
Survivability											
Fabrication/ Quality											
Supportability											
Structures & Durability											
Materials											
Cost/Schedule/ Benefits											
Intellectual Rights											
IPT Reviews	Technology Insertion Readiness	System Requirements	Material & Process Readiness	Key Features Design and Fabrication	Key Features Test/ Conformance	Preliminary Design	Critical Design/ Ground Test Readiness	Flight Test Readiness	Production Readiness	Operational Readiness	Decommission and Disposal Readiness

Figure 1.6 Technology Readiness Chart for a Materials Insertion IPT

ISO 9000 concepts were used to ensure that in each discipline at each TRL, there was an approach and a plan for how the IPT was going to achieve conformance with the requirements for the application and an assessment of the conformance of the knowledge (existing data, analysis, heuristic data, or test data) with the requirements before the data was committed to the Design Knowledge Base (DKB). Each discipline develops its own approach to meeting the requirements of the component, but the IPT has to approve the integrated plan including the approach to achieving conformance and assuring that each discipline will get knowledge consistent with its needs at each stage. The IPT must also validate conformance was achieved prior to committing the data to the DKB. Therefore, the approach for each element of IPT plan for conformance with requirements, there was an approach defined, data gathered, an assessment of the data gathered against the requirements and a committal to the DKB or a rework (or changed approach) in order to achieve conformance for that element of the plan.

The overall approach applied for each element of the plan is shown in Figure 1.7. This approach to DKB development used in AIM-C is entirely consistent with the concepts of ISO 9000. To have an approach defined prior to application, to monitor the application of the process, measure results to ascertain conformance, and to apply corrective measures if conformance is not achieved are all consistent with ISO 9000 concepts. The serendipitous product of this approach is that any DKB developed by the AIM-C approach is readily documented as ISO 9000 compliant.

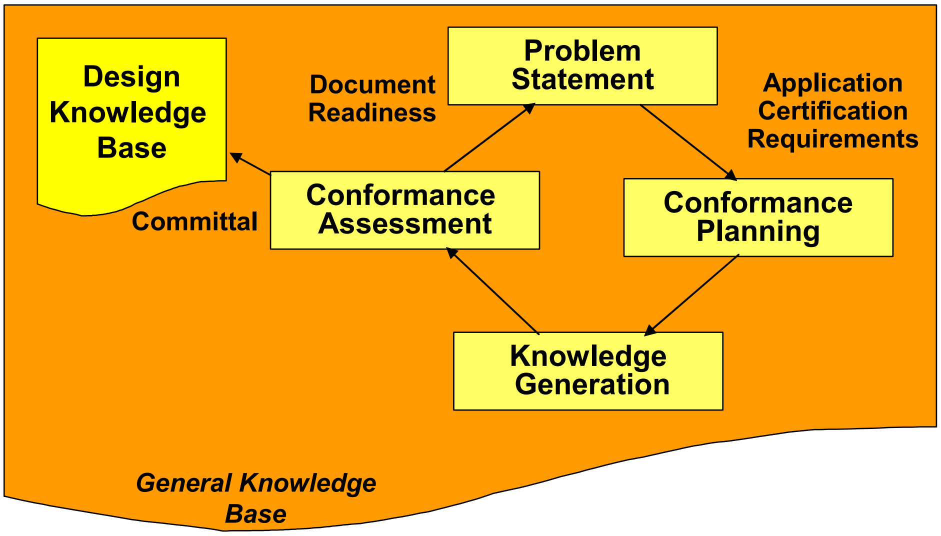


Figure 1.7 The AIM-C Process for Design Knowledge Base Development

1.4.2 Methodology Ground Rules - Methodology provides the disciplined process that captures the designer's problem statement, communications the problem to the integrated technology/product team via the AIM-C system, and provides solutions for the designer with confidence levels, risks/drivers, risk mitigation options, and links to further detail. Our methodology is built on the following ground rules:

a. Integrate the building block approach to insertion.
b. Involve each discipline in maturation.
c. Focus tests on needs identified by considering existing knowledge and analyses.
d. Target long lead concerns, unknowns, and areas predicted to be sensitive to changes in materials, processing, or environmental parameters

The methodology is imparted to users via the following formats:

a. User interface screens/prompts
b. Linked text files
c. Software documentation
d. Training
e. Methodology/process definition and change procedures document

The foundational practice used in the development of the AIM-C approach was the Building Block approach to structural maturity that has been used since the introduction of composite materials into aircraft structure before we had the kind of accurate and comprehensive toolset that we now have for these materials. Faced with the need to be able to certify such structures from a single static and fatigue test as had been done with metallic structures (and because the airframes were then primarily metallic), application development teams, in conjunction with certification agents, developed a method based on increasing complexity of testing that linked the final airframe test through component tests, subcomponent tests, critical detail tests, element tests, to the coupon level tests which could be used to wring out the performance limits of the materials under various service environments. The basic Building Block Approach is shown in Figure 1.8.

The Basic Building Block Approach as presented in Figure 1.8 is a solid and secure foundation for certification of aircraft structures and makes no assumptions about the level of analytical capability available since it was developed when composite analysis techniques were unproven. However, AIM-C also applies validated analysis tools that can radically reduce the amount of testing required to achieve the same level of confidence demonstrated in the Building Block Approach in an accelerated manner as shown in Figure 1.9. Here instead of relying on test data from each level of complexity to feed the next, the focus is on developing the database needed to support the fabrication and test of a full-scale key feature test article. This test article is used to ascertain readiness for certification of the application of the material, processes, fabrication technique, assemble, and the design.

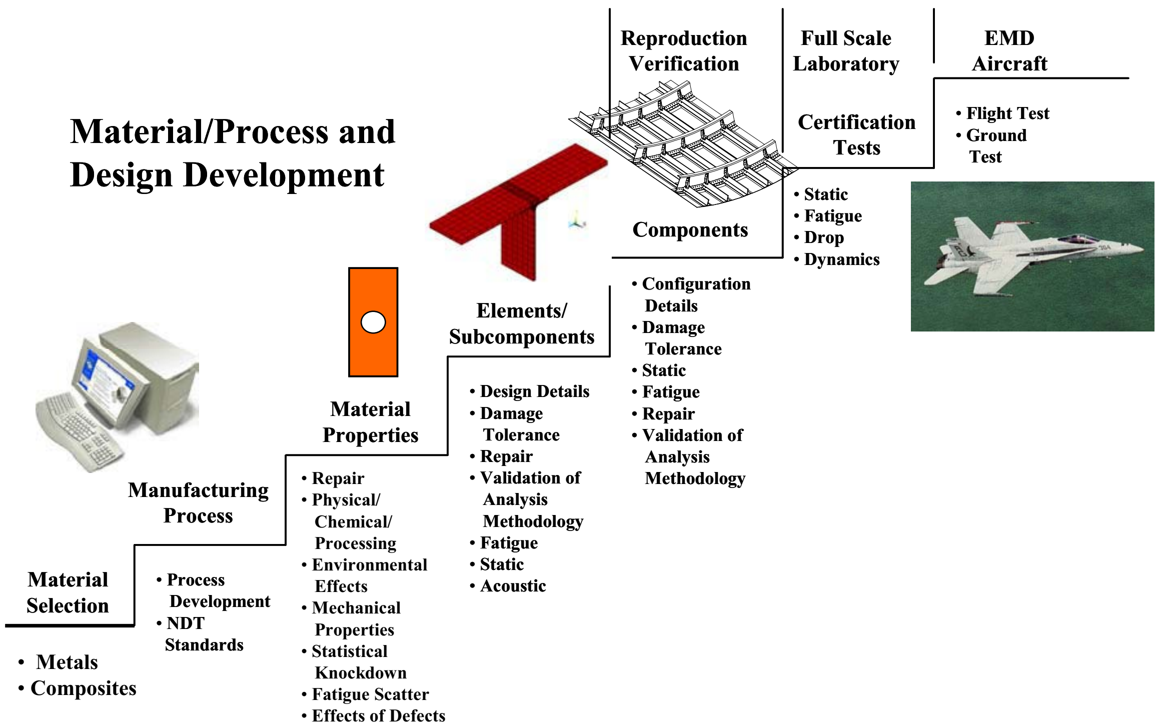


Figure 1.8 Conventional Building Block Approach to Airframe Certification

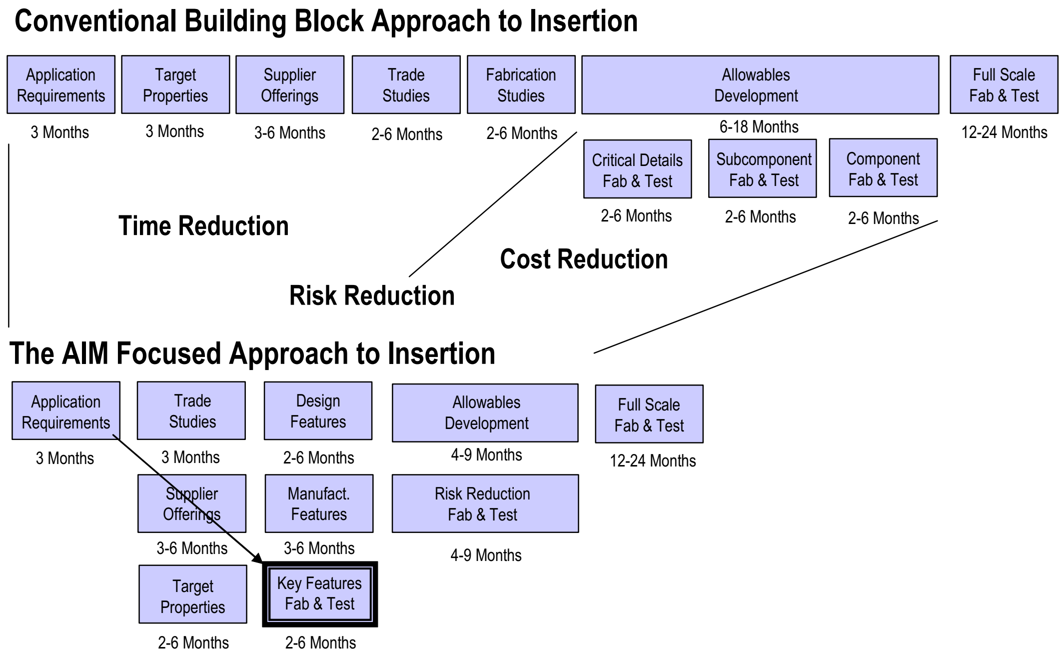


Figure 1.9 Comparison of the Conventional Building Block Approach with the AIM-C Approach

The AIM-C approach differs from the conventional Building Block approach in two ways to accelerate insertion of a new material system. First, and most obviously, the multi-disciplinary, integrated product team concept develops the DKB much more rapidly than the sequential Building Block approach. This is true even without acknowledging the effect of analysis capability, but is dependent only on the ability to cover a number of needs with a few tests when they are jointly planned. Second, the focus on the key features fabrication and test article provides a focus for the early knowledge development, a gate for the technology into certification, and a source of failure mode and repair information that can help focus and reduce certification testing.

1.4.3 AIM-C Features to Accelerate Insertions – A summary of the features introduced in the AIM-C approach is given in Figure 1.10.

Accelerated Insertion of Materials Is Achieved in AIM-C Methodology by

- Focusing on Real Insertion Needs (Designer Knowledge Base)
- Approach for coordinated use of
  - Existing Knowledge
  - Validated Analysis tools
  - Focused Testing
- Application of Physics Based Material & Structural Analysis Methods
- Use of Integrated Engineering Processes & Simulations
- Uncertainty Analysis and Management
  - Early Feature Based Demonstration
  - Tracking of Variability and Error Propagation Across Scales
- Rework Avoidance
- Disciplined approach for pedigree management

Orchestrated Knowledge Management to efficiently tie together the above elements to DKB

Figure 1.10 AIM-C Features to Accelerate Insertion

1.5 Summary - The AIM-C approach integrations these best practices, ground rules and acceleration methodologies into a process that can accelerate the risk reduction required to safely insert new materials into applications.

AIM-C methodology accelerates the insertion of materials providing a disciplined approach toward developing the design knowledge base as rapidly as possible to enable the fabrication of a key features test article that focuses the certification testing on the failure modes and loading conditions that control the design of the component. At the IPT level, and for each of the disciplines that make up the IPT, the approach revolves around problem definition to focus the team, conformance planning to determine as a team how they will pursue the DKB required to fulfill the requirements of the application being considered, knowledge gathering, conformance assessment, and committal of the data to the DKB and documentation of a remaining issues for maturity cycles or other approaches applied to meet the conformance criteria. This philosophy is consistent with that used in the ISO 9000 standards.

The AIM-C philosophy, with its focus on the key features fabrication and test article to guide development toward those features which drive design requirements, has embodied in it a planned rework cycle. In fact the Problem Statement to Conformance Planning, to Knowledge Development, to Conformance Assessment, to Committal or refinement has embedded within it a planned cycle, while working to minimize the reliance on that "rework" cycle in certification. The objective of this philosophy is to provide a gate for the technology at the key features test article to evaluate and mitigate the risks associated with successful certification. This is crucial. In examining past insertion failures, we found that the most expensive failures came when the technology could not be scaled-up to the sizes, or geometric requirements for the design. These lessons, learned the hard expensive way, led to incorporation of the key features full scale test article early in the development process and to evaluate risks before going further with certification.

Just to emphasize this point further, Figure 1.11 shows the benefit of understanding the new material and application in the context of experience as one progresses through the technology readiness levels toward production. Figure 1.11 shows an element called distance from experience. The further one deviates from known capabilities, the greater risk of rework is incurred. Therefore, the AIM-C philosophy is based on gaining experience with the technology as early as possible to develop as much knowledge as possible focused on the applications being considered so that the deviation from the knowledge base is as small as possible throughout the development and insertion process. This reduces risk and reduces the penalty associated with discovering that the technology was not as ready or as capable as was originally perceived.

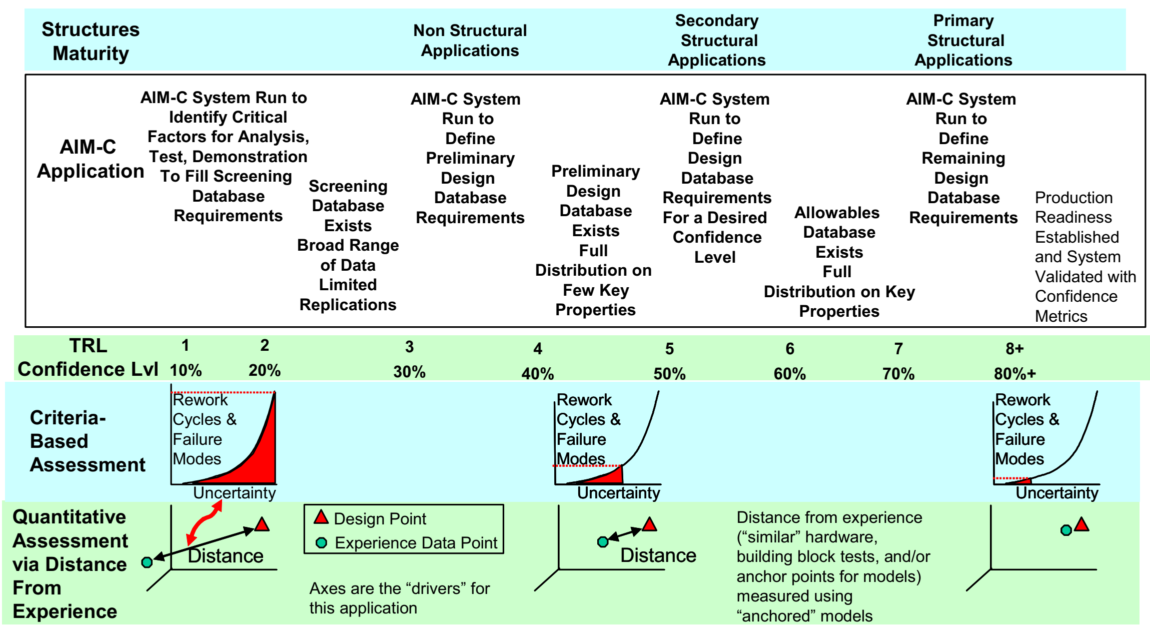


Figure 1.11 The AIM-C Methodology Impact on Traditional Certification from a Structures Perspective

The purpose of the AIM-C approach is to ensure that the distance between the insertion case and the design knowledge base is small so that risks are controlled and unknown risks are identified and mitigated early in the qualification and certification process.

2. Problem Statement

The problem statement bounds the qualification program by providing a clear statement of the desired outcome and success criteria. It delineates responsibilities for appropriate aspects of the program to the material supplier, processor, test house, prime contractor and the customer. It serves as the foundation for many decisions and as the basis of the business case as well as divergence and risk analyses on which the technical acceptability matrix is built. When the problem statement is found to be deficient in specificity, or to be so specific as to limit approaches, or to have a clear technical error, modifications must be made with the agreement of the qualification participants and stakeholders.

The Integrated Product Team (IPT) often encounters a situation in which there are several candidate materials for a given application having multiple fabrication process possibilities. Choosing the proper material and process combination for the application is made more difficult because very often the database supporting each combination is very lightly populated and rarely uses the same lay-ups, fibers, or processes to fabricate the specimens from which the dataset was developed

Having defined issues and the desired outcome, the problem statement is written to clearly describe and define the problem. It is the critical prerequisite to initiating the qualification program.

An effective problem statement contains a number of elements. First, the problem statement must state a clearly defined objective. It also must define what is new with the particular material or process under evaluation and indicate to what it is being compared (for instance, in terms of property thresholds or an existing baseline defined by a particular database). The problem statement gives a definition of the equivalence required for a stated objective. The statement should include cost targets for testing, for procurement, for fabrication, for assembly and for quality systems to be properly bounded. The problem statement also focuses on how the material or process will be used. The problem statement, together with the divergence assessment and business case, establishes the boundaries of the qualification effort before the qualification program begins.

Sample problem statements are as follows:

- A contract requirement for a prepreg second source has been established. The objective of the qualification program is to qualify a second source prepreg system in which the second source resin has the same formulation as the original resin. In order to meet the formulation requirement, the second source supplier is required to license the resin from the original supplier. There will be no changes in fiber reinforcement. The same laminate orientations and fabrication approaches are used as those used for the original material source.

- Program prepreg requirements have grown to the point where the prepreg supplier must add additional qualified prepreg lines to meet demand. The objective of the qualification program is to qualify a new prepreg line. There will be no changes in resin mixing or fiber reinforcement.

- A prepreg supplier is notified by one of their resin constituent raw material suppliers that they are relocating the fabrication of the raw material. The objective of the qualification program is to qualify the new raw material fabrication site.

- The current prepreg-based process for making a part (or class of parts) has unacceptable scrap/rework rates due to out-of-tolerance profile conditions. A resin transfer molded process offers the dimensional control needed. The objective of the qualification program is to qualify this new process.

- The program desires a second fiber source for the baseline AS4 and IM7 fibers in order to achieve the benefits of a true competitive pricing environment. The new fibers in this case would not be licensed, but would have properties equivalent to those of the current fiber system. The basis for comparison will be the results of the original material qualification for the baseline products rather than the material purchase specification values or the current quality control properties being achieved with the material. The aircraft is designed to the material qualification properties. Variations from those properties would require reexamining the structural analyses and would probably eliminate any cost savings that could be realized. The baseline resin will be utilized. For the materials to be classified as equivalent, the modulus of the new prepreg must match the original modulus within industry-typical modulus statistical boundaries and the failure strains must be equivalent or greater.

Practical Check of Problem Statement

- Is the problem statement (or application requirements documentation) captured in writing like a story problem?

- Is the objective clearly identified?

- Has the information necessary to solve the problem been identified?

- Has extraneous information been identified as such?

• Is this statement an identification of the problem or erroneously identification of a desired or anticipated solution?

• Are the critical checks/issues being captured for the next stage of the qualification/certification process, conformance planning?

• Are all of the appropriate stakeholders (including customers) involved and concurring to the statement?

• Have applicable assumptions, compromises, and contingencies been identified in writing?

• Is the problem statement in a useable form for a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis?

• Was a check made of past showstoppers/major issues related to problem statements of a similar nature? (This will be addressed in more detail in planning for conformance, but should also be addressed in the problem statement to help achieve early understanding among stakeholders.)

• Does the problem statement consider the applicable inputs needed from the following readiness level categories?

Application
Certification
Legal Considerations
Design
Assembly
Design Allowables Development/Structures
Materials and Process Development
Fabrication/Producibility
Supportability
Business Case

3. Conformance Planning

Conformance planning addresses what is known and what is unknown relative to the problem statement objectives and requirements. A series of questions are answered to form the foundation of conformance activities and from which conformance activity/area/item check sheets are generated (Figure 3.1).

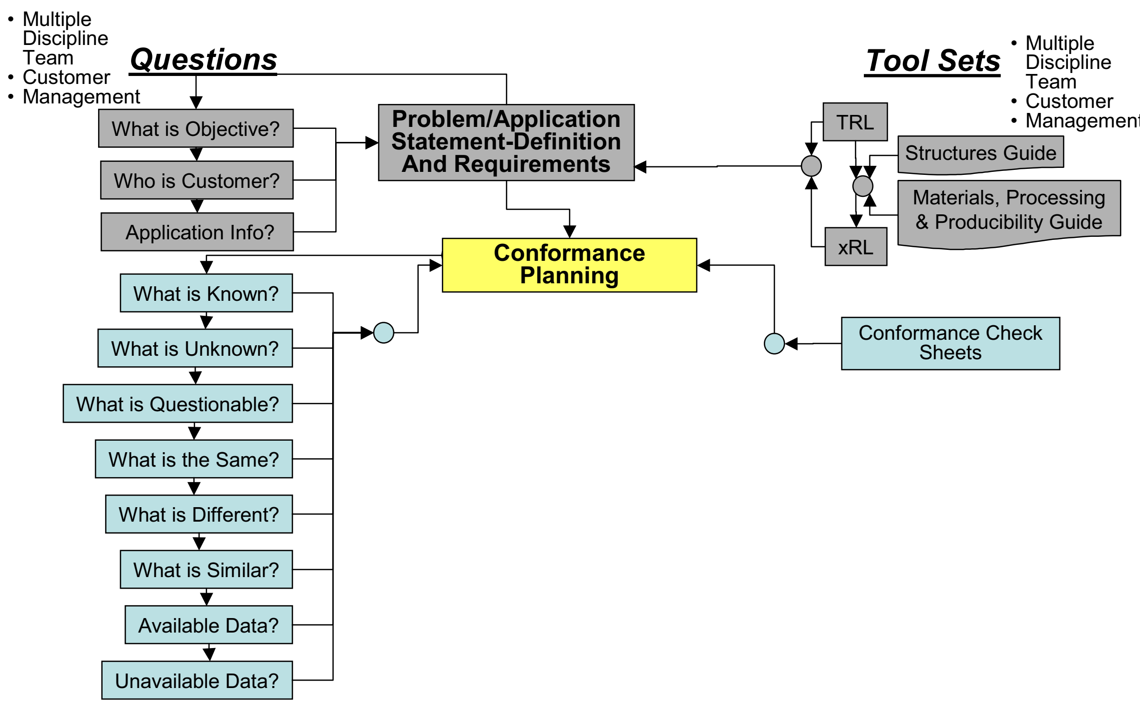


Figure 3.1 Top Level Conformance Planning Activities

Different questions are asked when starting the conformance planning activities. These questions establish what is known and what is unknown for conformance to the problem statement objectives and requirements. It is the first step in establishing what has to be conducted by multiple disciplines for qualification and certification of a new material and/or process. The answers form the nucleus of what existing information/data/ knowledge can be used and what has to be generated.

The process for conformance planning (Figure 3.2) includes asking questions about the detailed xRL exit criteria on how conformance will be met for materials, structures and producibility. A key item is that an Integrated Product Team (IPT) conducts this process with concurrence of results by the whole IPT and by customers. The outputs from these planning activities are a series of check sheets for materials, structures and producibility conformance activities listing what, when and how activities will be conducted.

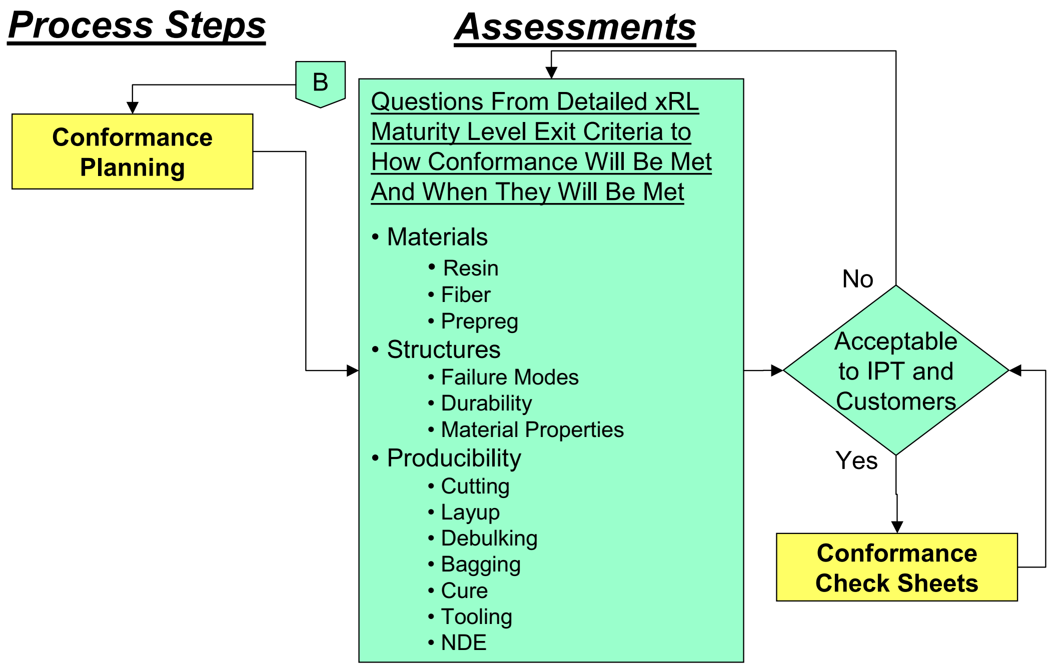


Figure 3.2 Conformance Planning Process

These are a series of steps in this question answering process. The following items outline these steps.

- Gather existing knowledge: heuristics, lessons learned, information on similar problems or applications, public literature, analyses, and test results.
- Address every question/requirement. Address functional/disciplinary issues. Address interdisciplinary issues/assumptions/decisions as an IPT with all stakeholders involved.
- Determine divergence risk on existing information.
- Assess the conformance of existing knowledge with requirements.
- Handle Error and Uncertainty (See Methodology Section 9). Determine additional knowledge needed based on knowledge gaps, unacceptable risk, etc.
    - Understand and Classify Potential Uncertainty Sources
    - Determine What Is Important
    - Limit Uncertainty/Variation by Design and /or Process
    - Quantify Variation (Monte Carlo Simulation or Test)
- Address long lead items.
- Perform prudent studies to flesh out the conformance plan – could include trials, test, analyses, and combinations thereof.
- Prepare the conformance plan. Initiate efforts as applicable, while studies are underway to address details of the next maturity level of the plan.
- Address cost, schedule, and technical risk.
- Set up criterion for committal gates – analytical tools, test methods, guidelines, specifications, knowledge committal, maturity assessment, etc.

- Secure commitment to the plan from all stakeholders.
- Address the business case as appropriate.

Conformance check sheets are generated by individual disciplines addressing the details of what needs to be conducted to achieve conformance to problem statement objectives and requirements. Figure 3. 3 shows a listing of the different types of conformance check sheets for three disciplines. Figure 3.4 shows a representative check sheet example for resin. Detailed check sheets for the same three disciplines given in Figure 3 are shown in Appendix D.

- **Structures**
  - Application Failure Modes
  - Material Properties
  - Durability
- **Materials**
  - Fiber
  - Resin
  - Prepreg
- **Producibility**
  - Cutting
  - Layup
  - Debulking
  - Cure
  - In-Process Quality
  - Final Part Quality

Figure 3. 3 Conformance Check Sheet Areas

RESIN - THERMOSET		0	1	2	3	4	5	6	7	8	9	10	How Obtained, Test or Anlaysis	Test/Analysis Identification
Uncured Resin														
Viscosity	➢	x	x	x	x	x							Test	ASTM D 4473
Reaction Rate	➢	x	x	x	x	x							Test	DSC via ASTM D 3418 and ISO 11357
Heat of Reaction	➢	x	x	x	x	x							Test	DSC via ASTM D 3418 and ISO 11357
Volatile Content/evolution temperature	➢	x	x	x	x	x							Test	TGA
Volatile Type	➢	x	x										Test/product knowledge	FTIR/Formula access
Volatile Vapor Pressure			x										Test	
Resin Cost		x	x	x	x	x							Specified Value	Based on vender input
Density			x	x	x	x							Analysis	Based on cured/uncured test data
Resin Cure Shrinkage				x									Analysis	Based on volumetric test data
CTE													Analysis	based on TMA or linear dilatometer data
Thermal Conductivity			x										Analysis	Assumed to be that of cured resin
Specific Heat			x										Analysis	Assumed to be that of cured resin
Kinetics Model			x	x									Analysis	Based on Reaction Rate
Viscosity Model			x	x									Analysis	Based on Kinetics Model, Test Data
Intellectual Property Issues		x	x	x	x	x								
HPLC	➢	x	x	x	x	x							Test	
FTIR	➢	x	x	x	x	x							Test	
Health and Safety Information		x	x										MSDS	
Morphology			x											
Ingredient Suppliers			x	x	x	x								
Cured Resin														
Tensile Stress to Failure		x	x										Test	ASTM D638
Young's Modulus, Tensile		x	x										Test	ASTM D638
Tensile Strain to Failure		x	x										Test	ASTM D638
Glass Transition Temperature		x	x										Test	ASTM D3418
Volatile Content	➢	x	x	x	x	x							Test	ASTM D3530
Density	➢	x	x	x	x	x							Test	ASTM D-792
Modulus as a Function of Temp				x									Test	Function of Temp and Degree of Cure
CTE				x									Test	ASTM E831 or linear diletometry
Thermal Conductivity				x									Test	ASTM C177
Solvent Resistance			x										Test	ASTM D543
Specific Heat				x									Test	ASTM E-1269 or Modulated DSC
Bulk Modulus				x									Analysis	
Shear Modulus				x									Test	ASTM E143
Poisson's Ratio			x										Test	ASTM E143 (Room Temp)
Coefficient of Moisture expansion				x									Test	No Standard
Compression Strength				x									Test	ASTM D695
Compression Modulus				x									Test	ASTM D695
Mass Transfer Properties				x									Test	eight gain vs time, Ficks Law and modelin
Viscoelastic Properties					x								Analysis	
Toughness Properties				x									Test	
Tg, Wet		x	x										Test	ASTM D3418
CME				x									Test	
Solvent (Moisture) Diffusitivity				x									Test	
Solvent Resistance			x										Test	

Figure 3.4 Example Conformance Check Sheet

4. Knowledge Generation

This section is divided into discussion of (1) general information on knowledge generation for an overall design knowledge base, (2) dealing with knowledge from heuristics, lessons learned, etc., (3) analysis, (4) test, (5) combinations of knowledge, analysis, and test, and (6) combinations of any category mix from different sources or different stages of maturity.

4.1 General

It is very important to reveal concerns early – cost, schedule, and technical – so that unknowns can be addressed and risk mitigation plans can be exercised if necessary. As such, it is good to ask *and document*, the handling of questions which interrogate every aspect of the material, process, application, threat, and opportunity. Performing this type of assessment requires different perspectives – assembly personnel, business personnel, customers, designers, fabricators, manufacturing personnel, system maintainers, suppliers, technologists, etc.

The information in this methodology and in the AIM-C system is helpful to performing strength, weakness, opportunities, and threats (SWOT) analyses on the materials, processes, and applications considered.

Thorough documentation is a very necessary practice. Seldom are the developers and implementers available when a system is in production, or for that matter, headed toward decommissioning and disposal. Sometimes it is hardly weeks or months before obsolescence, change in environmental laws, or business instability in a key or sole supplier creates the need for re-evaluation or re-qualification of some aspect of the insertion case.

4.2 Knowledge

Existing knowledge includes customer and supplier references, related quality records, previous databases, and lessons learned. It is important when using existing knowledge in an insertion assessment to understand and document the source and the details surrounding the situation in which the knowledge was first generated or understood. It is also important to identify the difference between opinion and scientific observation.

As discussed in Section 1, it is important to illuminate understanding with the quantitative assessment of distance from experience, Figure 4-1.

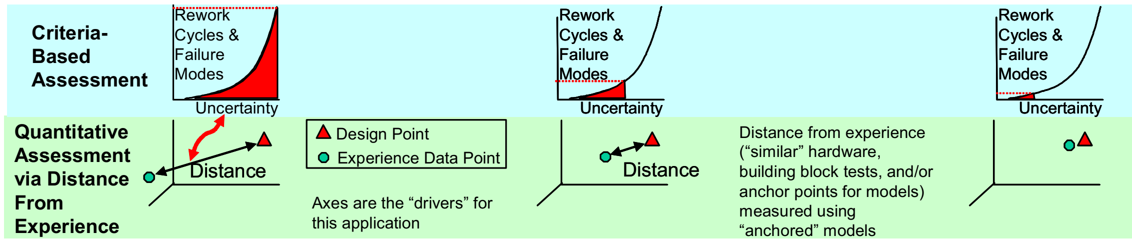


Figure 4-1 Assessment of Distance from Experience and Its Impact in Planning for Technology Insertion

4.3 Analysis

When using analysis to mature technology, one must understand the pedigree of the algorithms used, the assumptions made, the uncertainties introduced, the pedigree of the input files, and the validation performed to date. Similar to distance from experience expressed in Figure 1 for previous knowledge, is the assessment of the similarity of the analysis validation case to the particular application of the analysis method at the time of use for maturing technology/applications for insertion.

As with heuristic knowledge and with test data, it is imperative to document the input, the analytical method configuration control, the operating system used, and any validation planned or completed.

4.4 Test

When establishing the qualification test matrix, the plan should be sequenced to identify critical design and manufacturing properties early so that testing and analysis can be modified or discontinued if success criteria are not met. This will minimize qualification costs and risk by eliminating inadequate alternate materials and/or processes early in the test program before more expensive qualification tests are performed.

4.4.1 Specimen Traceability

When setting up the test program, the coordinator (typically the airframer) must decide how much traceability is desired and how easy is recovery of this information. In a typical test program, traceability information is generated by the resin and fiber manufacturers (batch numbers), the prepregger (batch and roll #), the part fabricator (panel # and autoclave cycle) and the specimen machining area (specimen identification or ID). Similar information must be included if using analysis.

Use the specimen ID to easily determine the location of the specimen in the as-fabricated panel and compare that location to the NDE data for the panel and the panel ply lay-up verification photomicrographs. For example, if two specimens produced low values in a test and they were cut from the same panel right next to one another it points to a possible problem in that area of the panel. The specimen ID should also be traceable to the actual autoclave cycle completed and any anomalies that occurred there as well as the roll of material used to make the panel and any variances that occurred in the lay-up or bagging of the panel. Traceability to the material batch number and the specific roll is important for problems that can be traced back to bad material as well as for calculation for equivalence.

4.4.2 Specimen Fabrication

With the move to outsource more testing and fabrication, control and documentation are becoming more important. For in-house fabrication a late change typically just impacts the number of hours used, whereas a late change for an out of house contractor may require modifications to the contract. More important is just agreeing to the work that is to be completed and the methods since it is unlikely you will be able to "stop by" the fabrication house to see if they are doing what you intend. All of the following items have become issues in at least one past material testing effort and should be defined prior to beginning fabrication.

- Are extra specimens required for testing/machine mistakes/investigate other environments?
- Is the fabricator responsible for verifying the panel lay-ups with photomicrographs or is a planning check off acceptable?
- Who is responsible for remaking substandard panels?
- Who supplies the material and remake material?
- Is the fabricator responsible for NDE?
- What is the inspection technique to be utilized and what are the criteria? Will it be tighter than the standard criteria? (dB loss for through-transmission ultrasonic inspection)
- How much edge trim is required?
- Is it acceptable to fabricate all of the specimens of a test type in a single panel or do you what them cured in two panels in different autoclave cure runs to create two fabrication "batches"?
- How many thermocouples are required?
- Do you want an actual cure cycle data submitted?
- Is the fabricator responsible for submitting the material batches used?
- Is it acceptable to use two rolls of material in a panel? Two batches?
- Is the cure cycle controlled with the free air temperature or the part/tool temperature?
- Is free air temperature overshoot permitted or required when approaching hold temperatures?
- What are tolerances on cure cycle hold time and temperatures as well as ramp rates?
- When is substitution in the bagging material sequence permitted?
- Is the part vacuum level taken from the active line or is a static port used?
- What number of vacuum ports is required per panel size?
- When the cycle calls out a vacuum only portion, is a minimal (10 psi) autoclave pressure permissible to improve heat transfer?
- Are autoclave abort and reprocessing procedures permissible?

- Is water jet cutting of specimens acceptable or must they be cut with a diamond wheel saw? Are cutting fluids permitted?
- Is a picture required of the specimen layout and reconstruction prior to panel cutting or is another method of specimen location in the panel required (angled lines draw on the panel for example)?
- What are the machining tolerances?

4.4.3 Specimen Testing

Specimen testing is moving away from the full service in-house test labs toward out-of-house entities that may or may not provide what you are expecting. The best way to limit the number of surprises and increase the usefulness of the data is to agree up front on what the testing house is to provide. The following is a partial list of issues that have come up in the past. This list assumes a test methods document or list of standard test methods have already been agreed to. Even standard methods often leave substantial room for interpretation.

- What methods will be used for moisturization? Water boil or humidity cabinet? Must the specimen be dried prior to moisturization?
- Are specimens to be conditioned until weight equilibrium?
- Is the moisture content at failure reported (as distinguished from the moisture content prior to test) Note that high temperature test specimens (especially those tested at 350 deg F or greater) can have significant desorption prior to failure.
- Are the room temperature specimens to be dried to the point of weight stabilization? This will typically take about three weeks.
- Are traveler specimens going to be used to monitor the moisture weight gain?
- Is the data to be supplied in MS Excel or is MS Word acceptable?
- Is a photo of each test set-up required?
- Are photos of each failed specimen required? A typical failure?
- Are plots of each specimen’s load response required or just the failure levels? Strain gage response or loading head travel?
- Which strain reporting points are required to be loaded into a table format from the raw data? Load at 100, 1000, 3000 or 6000 microinches, for example.
- How is confirmation of acceptable failure modes handled? Test house judgment or a digital photo sent to requester of failed specimen?
- Must an acceptable failure mode/load be confirmed for the first specimen prior to testing the remaining specimens?
- If specimens are to be tested at two temperatures, are they to be sequentially taken from the specimens provided or alternated?
- Is there the ability to test an extra specimen within the contract if an odd failure occurs or is that a contract add-on?

- Is a summary of the data required? In what format? Average values, standard deviations, nominal thickness stress level calculations, thickness, lay-up or lay-up identifier? Is the material traceability information required to be part of the test report?
- Are notations of unusual failure modes required?
- Is there calibration information on the test equipment?

If an analysis approach is being used, the issues listed above must be addressed and all assumptions made in the analysis must be clearly stated.

4.4.4 Test Variability

All testing has variability. It is very useful to have a list of expected test results and typical coefficients of variability (COV) based on previous testing with similar materials. When doing a second-source qualification, the COV's are available for the existing material based on the quality control data and the original test matrix. When generating data by analysis (analogy, interpolation or extrapolation), the statistical approach to generating COV's must be clearly stated along with assumptions and a statement regarding the validity of that approach.

4.5 Combinations of Knowledge, Analysis, and Test

Methodologies for use of combinations of knowledge, analysis, and test are provided in Section 9 and its associated attachments.

5. Conformance Assessment and Committal

Review available knowledge: heuristics, lessons-learned, information on similar problems or applications, public literature, analyses, and test results.

Address every question/requirement. Address functional/disciplinary issues. Address interdisciplinary issues/assumptions/decisions as an IPT with all stakeholders involved.

Determine divergence risk on existing information.

Evaluate the handling of error and uncertainty.

Assess the conformance of existing knowledge with requirements.

Determine additional knowledge needed based on knowledge gaps, unacceptable risk, etc.

Audit documentation, marking, completeness of information, version controls, etc.

Secure agreement from all stakeholders. Note differences, concerns, assumptions, and highlight critical information to the committal gate at the next level of maturity.

Commit appropriate files to the master database.

Make a plan for corrective action on that data which did not meet committal criteria, marking, uncertainty management, etc.

Make the committals of maturity advancement in the readiness level files. Include all required documentation at the time of committal.

Address the business case as appropriate.

Make the decision to continue maturing on the problem statement or revise the problem statement as appropriate.

If the problem is not continued, prepare and commit the decision and rationale to the knowledge base for archival purposes and future lessons learned.

6. Qualification

Qualification of equipment, consumable materials, materials, and processes is usually required in addition to certification of specific structure. Following are some of the elements of qualification.

- Supplier audits, along with a jointly signed Process Control Documents (PCD), and verification of appropriate supplier documents
- Material specifications developed with appropriate requirements
- Process specifications developed with appropriate robustness
- Inspection plans - receiving, quality conformance - destructive and non-destructive
- Standard drawing notes
- Design guidelines
- Material call outs - preferred materials lists and criteria
- Fabrication call outs - preferred suppliers' list and criteria
- Material life information and technical impacts "outside the processing window"
- Standard disposition and repair information
- Tooling guidelines
- Consumables listings, specifications, and results of evaluations such as foreign object detection, contamination, and quality conformance evaluations
- Effects of defects determinations – detection and ramifications of defects
- Multi-site round robins and sensitivity studies and their documentation
- Common test method/standards - one time and basis of repeated use
- Environmental considerations of processing, the application, out-time, storage, re-qualification for life extension, chemical resistance, etc.
- Peripheral/accompanying materials qualified and specifications - barrier ply, multiple needed product forms for processes and applications, adhesives, sealants, repair materials, etc.
- Intellectual property understood and documents in place
- Safety and medical documents approved and personal protective equipment, training, etc. documented and in place
- Raw and cured disposal, fire and crash handling procedures, shipping procedures - raw and part, etc.
- World wide laws understood - use, disposal, personal protective equipment, etc.
- Life cycle costs understood and plan for capture of remaining factors
- Risk mitigation plans - multi sources, plan for licensing or related qualifications, etc. for material, suppliers, fabricators, and development/implementation information
- Joint design, methods, test results, parts/materials, etc.
- Paint, de-paint, special coatings

Section 7. Certification Requirements for New Materials/Applications

The overall AIM-C methodology for inserting a new material into an application is a multidiscipline, multi-gated process to be performed by a multi-functional team, an integrated product development team (IPT) that includes technology developers and application designers in key functions. While it is difficult to assimilate the entire process for each function, it is relatively easy to provide an overview of the process and the steps to be taken by each discipline involved in the IPT. That summary is provided here. The role and process for each of the individual key disciplines is defined in subsequent sections of this document.

7.1. Certification Readiness Guides the AIM Methodology – The AIM methodology promotes the introduction of new materials by enabling the development of an integrated design knowledge base addressing all functional requirements and significant interactions. The methodology allows materials to be qualified and their applications certified rapidly for use in DoD products. The key to acceleration is the development by the joint application and technology development IPT of a key features fabrication and test article, Figure 7-1.

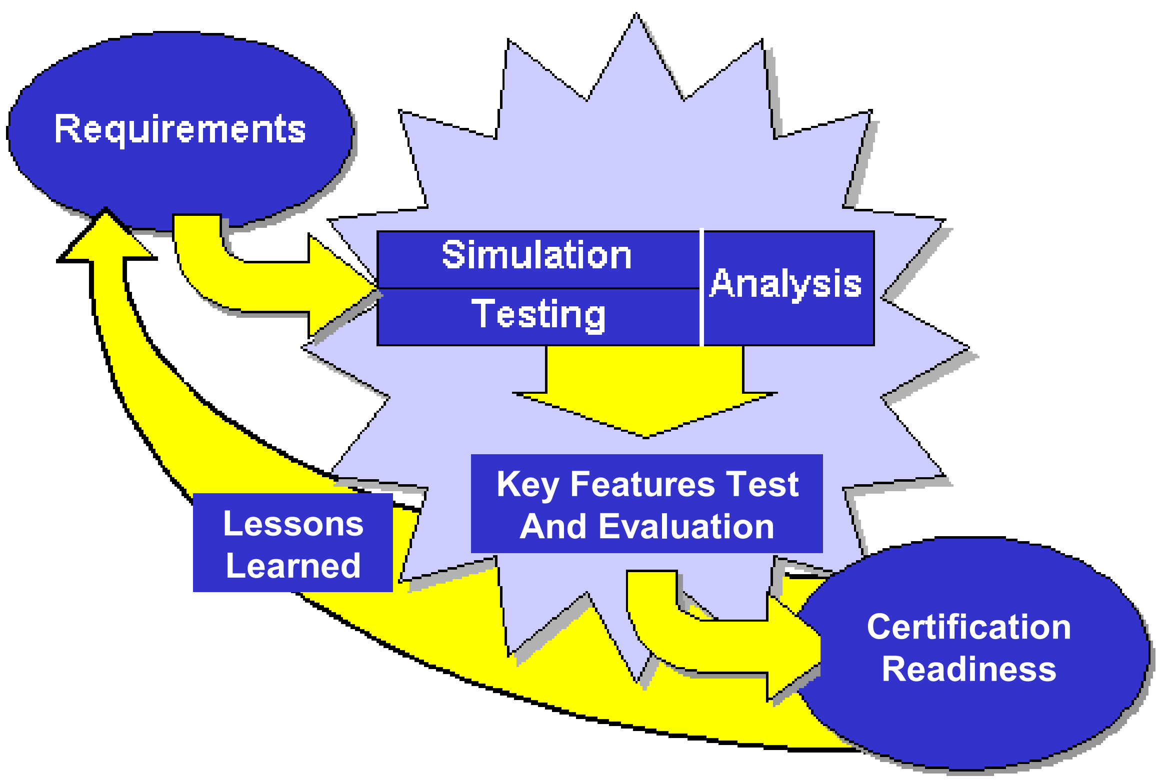


Figure 7-1. The Early Focus of the AIM-C Methodology is the Key Features Fabrication and Test Article. It Focuses the Insertion Activity on Certification Readiness

The key features article embodies those features considered potential showstoppers for each of the disciplines involved in the IPT. It focuses the materials and process development, as well as fabrication and assembly development prior to fabrication and it helps focus the risk reduction testing required to ensure successful certification after testing. It drives the IPT to answer every question regarding the application of the material to such a component and drives the development of the design knowledge base. For once the failure modes and loads have been determined by test for this complex, full-size structure, the tests required to develop the proper design values, or allowables, can be focused on those properties and designs that truly drive the integrity of the design.

7.2 JSSG Formed the Basis of Our Approach – In the AIM-C program, and in the software developed under AIM-C, we modeled our certification methodology after the one presented in the Joint Service Structural Guidelines Document. While we did divide the requirements up a little differently, to map them to their appropriate disciplines, we basically took the document and mapped it into the AIM-C software methodology by way of a series of Excel Spreadsheets that became our guide to certification. Figure 7-2 shows, in yellow boxes, the portions of the JSSG for Structures that were used in AIM-C Phase 1.

•***Loads and Criteria***: Consists of the development and evaluation of design criteria, external forces acting on the airframe, and repeated loads derived from aircraft design usage or usage obtained from operational data.

•**Flutter and Dynamics:** Evaluating the effect of unsteady aerodynamic forces acting on flexible structures and other dynamic loading conditions.

•**Vibroacoustics:** Dealing with developing the vibration and acoustics criteria used for design and installation of the aircraft structure and associated equipment items.

•***Strength***: Evaluating internal loads and stresses to determine whether adequate strength and safety margins exist under applied load and exposure to extreme environments.

•***Durability and Damage Tolerance***: Determining the service life of the airframe by evaluating accumulated damage (e.g. cracking) of components due to repeated load sources and exposure to operational environments.

•**Mass Properties:** Assessing the weights, centers of gravity, and mass moments of inertia to determine whether these are within allowable limits. Also, we manage the Automated Weight and Balance System, a flight essential tool for tracking individual aircraft mass properties in support of each mission of every USAF aircraft.

•***Manufacturing***: Including all the steps necessary to assemble a subsystem, component, or system. This process begins during product design with manufacturing and design engineers developing designs and production processes so the systems can be readily produced.

Figure 7-2 Elements of JSSG Used in AIM-C

We didn't use the JSSG alone. The FAA and NASA were doing some excellent work on aiding the private aircraft industry into methods for rapidly certifying materials using similitude with previously certified materials to decrease the number of tests required to ensure the use of existing allowables in their AGATE program. In the AIM-C program we followed this path and offer numerical and statistical analysis tools that allow the user to verify the confidence levels. In addition, the FAA was about to undertake a new National Program for Certification of Composite Structures that influenced some of the decisions made about the breadth of what we incorporated.

But A and B basis allowables are not the only requirements for certification of composite structures. Composites are unique in that their processesing methods and fabrication techniques impact the strength, durability, and stiffness of the structure much more than is true of more monolithic, isotropic metallic materials. And so the certification of a composite structure must include not just the material and its constituents, but the fabrication method, the processing methods, and in some cases, the assembly method in order to meet the requirements of knowing that one has the strength and durability required to meet the rigors of the flight environment into which the vehicle is to be deployed.

7.3 Requirements Drive the Design Knowledge Base (DKB) Development – But allowables and the impact of the material on structural properties are not the only elements of the design knowledge base. One of the primary objectives of the AIM-C program was to define the design knowledge base required to certify a vehicle for deployment. Figure 7-3 shows the summary of these elements of the design knowledge base as defined by the design team and the AIM-C team for the AIM-C Phase 1 program. While allowables and the effect of environment and defects are crucial parts of the knowledge base, there are many other aspects that have to be looked at and decisions made about how they will be handled.

Figure 7-3 The Design Knowledge Base Definition for AIM-C

7.4 What Can Be Done by Existing Knowledge, What Cannot – In general, material families can be qualified for use based on a rudimentary set of tests and extensive knowledge of the properties and characteristics of a composite material, if the design values are sufficiently below the test results obtained. If the designer is willing and able to use the properties and durability characteristics given, without excessive weight burden, then the use of generic allowables is feasible. This was determined, verified, and documented under the AGATE program.

However, it is rare that a design for flight has the weight margins required to accept certification by similitude. In general these vehicles are optimized and tailored to provide structural and material efficiencies that drive the design as close to the allowable limits as we can support with desired durability. Still, even in these cases, existing knowledge of fabrication methods, assembly techniques, and processing can play a pivotal role in reducing the fabrication and testing required to achieve confidence in the ability to deliver reproducible parts and assemblies for any particular application. By contrast, lessons learned from previous material systems give us some rather specific do's and don'ts that can spell the difference between successful insertion and insertions stopped without recourse.

Some of these lessons learned are identified and categorized in Figure 7-4. In that Figure, we have segregated the lessons into particular disciplines so that the lead for that

Customer / Stakeholders	IPT	Design	Allowables
Regulatory agency understands and approves methods used to insert materials	Full time focus of development team	Design teams can make design decisions before design guidelines were established	Testing for allowables costs too much
Customers are ready for 1) price, 2) service level, 3) maintenance & Inspection reqs, and 4) repair requirements	Development maturity in one area that outstrips the general maturity can be detrimental to the overall process	Preliminary design values can be developed with very few tests in prototype. How do we move into this paradigm with reduced risk for operational vehicles?	Must establish the requirements for the material
Customer is part of IPT in good and bad times	If materials development lags product development, the product is at risk	Concept development is done without regard to materials - this imposes limitations on designs, concepts, and costs	Early specs did not address the variables which impacted the process downstream
When customer changes, the tolerance for risk, vision, and technical criteria change	Has the material been used on other products or is it currently in use on other products?	Multifunctional parts require different designs than we traditionally look at.	Must test durability, aging, and environmental effects
Identify stakeholders early	Is an industry database available?	Design criteria that are late in being developed or established can eliminate new materials from the design space.	Moisturization takes a long time
Need to resolve conflicting requirements	IPTs need to be much larger than is currently perceived. They must include more administrative disciplines.	When designers do not follow composite design guidelines, there will be problems manufacturing parts.	Must understand long term environmental exposure effects
Material decisions must be made with the head and not with the heart.	Must demonstrate the ability to manufacture parts as designed	Design capabilities for composite parts and tools are required.	The impact of proof testing on certification and risk reduction must be determined
Government programming - large scale demos instead of basic materials and structural data. These programs leave many unaddressed issues and uncertainties	Need an On-the-Floor support staff capable of identifying problems and resolving them.	Conceptual design tools impose load paths that make composites a tough sell.	Due to miscommunication, the entire materials qualification program was run with an incorrect postcure - autoclave cycles used in the lab were not validated.
	Material form not compatible with design requirements and manufacturing process (K-3 wing, tow vs slit tape, fabric types, large Ti castings)	Incorrect ply stacking design or lay-up sequence	Lower performance of the materials in design details
	Lack of interface between design, materials, and manufacturing	Product design requirements and objectives must be met	Coupon data doesn't translate into elements

discipline can review and refresh the understandings that drive designs in particular directions (away from one fabrication method, toward another for example).

Figure 7-4 A Portion of the Lessons Learned from the AIM-C Design Team

7.5 What Can be Done by Analysis, What Cannot – Our ability to simulate and analyze structures and materials, including assembly, fabrication, and material processes has come a very long way in the last few years. The potential for similar strides in the next few is dramatic. In many cases these analyses have given us knowledge on a level we have not had before. A primary development of the AIM-C toolset has been to integrate the scientific toolset that allows us to determine the impact of a change made by one discipline on the parameters that affect other disciplines. Most noteworthy in this regard has been the interaction of design, structures, materials, and manufacturing to develop design solutions that are more robust than those produced in the past. We have the ability to "place" anomalies (tool mark off, area of less dimensional control, fiber waviness, etc) in regions in which they do not affect strength, stiffness, or the function/durability of the application.

However, there remain a number of elements of the design knowledge base that cannot be developed by analysis or test, but must be gathered from experience. The selected manufacturer need not have performed fabrication, processing, assembly, or test of the type of product being considered, but history shows that where experience is the driver, nothing but hands on experience can circumvent the perils in the early portion of the learning curve. That is why the AIM-C methodology leans so heavily on risk reduction leading to the key features fabrication and test article. This gives the fabrication house time to get familiar with what is being developed, the design requirements, and the hands on experience required to deliver reproducible parts with predictable failure modes for application to Department of Defense (DoD) systems. It is the demonstration of this capability that is a key to providing robust products for our customers.

7.6 How Analysis, Test, and Existing Knowledge Accelerates Satisfaction of the Requirements – It is pretty easy to see how existing knowledge leveraged against the requirements of the design knowledge base can accelerate the development of the design knowledge base for a material system. If the existing knowledge contains data for a similar system, whose behavior is known to mimic that for which the knowledge base is being developed, then that existing knowledge can be either accepted in part or in total and, when necessary, one can ratio the data to produce a knowledge base even closer to that expected for the new material.

However, one of the primary benefits of the AIM-C program was to provide in an easy to use format the best of the analysis tools available for prediction of the behavior of composite materials and structures. Tools for materials and processing, structural analysis and allowables development, and manufacturing simulation all exist in AIM-C. Moreover, these analysis tools are tied into templates that guide the user toward integrated solutions – solutions that span materials, processing, and structures. This is very important because while any structure is made up of the materials, processes, fabrication methods, and design, it is the integration of these disciplines that create a reproducible product.

The AIM-C system offers producibility tools that minimize variability and its impact. The ability to predict the as-manufactured part capability is another tool that AIM-C brings to the insertion of composite materials. No longer are models run independently, verified independently for material properties, structural properties, and manufacturing capabilities, but all data is generated to satisfy and verify the as-manufactured part properties and their variations. This means that the certification database for the application is the sum of the data used to predict the performance and variability of the as-manufactured part. While the same methodologies and analytical capabilities could be applied to metallic parts, the payoff is not generally as great because the ability to change the material system by processing or handling is not as great as it is in composites.

One element that does pay dividend to both the metallic and composite structure predictions through AIM is the statistical and probabilistic analysis capability available to ensure the robustness of the allowables and design values produced. The power of these tools is that they tie the material constituents through the processing to the application and allow a common set of tests to generate allowables for the as-manufactured structure. No longer are we simply pooling materials data to get approximate allowables, but we are pooling data from the materials, processes, and design to develop allowables that are unique to a component and its failure modes and loading conditions.

The AIM-C approach also provides guidelines for effective use of knowledge, test, and analysis – a recommended approach for each element of the AIM-C methodology. But we know that as the experience with these materials grows, and the knowledge base increases, these guidelines will need to be revised and so provision is made for that as well. For now, these guidelines, shown as a limited set in Figure 7-5, become the baseline against which cost, schedule, and performance are evaluated.

		(Uni and Cloth, ie 5hs or plain or 8hs etc.)		x	x									
2.1.1	➢	Tensile Strength	x	x	x	x	x							Test-Analysis
2.1.2	➢	Tensile Modulus E11 (longitudinal)	x	x	x	x	x							Test-Analysis
2.1.3	➢	Tensile Strain to Failure	x	x	x	x	x							Test-Analysis
2.1.19		Compressive Strength				o								Analysis
2.1.20		Cost	x	x	x	x	x							Specified Value
2.1.21		T(g)		x										Test
2.1.22		wet T(g)		x										Test
2.1.23		Health and Safety		x										MSDS
2.1.10		CTE - Radial			o									Analysis
2.1.11		Filament Diameter	x		x		x							Test
2.1.12		Filament Count	x		x		x							Test
2.1.13		Transverse Bulk Modulus			o									Analysis
2.1.14		Youngs Modulus, E22 Transverse			o									Test
2.1.15		Shear Modulus, G12			o									Analysis
2.1.16		Shear Modulus, G23			o									Analysis
2.1.17		Poissons Ratio, 12			o									Analysis
2.1.18		Poissons Ratio, 23			o									Analysis
2.1.4	➢	Yield (MUL)	x	x	x	x	x							Analysis
2.1.5	➢	Density	x	x	x	x	x							Test
2.1.6		Heat Capacity (Cp)			x									Test
2.1.7		Thermal Conductivity Longitudinal			x-o									Analysis
2.1.8		Thermal Conductivity Transverse			x-o									Analysis

Figure 7-5 Guidelines for Meeting Qualification/Certification Requirements Are Part of the Conformance Planning Activity

7.7 Metrics for Acceleration – As the IPT begins to develop its conformance plan to demonstrate that the as-manufactured part meets its requirements and the requirements for certification, it must decide to what level of risk reduction (confidence building, if you will) it will seek given the time/cost constraints under which it operates. The metrics for insertion are cost, schedule, and technical performance. Any one of these can always be sacrificed to achieve an acceptable result for another, however, the goal of the AIM-C program was to allow the IPT to weight these metrics as necessary to meet their insertion needs in the most rapid, cost effective, and least risk manner possible. The AIM-C team developed a means for tracking progress according to a schedule, cost, and technical performance according to the level of confidence developed for each as part of the maturation plan.

Figure 7-6 graphically represents the maturation tracking system in the AIM-C methodology. This tracking device is a summary of conformance, for each discipline on the IPT, required to meet the goal of certifiable insertion of a new material into a DoD system. This particular version assumes that validated analytical and experimental capabilities defined in the AIM methodology are available to meet those goals. From the design, fabrication, and test durations associated with each of these test plans, an overall summary schedule can be produced that is tailored to the application that is being examined. From these same definitions, the costs for design, analysis, fabrication, and test can be determined and used to project the total cost to reach readiness for certification.

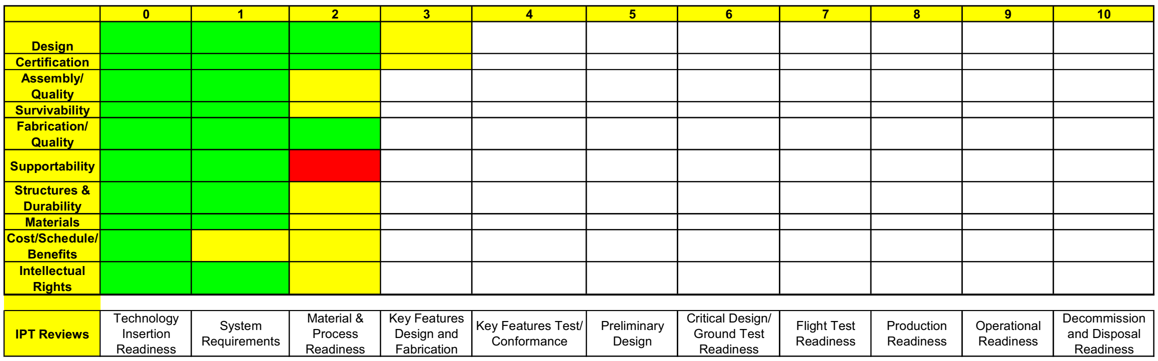


Figure 7-6 AIM-C Maturation Tracking System

But certification plans, costs, time, and risks are all negotiable between the IPT and their customer. If the team and its customer agree to take a higher risk approach in order to achieve certification readiness in a shorter time, then the tracking device will never show every thing green (for example), but will show those element s whose risks were considered acceptable as yellow and the cost and schedule modules can be used to develop the projected cost of the plan and the projected schedule. The reduction in the cost or schedule versus the guideline plan can be metrics against which the team can select between alternative plans to meet their specific goals. One method to track cost and schedule is shown in Figure 7-7 and for risk in Figure 7-8 as examples of how these metrics can be tracked for a given application.

AIM Methodology: Hat Stiffened Models and Approach (Template 14)

	Labor (Hrs.)	Flow (Wks)	Risk Factors Probability	Impact
Problem Definition and Collection of Data	37		20	2
Load, Validate, Verify HSP Global Model. Collect Data.	53		15	2
Determine load cases, document 5 most significant, for example.	53		75	0.5
Configure structure w/ aid of RDCS. Design scan/uncertainty analysis.	106		5	2
Exercise local models to compliment analysis	106		10	4.5
Add functionality to model(s) because of need identified in initial analysis	160			
Re-check load cases. Determine new significant cases, if any	37		5	4.5
If new load cases, then repeat above steps.	106			
Summarize and Report Design	27		5	3.5
Totals	686	14-wk effort		
Cost at $100 per labor hour	$ 68,628			

Conventional Methodology: Blade, J, or I Stiffener

	Labor (Hrs.)	Flow (wks)	Risk Factors Probability	Impact
Problem Definition and Collection of Data	37		20	2
Create deterministic FEM model of stiffener, Collect Data	80		30	3
Determine load cases, document 5 most significant, for example.	53		90	0.5
Configure structure, evaluating layup and materials choices (no geometric effects)	64		50	2
Develop local FEM models to compliment analysis	80		30	3
Iterate on geometry to configure structure -- dependant on allotted time	399		40	2.5
Iterate on local FEM models compliment analysis	346			
Re-check load cases. Determine new significant cases, if any	37		35	4.5
If new load cases, then report above steps.	160			
Summarize and Report Design	27		5	3.5
Totals	1282	30-wk effort		
Cost at $100 per labor hour	$ 128,212			

Figure 7-7 Cost and Schedule Metrics for a Given Application

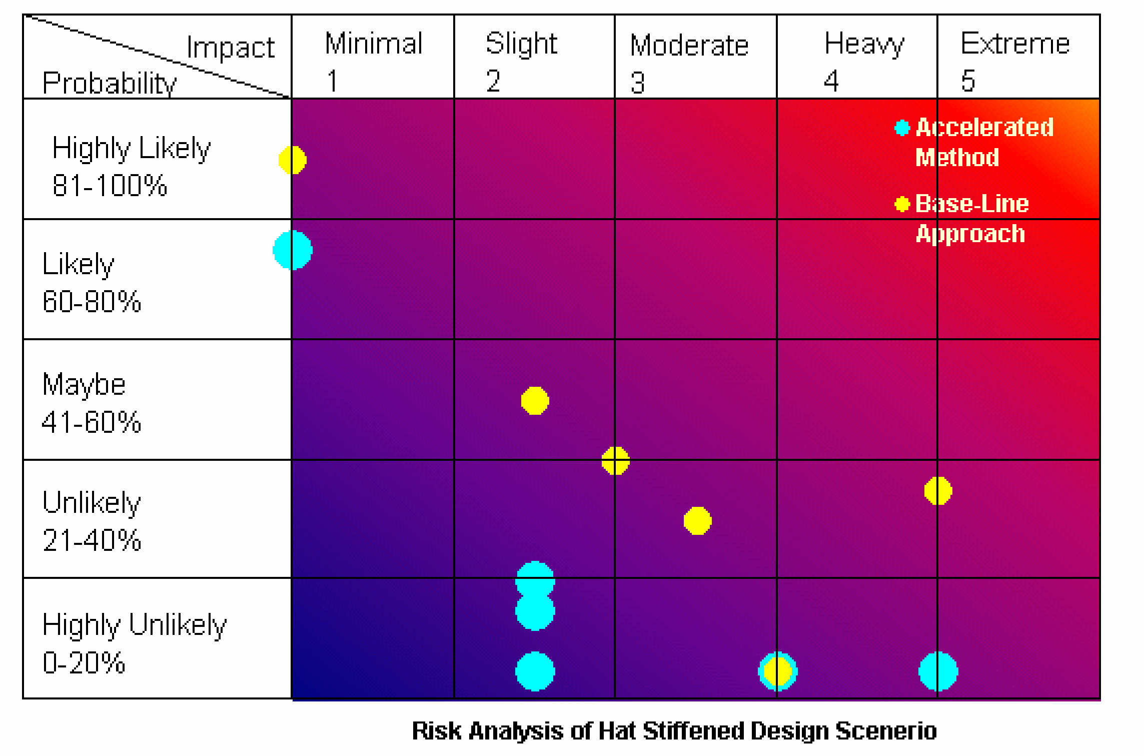


Figure 7-8 Risk Assessment for a Given Application

7.8 Joint Service Specification Guide

This guide, jointly developed by the Air Force, Navy, and Army, establishes the structural performance and verification requirements for the airframe. These requirements are derived from operational and maintenance needs and apply to the airframe structure which is required to function, sustain loads, resist damage and minimize adverse operational and readiness impacts during usage for the entire service life. This usage pertains to both land and ship based operations including take-off, catapult, flight, landing, arrestment, ground handling, maintenance, and flight and laboratory tests. This guide also provide for trade studies and analyses to identify and establish certain structural design parameters and criteria which, as a minimum, are necessary to enable the airframe to meet these structural performance requirements, consistent with the program acquisition plan for force level inventory and life cycle cost. These guidelines are provided in detail in US Department of Defense Publication JSSG-2006.

7.8.1 Brief Summary of the Joint Service Specifications Guide – The Joint Service Specifications Guide includes definitions of the type of information required to provide certification agents with the confidence levels required to certify aircraft airframes. Moreover, it covers the following topics: airframe configurations, equipment, payloads, weight distributions, weights, center of gravity, speeds, altitudes, flight load factors, land-based and ship-based aircraft ground loading parameters, limit loads, ultimate loads, deformations, service life and usage, atmosphere, chemical, thermal, and climatic environments, power or thrust loads, flight control and stability augmentation devices, materilas and processes, finishes, non-structural coatings, films, and layers, system failures, lightning strikes and electrostatic charges, foreign object damage (FOD), producibility, maintainability, and supportability. Where standard values exist they are provided, but the product definition always supercedes this document in defining requirements for the aircraft and its airframe. This guide not only defines the values that are required, but also helps define the testing required to demonstrate satisfaction of the requirements. The user will recognize at once that a number of different disciplines are involved in defining and satisfying these guidelines. The need for an integrated product team to perform these activities and integrate the means toward their satisfaction is key to removing duplicative effort, testing, and disconnected requirements from the plan to achieve conformance with these guidelines – which is one of the key focal points for the AIM-C acceleration effort.

7.8.2 Summaries of the Guidelines for Design, Systems, Structures, Manufacturing, Materials – With only a little modification, we can divide the areas addressed in the JSSG Document into the subject divisions. This will help us organize and segregate what each discipline in the IPT is responsible for answering. However, if the IPT is performing as it ought to do, the entire team is involved in and responsible delivering the best solution for all competing requirements throughout the guide. In this vein, then design would lead the team in addressing: airframe configurations, equipment, payloads, weight distributions, weights, center of gravity, speeds, and altitudes. Systems would lead the team in defining solutions for the power or thrust load requirements, flight control and stability augmentation devices, as well as system reliability in service, after lightning strikes, and after electrostatic discharges. Structures and Loads would lead definition of flight load factors, land-based and ship-based aircraft ground loading parameters, limit loads, ultimate loads, deformations, service life and usage, as well as foreign object damage. Manufacturing would lead the team to define producibility and maintainability. And Materials and processes would address the areas of atmospheric, chemical, thermal, and climatic environments, materials and processes, finishes, non-structural coatings, films, and layers. All members of the team would be responsible for determining the requirements for inspection and supportability, although in many companies these elements are led by a supportability discipline specialist.

7.8.3 Benefit of Addressing the Guidelines as an Integrated Team – With so many potentially conflicting requirements to be faced and with a mandate to accelerate the insertion of productive, high payoff materials, the most rational solution was to address these guidelines with an integrated team of specialists in each of these disciplines so that the insertion had maximum potential for successfully meeting the various criteria. And, in those cases in which all the criteria could not be met, the team was charged to deliver a choice between criteria in order to best meet the objectives of the airframe application. The team then could review the requirements, select those best suited to the application, modify those applicable to best fit the system requirements to fit the application in question, develop a plan to meet these requirements, develop the database/knowledge base required to fill in what was not already known, and to provide a test plan and oversight to ensure that only the most necessary data is delivered to satisfy the requirements. The integrated Product team was also assigned the tasks of assessing the conformance of the knowledge base developed with that required and to approve the pedigree of the information used to feed the knowledge base and satisfy the program and certification agents.

The integrated product team also includes the certification agent, the cost, and schedule leads so that there is constant review and approval of the conformance plan, data development, and knowledge assessment by the team members that determined the metrics for both acceptance and need by the program. It is cost, performance, and risk that are the metrics used to measure acceleration of materials, or technology, insertion.

Sections 7.9 through 7.11 provide an interpretation or example of the use of AIM-C from the perspectives of Structures, Manufacturing, and Materials Engineering Viewpoints.

7.9 Use of AIM-C for Structures

For all disciplines involved in the integrated Product Team, the AIM-C methodology carries the same steps: Problem and Requirements Definition, Conformance Planning, Knowledge Generation, Conformance Assessment, Acceptance and Committal to the Design Knowledge Base, and Documentation of Lessons Learned. The next few sections address these steps as they apply to three primary disciplines involved in the insertion of a new material system, but they apply equally well to other disciplines, other technologies, and other applications. Structures Technology is one the disciplines that is closer to the application than many of the disciplines involved in the IPT, perhaps closest except for Design. However the steps of the AIM-C methodology apply to them just as they do to the others as will be demonstrated in the discussion.

7.9.1 Problem Statement and Requirements Generation – Structural design requirements come from three primary sources: the Joint Service Specification Guidelines that we've been discussing already, the specific requirements called out by the customer, and requirements imposed by other disciplines in order for them to meet their requirements. It is the third of these sources that requires the application of the IPT to design integration and ensures that all disciplinary requirements have been either accommodated or looked at and determined to be secondary to the other requirements imposed on the system.

In the past, Military Service Specifications were the primary source for structural design requirements for any system, but as systems became more sophisticated and the interaction of disciplines became more pronounced, Mil-Specs have been replaced by the JSS Guidelines and requirements defined by the funding customers. Whether general specifications will be developed for structures in the future remains a continuing question. But no matter where the requirements come from the AIM-C Process is capable of handling them.

7.9.2 Conformance Planning – There is a hierarchy to conformance planning that is related to the testing performed to support it. Strength and stiffness come first because the analytical tools require this data early on to develop models for the structural analysts and design community. Non-linear failure modes: buckling, crippling, collapse come next as compression and shear loadings are defined from the finite element model built based on the stiffness data and strength data provided in the first steps. Finally, durability and damage tolerance assessments are performed to develop the data required for life prediction and damage progression are developed. Strength and durability of the attachments (be they bolted or bonded) are a major effort in this knowledge generation task and is so reflected in the conformance planning.

The improved analytical procedures incorporated into the AIM-C toolset allow some reduction in these tests, but these reductions are largely offset by the need for variational analyses of the materials, processes, and geometries involved in the application.

1. Obtain preliminary lamina properties (modulus, etc) so that finite element models of the structure can be built for preliminary analysis. Lamina properties are also needed to predict laminate allowables. Traditionally, lamina properties are obtained from test. However, AIM-C Tools are available to generate these properties given resin and fiber properties. Tasks include: enter known data into AIM-C System; get material info from Materials (fiber & resin) module; check airframe requirements (temperature range, environment, etc); run Lamina module to get predicted lamina properties; pass lamina properties to IPT's and other AIM-C modules; identify additional resin, fiber and prepreg data needed to increase confidence level in predictions for next cycle of allowables predictions (Item 5)
2. Generate preliminary Laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI) based on nominal parameters. These preliminary allowables will be used to size the structure. Need to include the effects of environment and design features (open vs filled, countersink, hole size, edge distance, etc). Again, this data would all come structural testing. However, AIM-C Tools are available to generate some of these properties. Specifically unnotched and open hole tension and compression data (UNT, UNC, OHC, OHT) may be generated for a range of laminates using the AIMC tool. Some test data is required. At a minimum lamina testing at 10 and 90 degree fiber orientations are required in order to obtain data for the Strain Invariant Method (Template 10). In addition, the point stress method used to generate strength data using Template 7 requires lamina strength data obtained from testing at 0 degree and 90 degree fiber orientations and requires testing of an open hole laminate. The laminate lay up may be common lay up desired for the application but it is best to not use one strongly dominated by +/- 45 degree plies. Tasks include: enter known data into AIM-C System; get needed info from lamina module; run Laminate module or Templates 7 or 10 to get predicted laminate carpet plot data.
3. Preliminary size the part using data generated in previous steps. AIM-C tools exist for a specific class of structural problems that deal with the sizing of a hat stiffened panel (Templates 14,16 and 17). These provide additional insight into the properties needed for conformance.
4. Predict in-plane laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI). Include Environmental impacts. (This task is completed at the beginning of the ALO phase to minimize the amount of redesign because of allowables changes downstream. Need to refine the design allowables based on proposed processing, tooling, effects of defects, etc.) Tasks include: run structures module to update design allowables based on MP2 input; run durability module to determine impact of fatigue

(based on preliminary spectrum); run materials module to determine impact of fluid resistance, etc.; release updated allowables to IPT's.

7.9.3 Knowledge Generation – Conformance planning leads to the initial development of design properties for initial sizing and trade studies. These elements include:

5. Pilot batch of material available - First batch of material fabricated using proposed nominal production parameters but on a pilot line.
6. Lamina and Laminate tests, including environment, of Pilot Batch. Number of tests are variable. The objective of these tests is to determine batch variability. This data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.
7. EMD Go ahead - Official start of the Engineering Manufacturing Develop phase. Product teams launch into intense design phase.

7.9.4 Conformance Assessment – Conformance assessment requires a disciplinary review of the data obtained by analysis, test, or previous data; an IPT review of the same data so that problems for any discipline can be addressed, and finally, a review by both IPT and certification agent is performed. Once good rapport between the IPT and the certification agent has been developed, then normally, we would expect to see the certification agent in the IPT final review of the material system.

8. Determine impact of selected materials (components variability, etc.), processes (cure cycle window, etc.), and producibility features (i.e. tooling, part configuration, etc.) on design allowables. Design allowables may need to be refined based on proposed processing, tooling, effects of defects, etc.
9. Update preliminary allowables with pilot batch data - update previously estimated allowables based on pilot batch data. These allowables will now be available for Concept Lay out (CLO). Again, this data will be used for extensive structural configuration and sizing exercises by structural designers and engineers

7.9.5 Committing the Knowledge to the Design Knowledge Base – Knowledge is committed to the design knowledge base when the IPT, including the certification agent agrees that the knowledge is being used for the design of the application. In this case, this knowledge includes the pedigree and data associated with the material, its processing, and the design that was tested.

10. Production qualification material batches. - The number of batches and testing must be coordinated with Certifying Agency. The batch qualification data and the elements, coupons, and components made from it should be accessible to the IPT.
11. CLO – Concept Layout - Product team task – here the knowledge base and the design are linked together and bookkept electronically so that all the knowledge supporting this phase of the design are housed or can be referenced from the design knowledge base. The IPT and certification agent document their agreement with these elements of knowledge prior to the placing of the knowledge into the knowledge base.

7.9.6 Capturing Lessons Learned – Even after the design values, the configuration, and the manufacturing and materials specifications have been documented, the AIM-C methodology requires that lessons learned from the process be captured. These are captured within the AIM-C System so that future users are able to see and learn from the lessons learned by those who had gone before. This is crucial because it can avoid costly learning experiences from being repeated.

12. Allowables modifications, as dictated by tests - Continuously evaluate predicted allowables versus test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

7.9.7 Application To Further Design Cycles - As described herein, the phases of this effort are just the first cycle of the design-build-test process. The cycle is repeated for ALO including:

13. Allowables validation tests (coupon tests) - Validate predicted design allowables from the AIM-CAT tool. Need to do theses tests with the production qualification material – including: Select critical tests to perform first based on risks (cost, schedule, technical) identified by what we know; tests coupons should be fabricated by the shop that will fabricate the production parts; use the selected production processes to build in the predicted MP2 parts; choose proper test methods, test labs, etc.
14. ALO – Assembly Layout - Product team task

Finally, the same process is applied to the design before the Build-To packages are released to the manufacturing shops. These steps include:

15. Effects of defects (coupon/element tests) - Based on identified expected defects, determine via tests impact on design allowables. Performed earlier enough in program that design changes can be made to increase robustness and minimize cost.
16. Element Tests, including fatigue - Test critical joints and splices, including fatigue tests. Include defects as required.
17. BTP – Build To Patches and normal Redesign effort based on coordination with manufacturing
18. Allowables modifications, as dictated by tests - Continuously evaluate predicted allowables vs test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

7.10 Use of AIM-C from Manufacturing Perspective

This section provides an overview of the producibility methodology for new material qualification and certification. Several new and unique areas are associated with the AIM-C producibility methodology. First and foremost is the aspect of feature based producibility assessments where standard producibility components with increasing complexity are fabricated and evaluated in stages associated with increasing maturity levels. As the knowledge base for different materials is established, this will allow better material-to-material comparisons of producibility. Second, the approach addresses both producibility operations and quality technical areas and production readiness. The approach structure enables early identification of any show stopper issues to minimize rework or redoing of activities because of problems.

Composite producibility operations/processes include cutting, layup, debulking, bagging, cure, tooling and non-destructive evaluations (NDE). Quality includes in-process and final part. For aircraft applications, the integrated product team (IPT) disciplines involved in producibility activities include manufacturing, material and processing, tooling, and quality.

The overall AIM-C methodology process flow is requirements, conformance to requirements, knowledge gathering, conformance assessment, and knowledge committal activities. A unique aspect of the methodology process flow for producibility requirements is the addition of production readiness as part of the requirement package. This requirement package is addressed by conformance to requirements and conformance activities.

7.10.1 Problem Statement and Requirements Generation – Component requirements flow down to specific exit criteria according to categories of disciplines or areas. Producibility/Fabrication exit criteria are primarily based on successful part fabrication through a phased approach from producibility development through producibility readiness for the application. For new material insertion, the primary goal is that producibility stability has been demonstrated with multiple parts and that final process specifications exist. The intent for this stability is to enable generation of design allowables, subcomponents and components for certification. Previous experience has shown that stability for applications that has not been achieved with scale up has required significant rework because of a show stoppers that only surface when full scale parts are attempted. For this reason, the exit criteria address application features from elements, through subcomponents, to full scale components to minimize risk at the time of actual application to component fabrication.

The feature based part fabrication approach is for knowledge generation and is compatible with the exit criteria for the application itself and with the producibility maturation process. Three issues arose when establishing the producibility methodology/process.

1. There is a different perspective of readiness levels when looking at maturity from a producibility perspective.
2. Producibility subdivides into the manufacturing operations/processes of cutting, layup, debulking, bagging, cure, tooling, and NDE where each could be at a different maturity level and not be captured correctly at the TRL level.
3. Production readiness for each of the operations/processes in producibility is not captured.

The technology readiness level (TRL) approach for measurement of maturity is driven by certification requirements. It looks at maturity from the application or system point of view for design and test items or steps. This qualification readiness level concept then leads to the question of how can production readiness be incorporated into requirements for qualification. Production readiness has a series of generic evaluation categories that have to be addressed, regardless of the technology (materials, processing, producibility, etc.).

By combining the production readiness categories with XRL maturity step numbering, a matrix can be established where individual blocks can be filled in for exit criteria for production readiness and technology readiness requirements that is applicable for composite materials, processing and producibility. The categories include technical requirements and ones associated with production readiness. Being generic, it covers all assessment areas. It should be noted that not all areas or maturity level exit criteria may be specifically applicable to qualification and certification of materials, processing, producibility or answering of the problem statement.

7.10.2 Conformance Planning - The approach for producibility requirement conformance is comprised of two steps. First is to generate the producibility knowledge and information at an item level for each item to satisfy qualification and certification requirements. Second is to summarize information from each item as to its impact on either in-process quality or final part quality.

The in-process quality information goes into material and processing guidelines/specification for controls and tolerances. Final part quality information is used for comparisons of capabilities to application requirements as a means of assessing whether the application parts can be made with the materials and producibility operations.

7.10.3 Knowledge Generation - The feature based producibility approach is a key aspect of producibility methodology. This approach is based on manufacturing a series of increased complexity parts starting with flat, constant thickness panels going up to full scale generic components based on the application. Parameters for producibility areas and items are established using flat and ramped panels. These parameters are then either validated or modified when making multiple thickness flat panels, application elements, and generic full scale components. One of the unique aspects of this approach is that mechanical and physical properties can be obtained during producibility development and utilized for the design knowledge base properties and effects of defects very early in qualification and certification activities.

Initial fabrication trials are representative of the applications being considered and evaluation results are used to establish producibility parameters. Later parts are generic components that are based on the application being certified. These parts would contain key features of the application for early producibility evaluations and assessments.

These feature based producibility parts are fabricated at different stages or maturity levels and are a metric of producibility maturity. Flat and ramped panels are the basic parts for producibility assessments and comparisons at all maturity levels to ensure that any specific changes to parameters do not impact overall parameter impact on quality.

7.10.4 Conformance Assessment – Conformance assessment fall into two categories for producibility. In-process quality addresses item variability that is measured/controlled during individual item or operation execution. For composites producibility, in-process quality variability covers: indirect/support materials, ply angle, ply lap/gap, out time, freezer time, cure time, temp, pressure, heat up rates, cure abort conditions, debulk time, temp, pressure, methods, bagging gaps, breathers, bleeders, and NDE standards.

The investigations and assessments of in-process variability impact is conducted on each individual item during quick look assessments initially and detailed assessments for IPT review. Final part quality addresses accept/reject criteria commonly used for composite parts: geometric dimensions, thickness, voids, porosity, inclusions, surface waviness, surface finish, fiber volume/resin content, in plane fiber distortion, out of plane fiber distortion. These evaluations yield capabilities for material and producibility which is then compared to application requirements to see whether these requirements can be met with the capabilities. This information is also used during part producibility assessments.

Producibility part assessments are conducted when answering questions about manufacturing application components. It is a way of using the knowledge base information from producibility item assessments, final part quality and other knowledge to answer manufacturing questions in an IPT environment. The size of this is huge relative to application diversity and the needed amount of information is therefore very large.

As a step in conducting part producibility assessments, an evaluation was conducted to address producibility information needed at the time of part trade studies on a hat stiffened panel. A review of IPT activities was conducted from a producibility standpoint and results are listed as seven activities: ID defects to be minimized, ID surface(s) that need to be maintained, ID acceptable tolerances, define assembly/manufacturing method, define tooling approach, define producibility, quality steps, and make parts. The first three items are from part requirements. Items 4 and 5 are a trade off of manufacturing (final part quality from producibility item assessments) and tooling capabilities (from previous knowledge other than what is generated in the AIM-C process) is compared to requirements. Items 6 and 7 are the producibility operations, in-process quality and final part fabrication.

The information or knowledge for assessment steps 2, 3, and 4 comes from previous knowledge or history. Information or knowledge for assessment steps 5 and 6 comes from producibility item assessment results and from previous knowledge or history. One information and history void area is dimensional quantification of defects relative to tooling, producibility and materials. Consequently, results from this part assessment process are very subjective and vary from person to person and company to company according to previous experience and opinion.

7.10.5 Committing the Knowledge to the Design Knowledge Base – The most consistent way to capture the manufacturing or producibility knowledge base is to document the specifications and fabrication processes as part of the product definition package (the build-to package as Boeing refers to it). The couples all design, producibility, and certification knowledge in a single design knowledge base for use by any fabrication house or shop so that they know how this component is to be manufactured and why it looks and is fabricated the way its is defined. The mechanism for this documentation exists and it is being used for much of the knowledge base as defined by AIM-C currently. We are talking about a significant, but not unwieldy expansion to include the manufacturing pedigree of the component.

7.10.6 Capturing Lessons Learned – As noted before, the AIM-C methodology requires that lessons learned from the process be captured. These are captured within the AIM-C system, by discipline, so that future users are able to see and learn from the lessons learned by those who had gone before. This is crucial because it can avoid costly learning experiences from being repeated.

7.11 Use of AIM-C from Materials Engineering Perspective

Up-front consideration and thorough planning for a program's combined material and process needs over the life of the program can significantly reduce both costs and risks. Qualification evaluations typically exhibit progressive cost escalations from coupon tests, to elements, to components, to parts, and eventually to aircraft. This progression is commonly known as the "building block" approach to qualification. It is important, therefore, to conduct initial planning to properly align and coordinate multiple sources, product forms, and processes early in the qualification effort. This planning allows better utilization of the existing expensive large scale tests by incorporating various considerations in left hand/right hand or upper/lower portions of the test items.

Materials can be evaluated for specific applications, which may allow for a partial replacement of the baseline material. It should be noted that if a partial replacement is considered, the cost of multiple drawing changes required maintaining a distinction between two materials must be considered. In addition, some cost must be allocated for analysis review to determine which application can withstand material properties that are not equivalent or are better than the baseline properties.

When a material or process-related change is identified or a material or process-related problem is defined remediation, the stakeholders may use the steps here to develop a solution.

7.11.1 Problem Statement - The problem statement bounds the qualification program by providing a clear statement of the desired outcome and success criteria. It delineates responsibilities and requirements for the aspects of the program to the material supplier, processor, prime contractor, test house, or Navy customer. It becomes the cornerstone for other decisions and serves as the basis of the business case as well as divergence and risk analyses on which the technical acceptability test matrix is built. When the problem statement is found (1) to be lacking specificity, (2) to be so specific as to limit approaches, or (3) to have a clear technical error; modifications may be made with the agreement of the qualification participants and stakeholders.

7.11.2. Conformance Planning – Conformance planning involves developing the business case for development of the knowledge base required to satisfy the requirements identified in the problem statement definition.

7.11.2.1. Business Case - Following development of the problem statement, a business case is developed (1) to clarify responsibilities, (2) to show the clear benefit of the qualification to all participants and stakeholders, and (3) to obtain and allocate resources for the qualification effort.

7.11.2.2. Divergence and Risk - Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how different the new material or process is from the known and understood materials or processes. Risk analysis is performed to determine the consequence of reduced testing, sequencing testing and so forth.

7.11.2.3. Technical Acceptability - Technical acceptability is achieved by fulfilling the objectives included in the problem statement, answering technical questions based on historic knowledge and practices, and by showing through test, analysis, and the results of the divergence/risk analyses that the material or process system is understood. Its strengths and weaknesses are then identified and communicated through design and analysis guidelines.

7.11.3. <u>Knowledge Base Development</u> – Knowledge base development includes data mining, data development, and analytical prediction of material and structural behaviors. The IPT uses these knowledge pools to determine whether or not the design they have developed will meet the desired, primary certification requirements. The allowables development and equivalency validation focuses on the quantitative aspects of the qualification. It provides methodologies for meeting the qualification and certification criteria. .

7.11.4. <u>Conformance Assessment and Commitment of Knowledge -</u> In the past, qualification programs have often fallen short because they ended with the quantitative aspects of design databases. However, a successful qualification program must include the conformance assessment needed to assure production readiness. Production readiness includes raw material suppliers, formulators, fiber suppliers, preformers, processors, quality conformance testing, adequate documentation, and other areas. Again, this protocol methodology does not provide all the answers for specific qualifications. Instead, it provides discussion to stimulate thought by the qualification participants and prompts appropriate planning based on the problem statement, business case, divergence or risk analyses, and technical acceptability testing established for the particular case by knowledgeable stakeholders. And the system documents this conformance and the pedigree of the knowledge used to attain that conformance.

7.11.5. <u>Lessons Learned -</u> Finally, the methodology admits that no qualification is perfect. Lessons learned from the past should be incorporated into the plan as soon as the tie is identified in the divergence or risk analyses. In addition, lessons learned from the current qualification should be documented and acted upon throughout the qualification.

Developing a qualification plan should provide a total system performance validation with a complete database.

7.12 How the AIM-C Methodology Reveals Unknowns and Risks

The conventional Building Block Methodology works to establish as much knowledge about a material system as can be generated in element and coupon level tests in order to reduce the risk for development and testing of the risk reduction articles that thereby reduce the risk for full scale articles. The AIM approach seeks to reduce the testing of the expensive and often misleading risk reduction article by replacing them with a very early development, fabrication, and test of what is called a Key Features Fabrication and Test Article.

The Key Features Article ensures that all disciplines of the IPT have addressed their greatest concerns with an article to be fabricated early enough in the program that, should redirection be required, there is still time to accomplish it. It ensures readiness for scale-up to full size components, since the article is the scale of the largest component to be fabricated. It ensures that data mining, knowledge gathering and test development is focused on only that data required to ensure the success of the Key Features Article. And, by virtue of the lessons learned from the testing, it focuses the certification testing that follows it toward those parameters that truly control the design of the component, its failure modes and loads. This alone can reduce the certification test cost by more than 50% (See Sections on Cost and Schedule).

7.12.1 How the Key Features Build and Test Feeds Conformance – In the AIM-C Methodology, Figure 7-9, the Key Features Build and Test Article is the focal point for the development of knowledge leading up to its build and test. As that focal point, it guides and directs all of the knowledge gathering processes to focus on those features predicted to control the design of the parts to be built using the prescribed material(s).

Conformance plans and test requirements are built around the development of the manufacturing processes and material qualifications required to ensure that a reproducible part can be delivered and tested. The IPT works hard to make sure that tests performed to satisfy materials requirements work to fulfill as many design, manufacturing, and engineering test requirements as they possibly can. Similarly, manufacturing tests are used to their maximum benefit for the team. No test is performed that cannot meet multiple needs within the IPT until those needs have been predominantly satisfied. As manufacturing approaches readiness for the key features fabrication, the processes are pretty nearly locked in for the production of the airframe hardware. This means that toward the end of this cycle, we can begin to develop allowables that reflect the manufacturing approach. And once the Key Features Article has been tested, assuming a successful outcome, the allowables development can begin in earnest knowing that the manufacturing processes have been validated and that critical design details have performed as predicted.

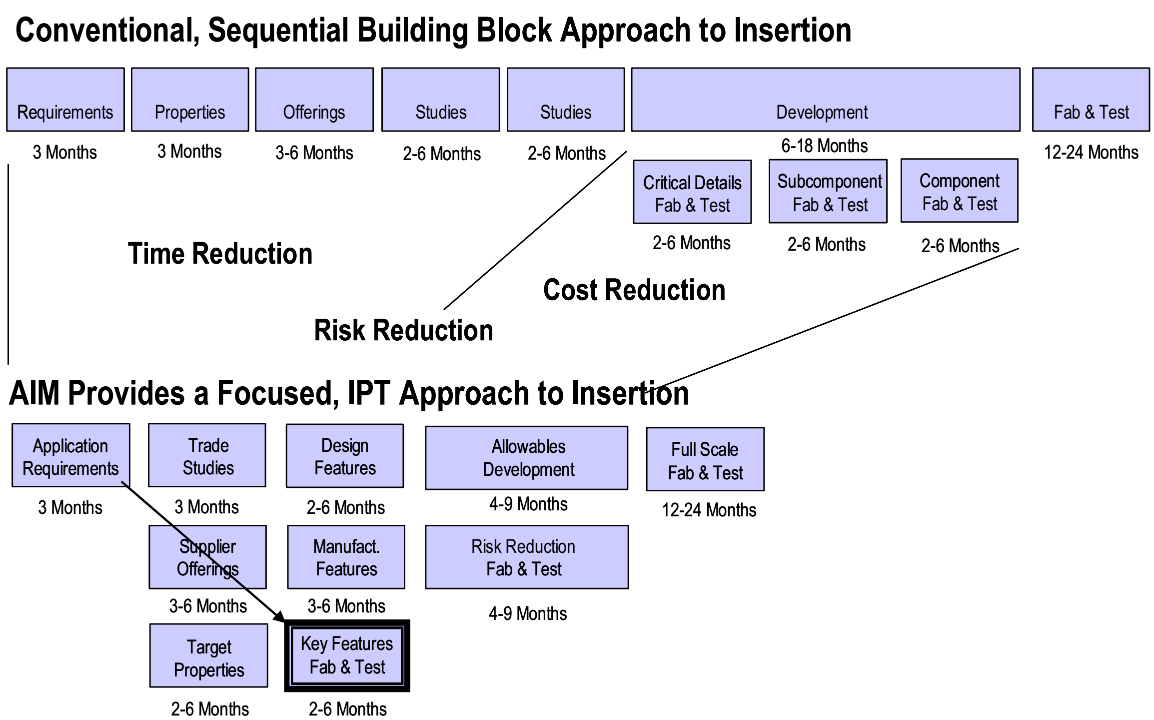


Figure 7-9 The Key Features Fabrication and Test Article is a Key to Acceleration

7.12.2 How the Results of the Key Features Test Focuses the Certification Plan – In addition to the role of the Key Features Fabrication and Test Article to focus the efforts prior to its testing, the results of that testing drives and focuses the development of allowables for design. For once the Key Features Article has been fabricated and tested, repaired and retested, we know what strength and stiffness parameters drive the design of the component. Thus we can begin to restrict the allowables to those failure modes and loads that control the design of the component. This allows us to focus our testing and knowledge mining on those parameters that control the design.

7.13 Summary

Figure 7-10 provides an example of how selected testing, validated analysis tools, and understanding of variability, and uncertainty management can be utilized for allowables determination. This approach is promising for further application in joints and other increasingly complex structural certification situations.

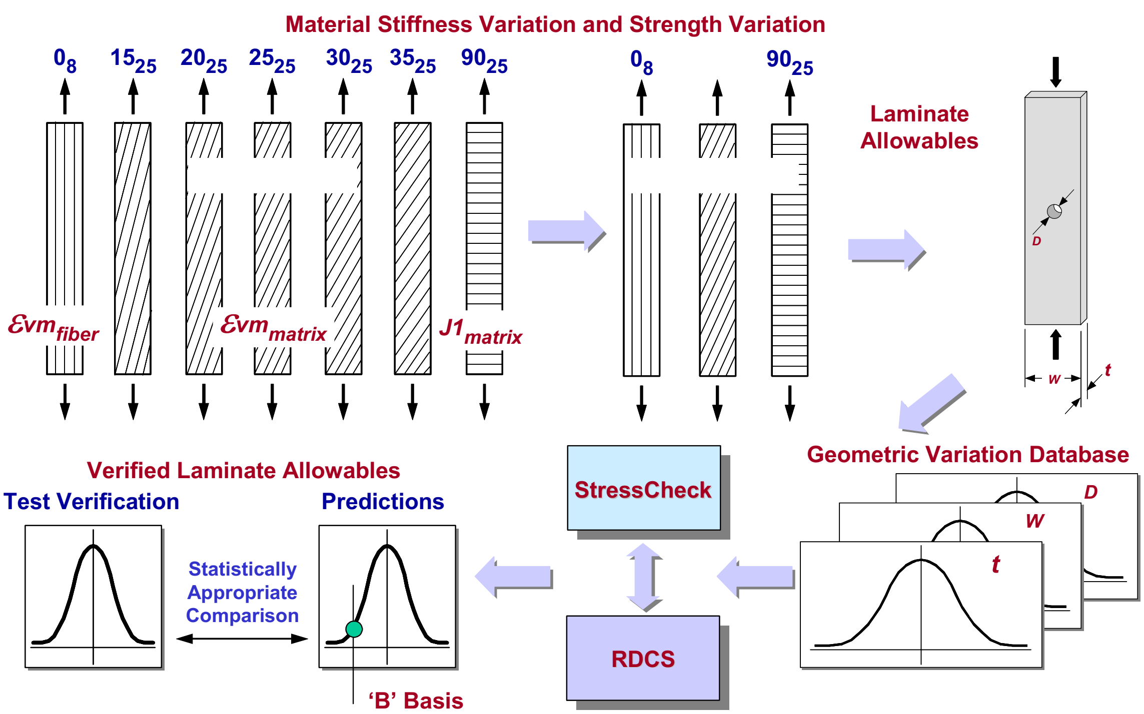


Figure 7-10 Traditional Allowables Using the Strain Invariant Failure Theory (SIFT) Based Approach

8. Legal Considerations

Regulations or legal considerations are of the highest priority when considered in development of the problem statement and requirements before conformance planning can begin. Most requirements are negotiated; some of these, however, are not negotiable and could pose to be show-stoppers.

• Safety and Medical – Evaluate the Material Safety Data Sheet to get approval for use and assess the cost of personal protection equipment for materials handling, needed facility or material handling changes, and other product liabilities such as toxicity, teratigen, carcinogen, etc. Check by-products during heat up, cure, dust, and leaching which could occur over the product life cycle in manufacturing, fabrication, assembly, support, use, and disposal.

• Check legislation, case law, and other regulations. These include environmental issues, international laws (if the use is a world wide application), safety and medical (as mentioned earlier), etc. Are there legal issues such as substance control, ozone depleting substance, etc? Are there Federal Acquisition Regulations (FARS) or Defense Federal Acquisition Regulations (DFARS) regarding the material or application, sources of the material or process, etc?

• Check program requirements/contract and those of your particular qualification/certification agency. Is first article testing required, live fire testing, etc? Are there milestone deadlines that are none-negotiable or critical path items? Are there restrictions on sources of supply for information or goods exchange?

• Check Intellectual Property status. Which items are protected? Which are not? Which should be? Are there hidden costs from licensing, sole source conditions, etc? Are the issues delineated and plans in place to cover licensing, copyrights, publications, etc?

• Are there existing proprietary information agreements or similar arrangements that must be addressed?

• Are there export restrictions?

• Are appropriate policies, marking guidelines, and authentication procedures in place to address all the issues uncovered?

Some of the obstacles that have been identified from these types of studies include:

- Conflicting requirements
- Prohibitive disposal costs
- Raw material source was not available/scalable for growth

- Personal protection equipment was available to deal with the hazard (carcinogen or mutagen), but the company did not want the risk or press of having the hazard in the working process or community.
- Material did not pass toxic characteristics leaching procedure so the cost of curing it before disposal was added to the consideration of its use.
- Dermatitis was a bigger issue than was anticipated.
- The odor of a material was obnoxious to workers.
- Volatiles could not be deal with economically in scale up.
- There were hidden costs to use of the material.
- The end product could not be used world wide, so the material selection was changed.
- Competing materials were clearly identified and a strategy for judgment was defined.
- A key resin toughener was not available for the product on a production basis.
- A critical analysis technique could not be used because of pending litigation. The schedule and cost profile had to be changed to accommodate additional testing.

9. Managing Error and Uncertainty

Part I. A Structured Approach for Managing Uncertainty

One key part of the AIM-C approach for accelerating material insertion is using a structured methodology for dealing with potential error sources and uncertainties. This section gives a brief description of the approach developed and used during the AIM-C hat-stiffened panel design selection process.

The basic AIM-C approach for addressing uncertainty consists of the following four steps:

–Understand and Classify Potential Uncertainty Sources
–Determine What Is Important
–Limit Uncertainty/Variation by Design and/or Process
–Quantify Variation (Monte Carlo Simulation or Test)

Step 1. Identifying and Understanding potential uncertainty and error sources

–Maintains Visibility of potential errors
–Forces step-by-step breakdown of the analysis/test process
–Forces agreement on responses of interest

Classifying them allows the team to determine appropriate strategies for addressing them. Figure 9.1 provides an example.

	Inherent variations associated with physical system or the environment (Aleatory uncertainty)	Uncertainty due to lack of knowledge (Epistemic uncertainty) inadequate physics models	Known Errors (acknowledged) e.g. round-off errors from machine	Mistakes (unacknowledged errors) human errors e.g error in input/outp
Lamina Stiffness/ Thermal Properties	Variation in all fiber and resin moduli, Poisson's ratio, and CTE	Unmeasurable Constituent Properties (transverse fiber modulus, etc.)	CCA: Use of model outside of bounds.(e.g., woven 3D preform)	CCA: I/O errors, code bugs Empirical:Testing machine not
Laminate Stiffness Calculation	Variations in ply-thickness, ply angles, etc.	Assumes thin plate with no shear	Use of model outside bounds for items listed	I/O errors (ply thickness, material, layup
Stress-Free Temps/ Residual Curing Strain Input	Many parameters can affect residual stress: local fiber volume fraction,	Micro-stresses are considered to be independent of meso-stresses; there are few	The formulation is believed to be most accurate when the cure cycle temperature	Errors in material property definition, errors in coding, errors in integrating
Coupon Geometry and Load/BC Input	Cured ply thickness variations, specimen			Errors in Coupon Geometry Definition or Improper

Figure 9.1 Example of Identifying and Classifying Uncertainties

•Types:
–Aleatory Uncertainty (Variability, Stochastic Uncertainty)
–Epistemic Uncertainty (Lack of Knowledge, e.g., unknown geometry)
–Known Errors (e.g., mesh convergence, round-off error)
–Unknown Errors (Mistakes, e.g. wrong material inputs used)

Step 2. Determining which variables are important.
Complex problems have hundreds of potential uncertainties. Since it is time-prohibitive to spend equal effort investigating each one, effort must focus on the most important uncertainty sources – those which are likely to occur, and/or those which have a large influence on the response(s) of interest.

It is interesting to note that this evaluation is similar to simple Risk Analyses, assessing both Probability of occurrence and consequences of failure.

Prior knowledge is useful in determining likelihood of occurrence. One good example of this is illustrated in Figure 9.2. In developing the analysis approach for predicting the performance of the hat-stiffened panel, it was necessary to account for the potential presence of structural defects. There are a near-infinite variety of potential defect types – over 100 are listed in Boeing quality documents for composite structures. Given our limited schedule and budget, there was no possibility to develop approaches to address all possible occurrences. Using data from past programs, the most frequent defects were determined for cocured and cobonded stiffened panels. These defects, comprising almost 75% of all defects, were determined to be Delaminations, Cure Cycle Inconformities, Ply wrinkles, and Voids/Porosity.

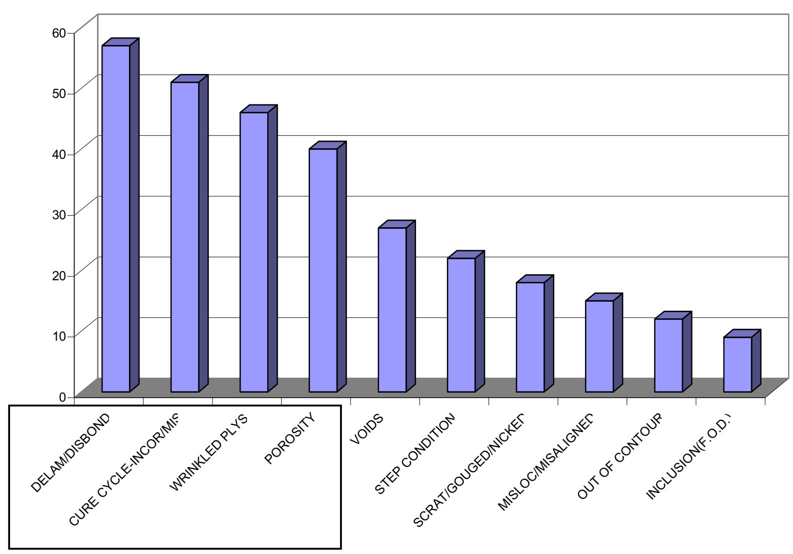


Figure 9.2 Pareto of Defects for Cocured Stiffened Panels

Tools such as Design Scans, analytical Design of Experiments (DOE), Analysis of Variance (ANOVA) Taguchi methods, and Sensitivity Analysis are useful in quantifying a variable’s influence on the result. The Robust Design Computational System (RDCS) provides this tool suite, Figure 9.3.

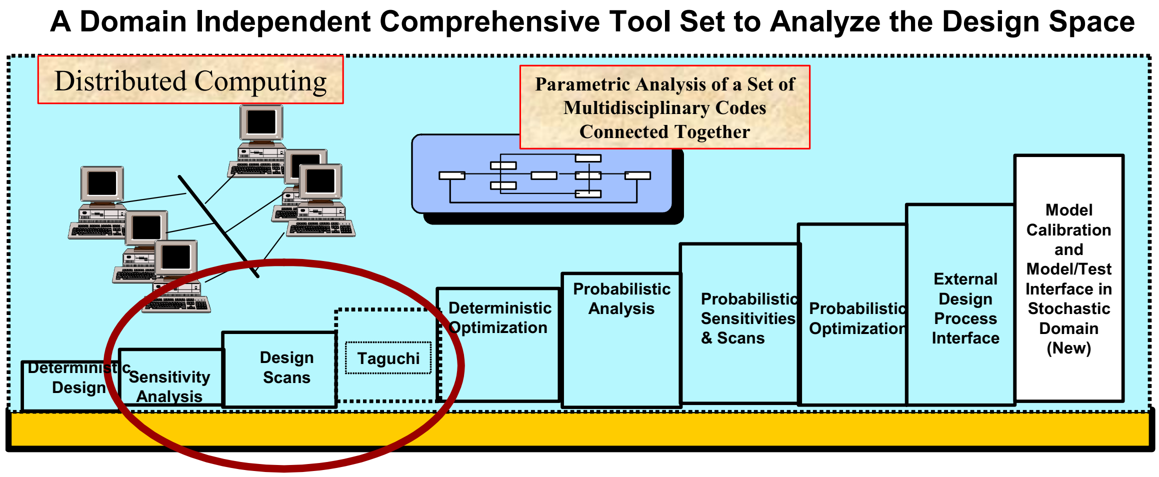


Figure 9.3 Robust Design Computational System Tools for Assessing Importance

The use of these tools has occurred frequently on the AIM program. One example from the AIM-C program is the investigation of fiber transverse modulus effect on composite laminate performance. The transverse modulus of the fiber is a very difficult property to accurately measure. This raised a very serious concern that any inaccuracy in this transverse fiber modulus estimated may lead to excessive error in laminate strength and modulus. Using RDCS Design Scan tools and ANOVA showed that, as expected, Fiber Volume and Fiber E_{11} had significant effects on laminate modulus, but Transverse Fiber Modulus (E_{22}) had very little effect on either laminate stiffness (Figure 9.4, left side). Using RDCS sensitivity analysis tools, data was produced (right side of Figure 9.4) showing that large ±20% variations in fiber E_{22} also had very little effect (about ±1%) on laminate strength.

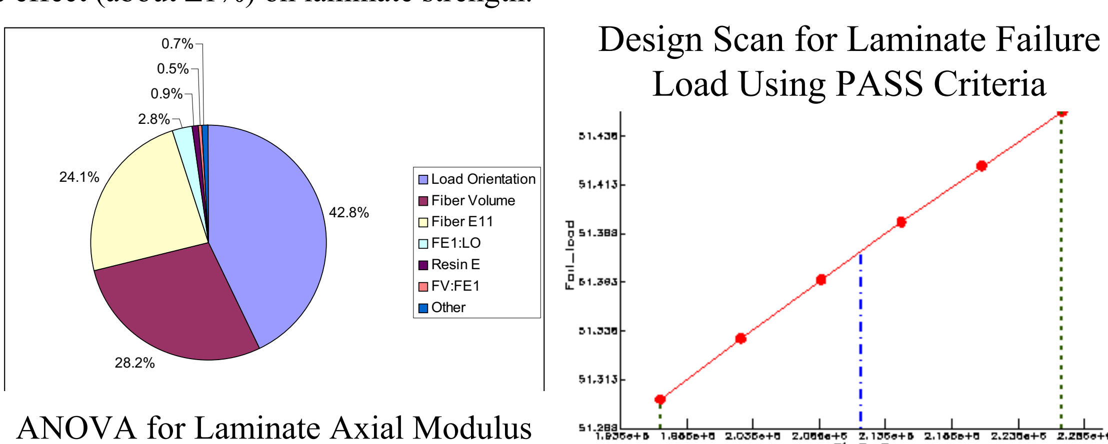


Figure 9.4 Effect of Transverse Fiber Modulus on Laminate Stiffness and Strength

Other examples from AIM-C include the effect of Stress Free Temperature on laminate performance and the effect of various geometric variables on Stiffener Pull-off load. In the first example, it was found that there was very little variation in stress free temperature for flat laminates over a wide range of cure cycles. This small variation had an insignificant effect on thermal stresses in the laminate, which, in turn, had almost no influence on laminate failure. In the second example, results showed that some geometric variables, such as stiffener cap width, had almost no effect on structural performance.

Step 3. Limiting Variation by Design (Robust Design)
Where possible, many uncertainties may be eliminated or reduced by design choices. The idea is simple – Pick the material and design to play to your strengths! One major advantage of this step is that the process produces data early in the design cycle, allowing negotiation between competing response variables (e.g., Structural Performance and Producibility)
This is a major philosophical shift for Structures (as well as many in other organizations). In the rush to obtain adequate functional materials and designs which meet all the requirements, making designs robust to variation and other uncertainties is typically thought of as a luxury that the program cannot afford. On the contrary, data suggests that the current approach, which ignores design robustness issues, may in fact result in an increased insertion schedule and increased costs. The left side of Figure 9.5 shows data from an actual program which illustrates that design rework to address unanticipated performance problems results in significant time and money expenditure. The right half shows an ideal situation, where the tools and procedures are available to address these issues in the initial design.

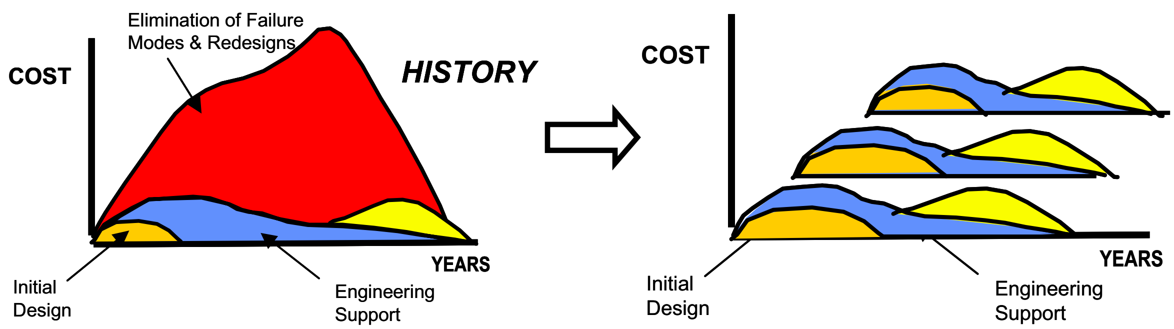


Figure 9.5 Effect of Better Design Selection on Insertion Time and Cost

Figure 9.6 shows the cost information of various phases of an actual material insertion into a stiffened panel design. The rework effort due to redesign activities exceeds the constituent, coupon, element, subcomponent and component tests combined! The only larger expense is the cost of the full-scale airplane testing.

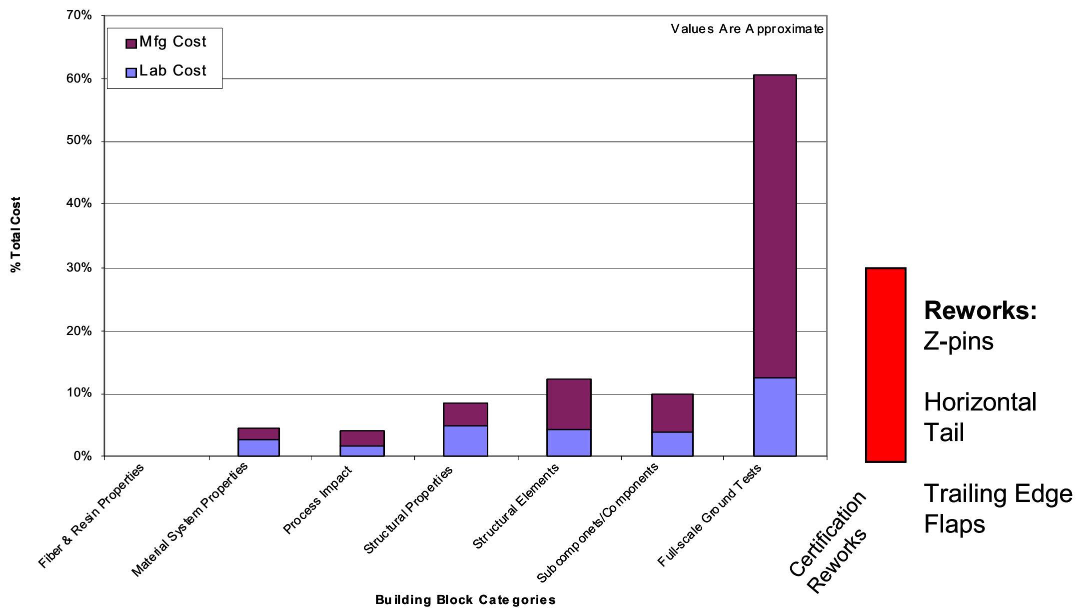


Figure 9.6 The Effect of Redesign Activities on Total Hat Stiffened Panel Development Costs

On AIM-C, we undertook a similar hat-stiffened-panel (HSP) insertion problem. With a goal of avoiding this time-consuming and expensive redesign activity and thus accelerating this insertion activity, we applied the latest emerging analysis tools and a robust design philosophy. The benefits were threefold. First, by applying simple versions of the tools to quickly perform design studies, we put data on the table early. This helped the integrated product team develop reasonable compromises that were based on data. Second, by combining these analysis tools with statistical techniques (such as DOE/ANOVA and Sensitivity Analysis), we were able to perform studies that allowed us to achieve a more robust design. Finally, we were able to both (a) build a configuration which was very close to the “as drawn” and (b) predict the performance of the as built configuration. In Structures, we expect that our enhanced focus on Design Robustness (rather than Absolute Mean Performance) will likely yield a better “allowable” failure load.

Problem 1:
• Bondline delaminations are commonly occurring defects
• They occur at structurally-critical locations
• The failure load can be very sensitive to bondline delaminations
Question: Can we formulate a design that is much less sensitive to delaminations?
Using a parametric SUBLAM model, we can focus on several geometric variables and their effect on propagation of small bondline defects (delaminations) in three areas where they commonly occur – at the edge of the flange, and two locations adjacent to the noodle (nugget). The goal of the study is to find reasonable values of the geometric parameters (attach flange length, lower radius, and angle of the hat sidewall/web which minimize the likelihood that these defects will grow. Using a parametric model (shown in Figure 9.7) and the distributed computing and ANOVA analysis capabilities of RDCS makes this study quick and easy.

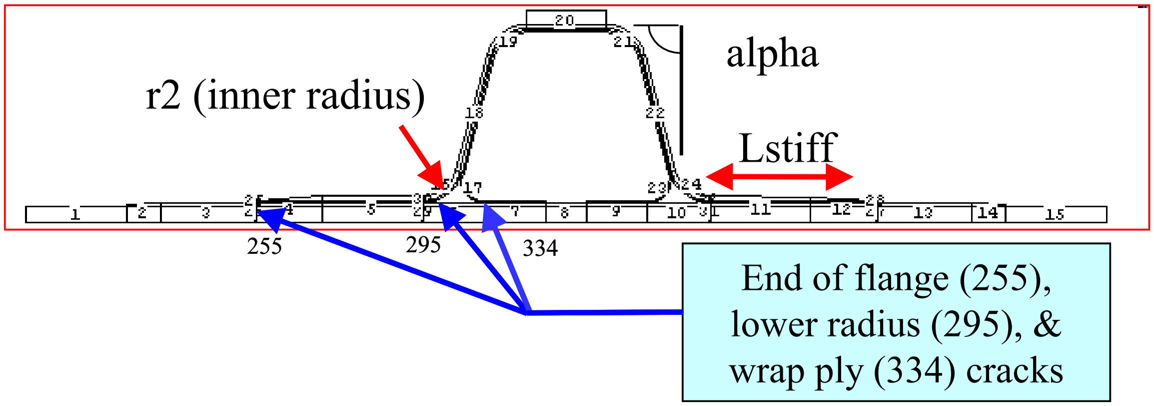


Figure 9.7 SUBLAM Pull-off Model for Hat-Stiffened Panel

Figure 9.8 shows initial results for the influence of the lower radius and the stiffener length on the Strain Energy Release Rate (SERR) at the delamination tips. In this figure, the web angle is fixed at 30°. The initial design point (web angle = 30°, radius = 0.25", and attach flange length = 0.75") is shown as a red dot. The data shows that this design is critical for Mode I growth of the delamination at the edge of flange (the red plane) and has a SERR of about 1.0. The green dot represents a new potential design point which minimizes the SERR. This new design with web angle = 30°, radius = 0.20", and attach flange length = 1.25" is simultaneously critical for Mode I growth of the flange edge delamination and mixed mode growth of the radius delamination. The SERR of this design is about 0.5. This means it has half the sensitivity to these defects (i.e., it takes double the pull-off load to cause defect growth).

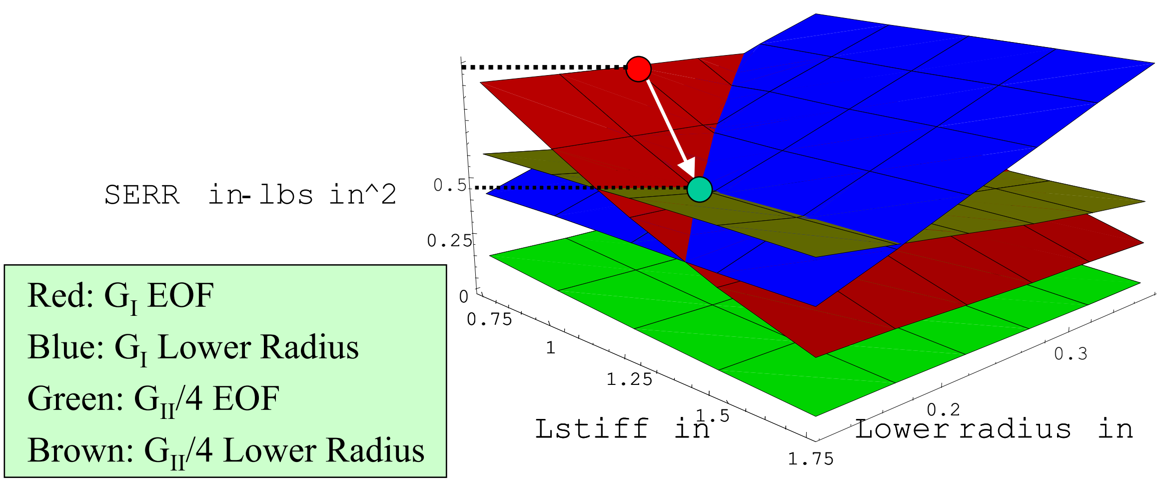


Figure 9.8 Effect of Stiffener Leg Length and Lower Radius on Delamination Defect Sensitivity

Figure 9.9 illustrates taking the study one step further. By reducing the stiffener spacing, adding wrap plies, and reducing the web angle to 20, the design is now critical for Mode I failure at the lower radius flaw and the SERR is again halved to less than 0.25. This design is now only one-fourth as sensitive to bondline flaws as the original design!

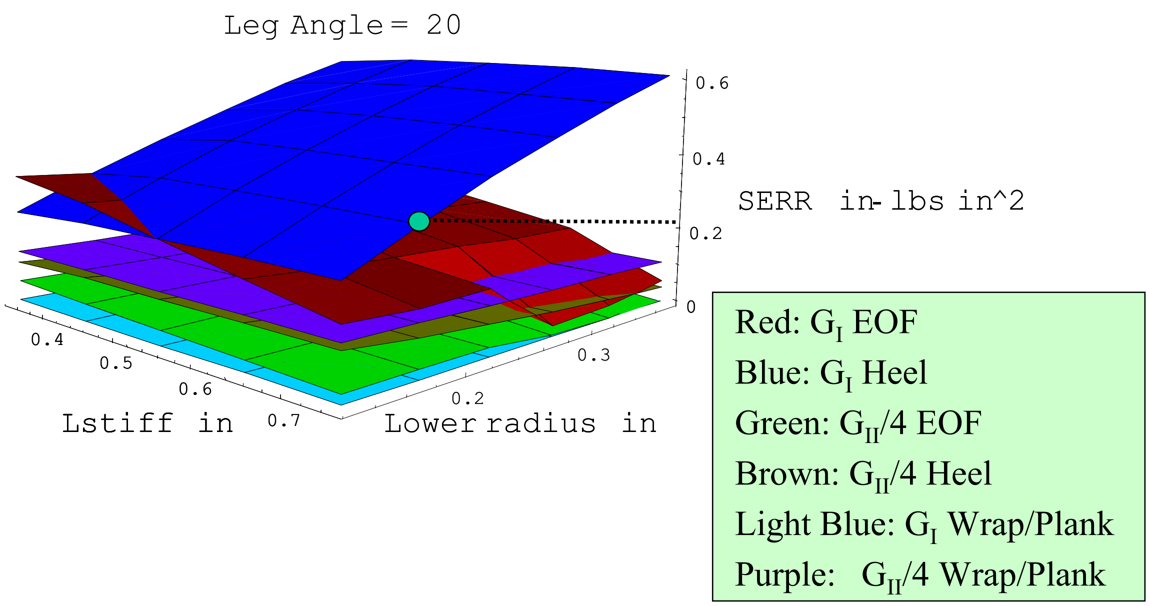


Figure 9.9 Delamination Defect Sensitivity after Design Iteration

Note that in the final design, we decided to use a "corrugated design' which has no edge of flange. This effectively eliminates the "edge-of-flange" defect location. This is another way to reduce the sensitivity of defect by design – instead of making the design robust to the presence of the defect, the IPT may choose designs which minimize or eliminate the possibility of defect occurring.

Problem Statement 2: A second example involves sensitivity to geometric manufacturing tolerances. Can we minimize the effect of off-nominal dimensions on the failure load? Basic strength and stability and weight considerations suggest the hat should be tall (say 1.91-cm, 0.75-inches or above). For tall geometries, the above results suggest that a gentle run-out angle (less than 45°) is required to "get on the flat area of the curve" (i.e., to reduce the sensitivity of the failure to the angle tolerance of the run-out), Figure 9.10.

For this study, a relatively simple parametric 3D shell model of the stiffened panel is used. Instead of using a Fracture Mechanics approach and seeking to reduce the SERR near known flaws, this study uses the Strain Invariant Failure Theory (SIFT) and seeks to find geometry combinations that reduce the dilatational and distortional strains (J_1 and ε_{vm}). The results are shown in Figure 9.10.

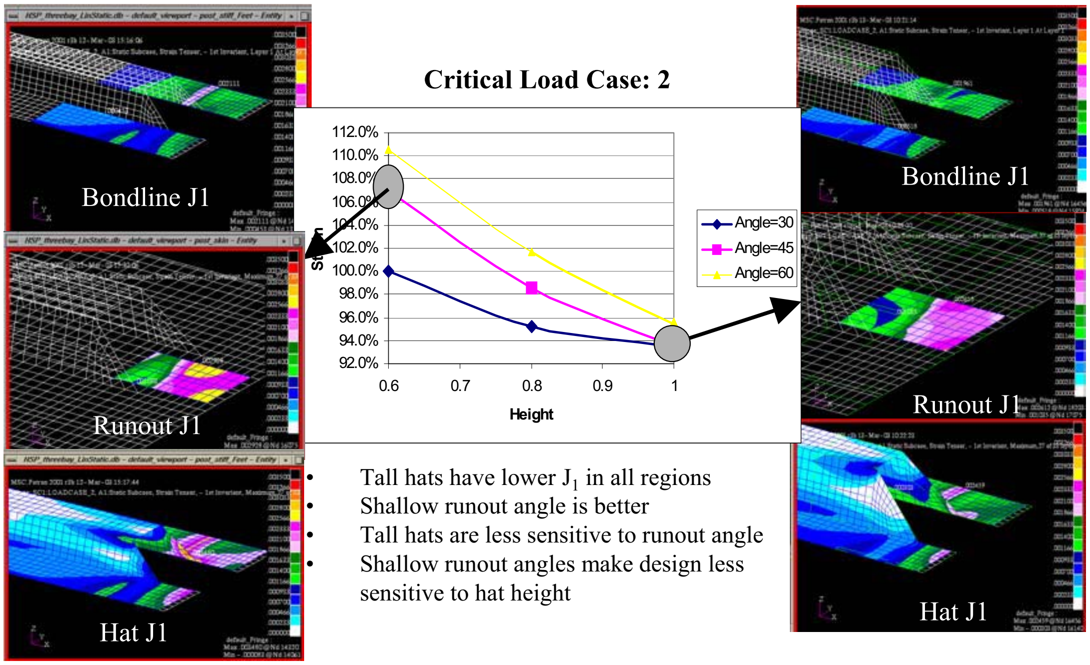


Figure 9.10 Effect of Stiffener Termination Geometry on Peak J_1 and ε_{eqv} Strains

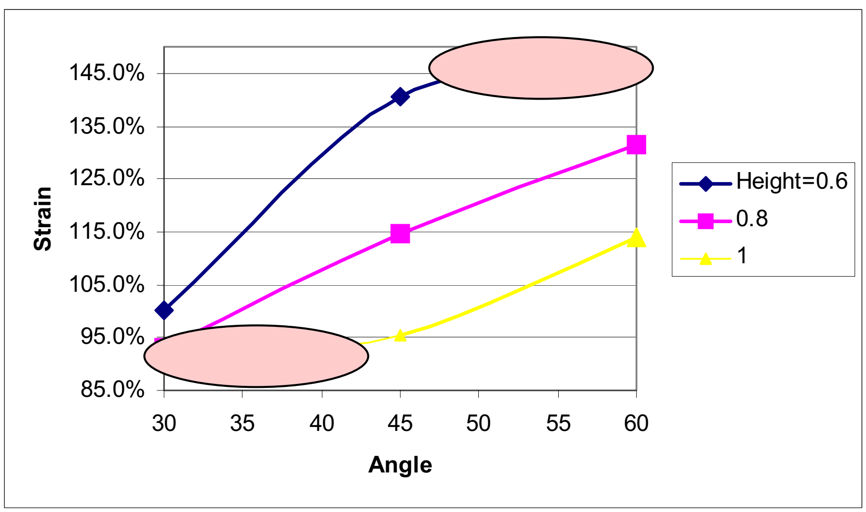


Figure 9.11 Effect of Runout Geometry on Peak Runout J1

Basic strength and stability and weight considerations suggest the hat should be tall (say 0.75” or above). For tall geometries, the above results suggest that a gentle runout angle (less than 45°) is required to “get on the flat area of the curve” (i.e., to reduce the sensitivity of the failure to runout angle tolerance. Figure 9.12 shows the sensitivity of some designs to the typical ±3° drawing tolerance.

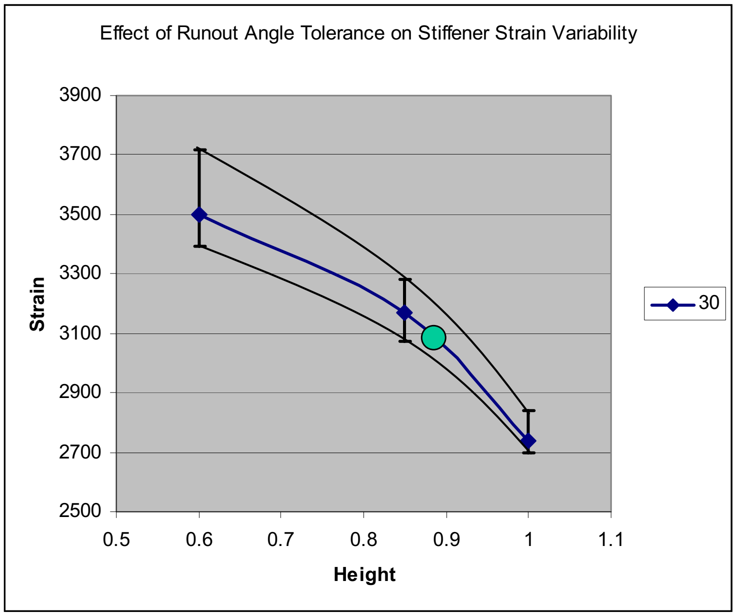


Figure 9.12 Sensitivity of Peak Runout J1 to Runout Angular Tolerance

The selected design, shown with a green dot, would exhibit 3% higher strains if the runout angle were cut too steep (but still within drawing tolerance). This would result in a failure load which is about 3% low. If this were unacceptable, the hat could be made taller, trading a bit of weight for additional robustness. The data suggests that very short (0.6”) hat designs would fail about 6% low under the same off-nominal condition.

Step 4. Quantifying Variation

The final step, after error sources have been identified and classified, impotant variations have been determined, and the design has been made as robust as possible, is to quantify the remaining important variations. To perform this step, Testing or Probabilistic Analysis Tools (Figure 9.13) are applied.

This is another change from current Structures and Materials philosophy, which currently only quantify certain uncertainties, such as material variability associated with coupon allowables. Many other variations are considered covered in “material scatter”, covered by factors, by or worst-case assumptions.

Major challenges exist to ensure widespread adoption of detailed uncertainty analysis. These include reducing the cost and schedule associated with testing, and developing tools and approaches which make analytical statistical studies fast, accurate, easy to use, and produce understandable results. The emergence of new physically-based analysis methods and the continued enhancement of RDCS have made great inroads toward this goal, but the determination of appropriate approaches and procedures for differing applications is still underway.

Recent RDCS improvements, Figure 9.13, have been made which greatly expand the operating space of uncertainty analysis. These improvements include:

- Continuous, discrete and enumerated variable types
- Sensitivity analysis on mixed space and constrained design space exploration
- Integration of external uncertainty analysis plug-ins with RDCS
  - Advanced design of experiments – Design Explorer
- Probabilistic (Robust) Optimization
  - A capability to define statistical parameters as design variables

A Domain Independent Comprehensive Tool Set to Analyze the Design Space

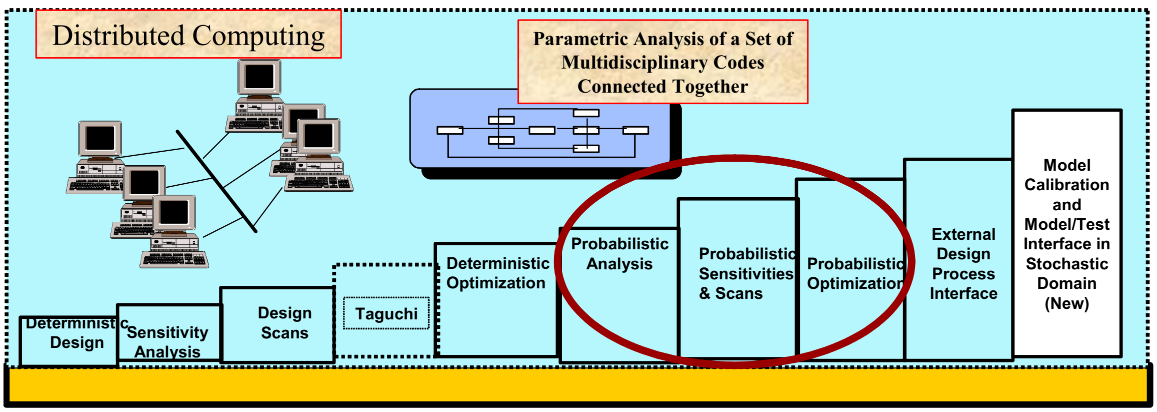


Figure 9.13 Robust Design Computational System Tools for Quantifying Variation

One simple example on AIM-C is the use of RDCS Probabilistic Analysis to assess the effect of constituent properties, prepreg properties, and geometric variables on the strength of open hole tension (OHT) coupons. The results of this Monte-Carlo Simulation are shown in Figure 9.14.

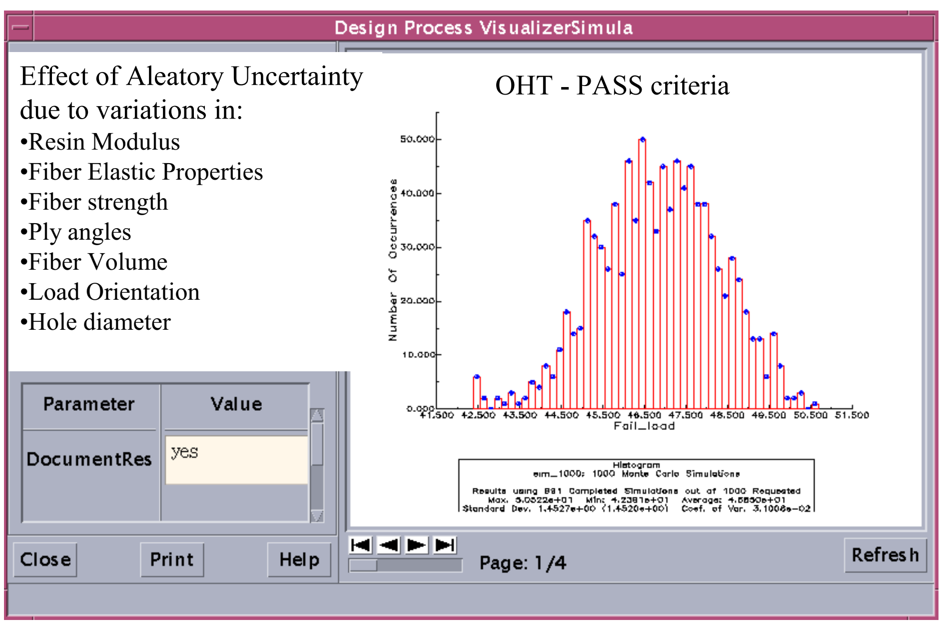


Figure 9.14 Monte Carlo Simulation Result for Open Hole Tension Strength

Figure 9.15 shows a summary of the results produced using various simple composite failure criteria. Note that the Maximum Strain Criteria failed to produce reasonable predictions for the mean and also significantly overestimated the variation of the test data. This result was expected, since the laminate was not fiber dominated. These results illustrate an important lesson – statistical analysis is not a substitute for physically meaningful domain analysis (in this case, an appropriate failure criteria).

	Test	1. Max.Strain	2. Hashin	3. Phase Avg.
Mean	37.274	57.585	34.231	42.39
Std.Deviation	1.683	3.1091	1.0371	1.4527
Coefficient of Variation	.04517	.06316	.02801	.031

Figure 9.15 Summary of Monte Carlo Simulation Results for Various Failure Criteria

Figure 9.16 shows additional information that may be obtained from the probabilistic analysis. On the left is a plot showing the effect of each input variable on the variation (rather than the mean). On the right is a cumulative distribution function of failure load. The 10th percentile value (an estimate of the B-basis allowable with undefined confidence level) is noted in this plot.

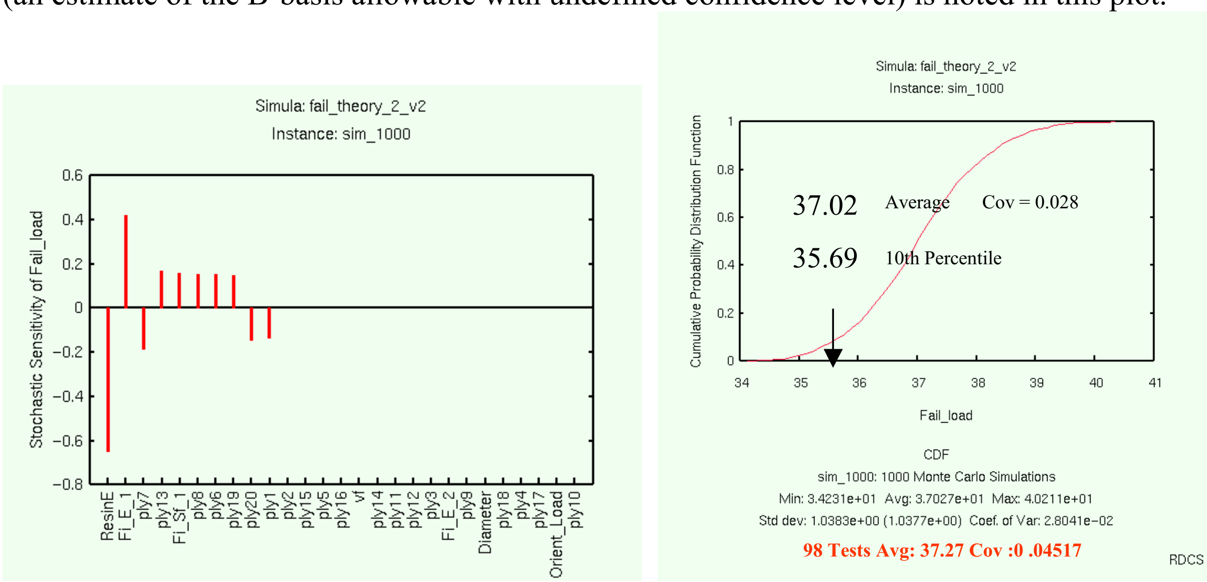


Figure 9.16 Additional Information Obtained from Probabilistic Analysis

A more complex example of quantifying variation is a study to predict hat stiffened panel pull-off strength incorporating effects of bondline delaminations, geometric variation, constituent stiffness variation, and critical failure property variation (from test). For this Monte Carlo Simulation, SUBLAM Fracture model similar to the one shown previously in Figure 7. The following parameters are considered random variables and assigned distribution information based on data and allowable tolerances:

–Length of stiffener flange (Mean = 1.25”, SD = 0.015”)
–Leg angle (Mean = 20º, SD = 1.5º)
–Lower radius (Mean = 0.2”, SD = 0.015”)
–Fiber volume (5% COV)

–Fiber modulus (5% COV)
–Resin modulus (5% COV)

The Robust Design Computational System (RDCS) math model shown in Figure 9.17 ties together the Resin, Fiber, Prepreg, and Lamina Modules and the HSP SUBLAM Fracture model to produce results.

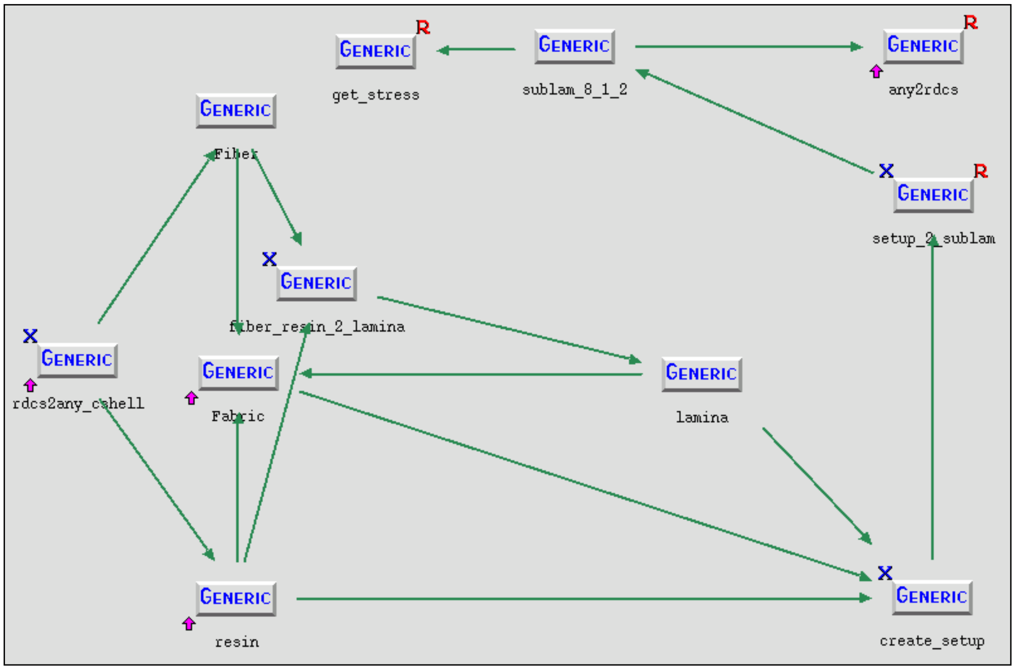


Figure 9.17 Robust Design Computational System Math Model

Numerical values of Mode I and II Strain Energy Release Rates (SERR) are reported for a 90 lb/in pull off load. For this geometry, Mode I and II SERR at the end of flange drive the failure results.

Variations in crack driving force due to geometry variation are significant (SD_{GI} = 0.036, SD_{GII} = 0.026). Adding the effect of variability in material elastic constants increases the SERRs to SD_{GI} = 0.068 and SD_{GII} = 0.041. The Mode I variation is shown on the left of Figure 9.18. The Mode II variation is shown on the right.

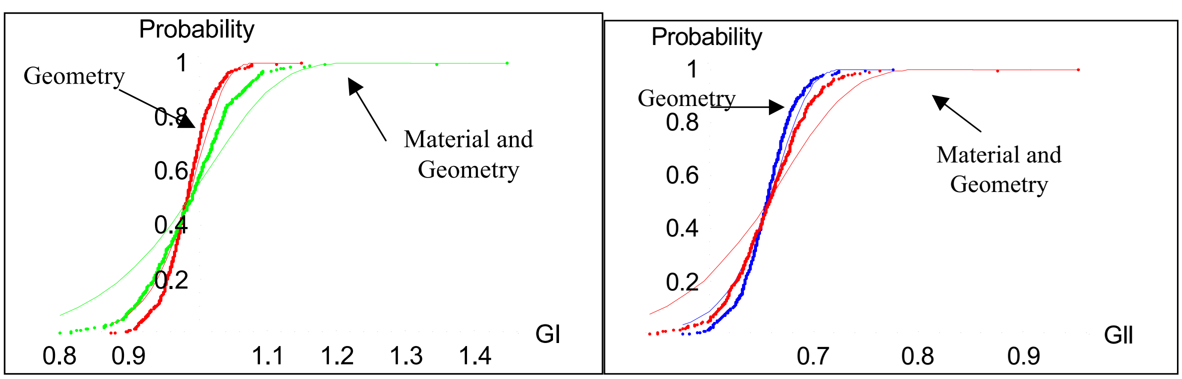


Figure 9.18 CDFs for Mode I and Mode II SERR Due to Geometry and Material Variation

Variations in critical failure properties, obtained by test coupon (DCB and ENF) experimental results, are shown in Figure 9.19. Comparing Figures 9.18 and 9.19, it is apparent that the materials measured resistance to crack growth (Critical SERR) is much more variable than computed variations in crack driving force due to other material/geometry variation. These large variations in coupon measured fracture strengths will increase the scatter in the failure load, thus complicating test prediction.

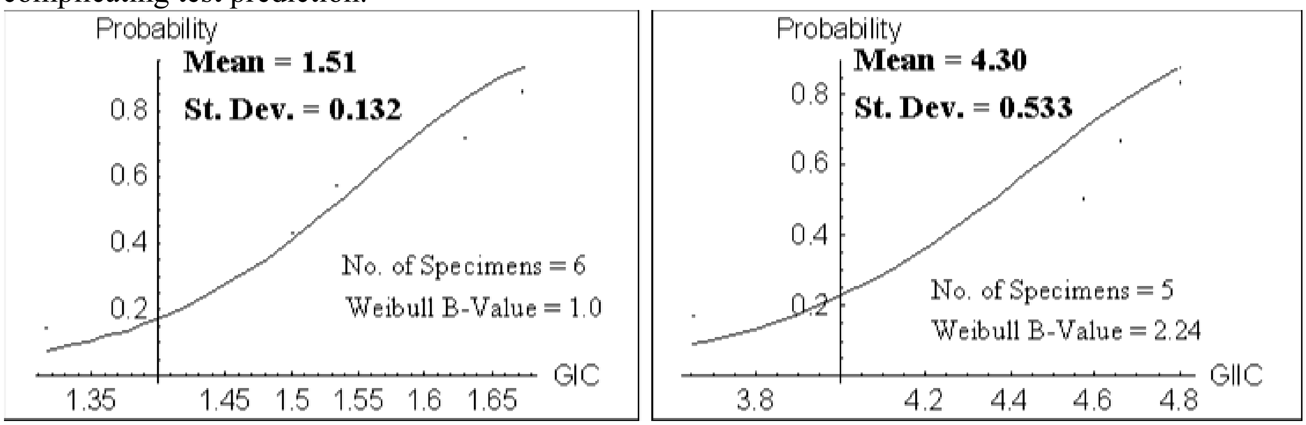
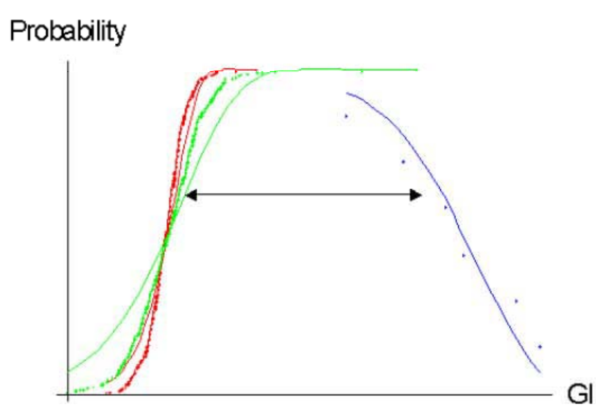


Figure 9.19 Variation in Critical Mode I and Mode 2 SERR from Coupon Test (DCB and ENF)

The failure probability, for a given load level is obtained as shown in Figure 9.20, by comparing the cumulative distribution functions (CDFs) of the SERR at the crack tip (the green curve on the left, determined by analysis) with the critical SERR (the blue curve on the right, determined by coupon test).



For continuous distributions, the probability of failure is:

$$p_f = \int_0^{\infty} F_{G,sublam}(G_{max}) f_{G,exper}(G_{max}) dG_c$$

$F_{G,SUBLAM}$ is the CDF of expected SERRs for the HSP system

$f_{G,exper}$ is the PDF of the experimental data.

Figure 9.20 Procedure for Determining Failure Load Distribution

The results of this analysis are shown in Figure 9.21. The two results columns represent another error source associated with the analysis method – the selection of the proper interaction criteria between the Mode I and Mode II fracture modes. The data shown for Criteria 1 assumes a quadratic interaction, while Criteria 2 assumes a more conservative linear interaction. Both assumptions are widely used in practice. For both criteria, the mean values, standard deviations, and B-basis values (90% of the population is above this value with a 95% confidence level) are predicted. Regardless of criteria, the data shows that the B-value prediction strongly depends on the confidence in the input data.

		Criteria 1	**Criteria 2**
Mean (lbs/in)		110	100
Standard Deviation		5.82	4.90
B-Values (lbs/in) Weibull Distribution	n = 6 (current number of experimental data)	77.5	72.6
	n = 10 (typical number of experimental data)	80.5	75.1
	n = 500 (simulation results)	99.8	91.6

Figure 9.21 Pull-off Failure Statistics

Following these four steps will help any IPT to better understand the effects of all uncertainties, and to maximize the likelihood of a successful material insertion into any design application.

<u>Part II. Using and Combining Data from Knowledge, Analysis, and Test</u>

As with any engineering endeavor, the "Designer" attempts to bring to bear information from all available sources. This may include data obtained from many sources, including:

–Previous Knowledge and Divergence Risk
–Analysis
–Test

To make proper use of this data, the design build team must understand the peculiarities associated with each source of data, as well as having appropriate methods for combining it into a rational, complete picture.

Data Obtained from Previous Knowledge and Divergence Risk
This may include information and conclusions from previous testing, analysis, and fabrication/service experience of similar materials and/or the same material used in a different structural concept or service environment.

The data may take the form of documented data or lessons learned, or may be in the form of "expert opinion". An example of such data is shown in Figure 9.22, which summarizes previous experiences of several experienced manufacturing engineering experts on the effect of tooling on part quality for stiffened panels.

Issue	Rigid Tooling	Soft Tooling Approach
Stiffener Spacing	Excellent control (+/- .03" possible)	Poor control. Expect movement of up to .13". Difficult to pin details that have limited rigidity.
Stiffener Straightness	Excellent control (< .09" out of plane over 36")	Decent control (< .13" over 36")
Edge Ramp Definition (ply drops)	Potential consolidation issues. The tooling forces the part shape. If plies are mislocated, fiber/resin movement is required to achieve consolidation. One ply (<7% thickness) mislocated is typically OK. Greter amounts cause problems. Misplaced ply ramps cause problems.	Excellent consolidation. Should be well consolidated even if plies are significanly out of place. (Does not address ply waviness at stiffener termination)
Traditional Composite Panel Defects (delaminations, porosity, inclusions, etc)	Possible Porosity due to long Volatile Escape Paths	No Unique Issues
Top Radii Thinning	Top radii expected to be slightly thicker than nominal (10-15%) (Rubber mandrels will produce less pressure in the corners	Top radii likely to be thin. Up to 40% thinnout will sufficient numbers of uni tape plies. Up to 20% with all cloth plies.
Crowning (Top & Sides)	No Unique Issues	Crowning Expected (~0.050)
Crowning-Skin (Thin skin under hat)	**10% Thinning Expected**	**10% Thinning Expected**
Bottom Radii Thickening	**5 to 10% Thickening Expected**	**15 to 30% Thickening Expected**
Thick/Thin Flanges	Flange thickness controlled by the full surface tooling. Not typically a noticable problem.	Flange edge thickness more variable. Flanges typically 15% thin due to tooling pressure. (Fiber volume change in flanges and skins under the flanges. Resin flowed out toward midbay and noodle area.)
Noodle Voids, Porosity, Delaminations	Dependant on proper amount of noodle material. Preforming adhesive helps as well as overstuffing by ~10%. (Overstuffing dependant on radii and surrounding material.)	Tooling/part variability makes the proper amount of overstuffing harder to predict. Therefore typically overstuffed by 20% which reduces voids and porosity issues but exacerbates radii thickening issues.
Noodle Fiber Waviness (plies around radii near noodle)	Typically not significant	Due to additional noodle overstuffing described above, this condition may result.

Figure 9.22 Expert Knowledge of Likely Defects Resulting from Various Tooling Concepts

Data obtained from previous experience is particularly prone to Epistemic error and mistakes. When documenting results, it is practically impossible to foresee all the potential future uses for the data. Also, engineering documentation is often not written with this purpose in mind. As a result, written reports and databases often omit key data required to completely assess the applicability of the analysis or test data. Sometimes, if the data was generated recently, it may be possible to find key individuals who can fill in the details and share undocumented data and conclusions. Unfortunately, human memory also can be faulty. Even if the events are remembered as they occurred, each individual tends to put them in a context based on the whole of their previous experiences. After witnessing a test, for example, most people walk away with a slightly different perspective of what occurred and what conclusions can be drawn.

All previous data requires interpretation and extrapolation to be applied to the current application. This brings up the question of Divergence Risk – What constitutes similarity and How do you characterize or quantify any differences from the current application?

–We do this all the time (Engineering Judgment)
–Example coupon COV from similar systems
–Mathematical or other structured approaches

Obviously, if the previous data was developed last week (little time for technology to progress) and is for exactly the same material, design, and application, there is no significant divergence risk. If it is from 20 years ago, using a different material, design, and application, it will likely provide much less applicable information and will require a great deal of engineering judgement to apply. In almost all cases, the reality is between these two extremes. In almost all cases, new empirical knowledge from analysis and testing will be required to "bridge the gap".

Data Obtained by Analysis

Data from analysis has a number of advantages. If appropriate analysis methods are available, it is relatively fast and inexpensive to develop analytical data. It is also the easiest method for dealing with most aleatory variations, even allowing assessment of variations which would be very difficult to vary and measure by test. Along with these advantages, there are some limitations. First, all analysis methods require some input data obtained from test. In the materials and structures realm, true material scatter must be obtained from tests. Using analysis, the influence of this scatter on failure load can then be assessed by analysis. Also, to provide accurate results with just material data, an accurate physics-based method must be available. Many analysis methods are semi-empirical, requiring additional test data for calibration and limiting the variables which can be analytically assessed.

Analytical data is naturally prone to Epistemic uncertainty.
–Is something missing in the Physics or Idealization?
–More difficult as complexity of shape or loading increases
–Surface Finish Example, Fillet Example
Examples of data obtained from analysis include the structural failure studies for Laminate Strength Analysis and Hat Stiffened Panel pull-off load discussed earlier.

Data Obtained from Physical Tests Test data is currently considered to be the "Gold Standard" of data because it accurately assesses the Physics…but only of the test specimen (with its associated boundary conditions, loads, environment, etc.). Physical testing cannot possibly duplicate the actual service conditions of the real application (aircraft, missile, etc.).

Small coupons and simple materials tests

Simple coupon tests often have more variation and error sources than is generally recognized. They are prone to excessive aleatory uncertainty that is often inadvertently lumped with "material scatter". Figure 9.23 demonstrates this effect. Filled Hole Compression (FHC) specimens have a typical manufacturing tolerance for both the hole and the fastener. Analysis shows that this tolerance has a significant effect on the failure load, which is generally considered part of the "material scatter" for this property. These phenomena must be recognized and accounted for in the specimen preparation and test procedures, otherwise a dull drill could bias the results, or the use of two different fastener lots could increase the scatter.

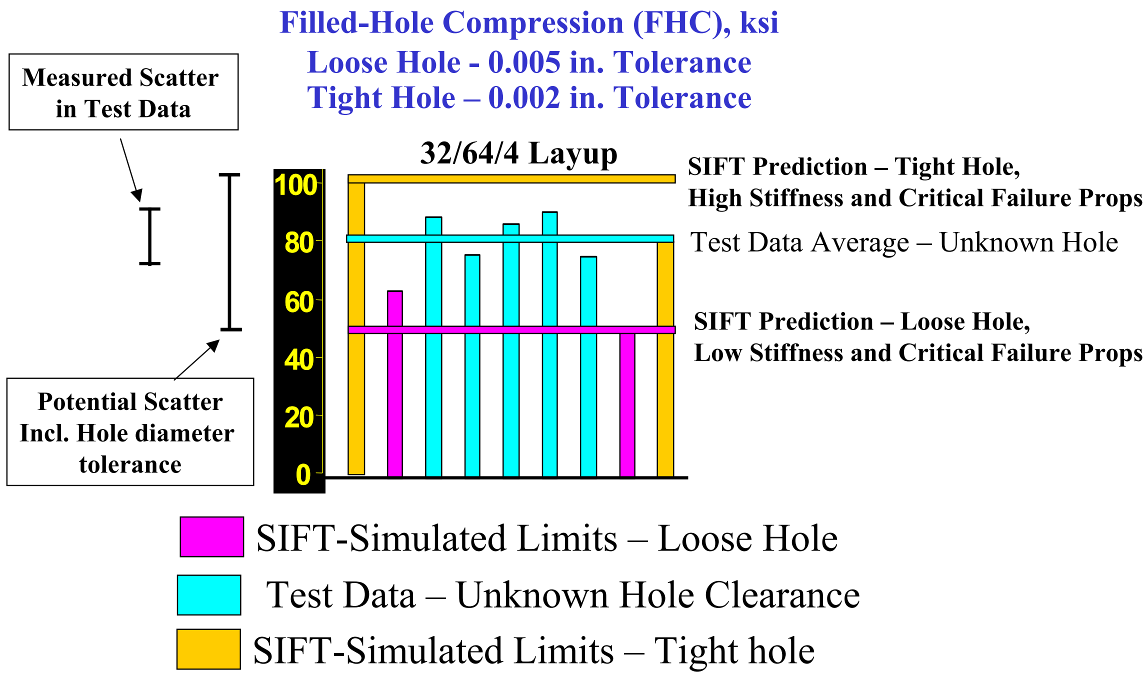


Figure 9.23 Specimen Hole Fit Tolerance Affects "Material Scatter"

Small coupon tests often also have specimen preparation and test setup variation which does not exist on the real aircraft. This is often inadvertently included in the "material scatter". One example is shown in Figure 9.24. In this example, the fixturing method for the open hole compression specimen influences the failure load. If not accounted for, this effect may show up as a bias in the mean, or (if combining data from multiple sources) added test variation.

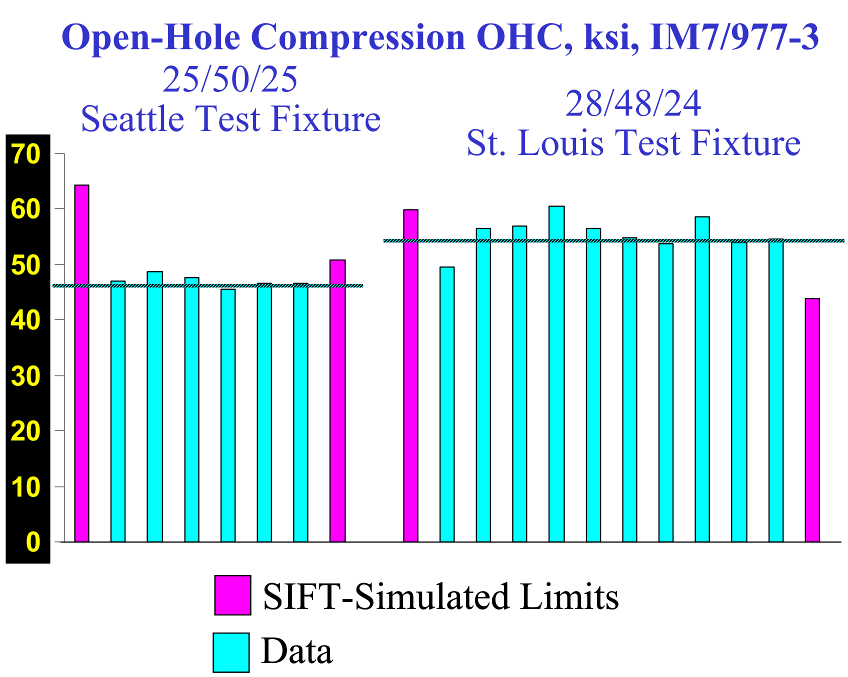


Figure 9.24 Test Fixturing Affects "Material Scatter"

In addition to effects such as those shown above, coupons and elements may not be representative of the actual structure unless excised from larger panels

Large-Scale Testing and Complex System tests

Large-scale system testing has the advantage of capturing scale-up effects (such as real manufacturing process effects, size effects, and interactions between the various elements of the system). In addition, big tests are very convincing – they look quite real – but, as with analysis, it is prone to idealization errors. For example, getting consistent known Boundary Conditions and Loading is often difficult. An excellent example of this difficulty is the full-scale thermomechanical fatigue test of the Concorde airframe, which was so complex that the results were very difficult to interpret. Large system tests can provide very useful validation data, such as verifying that the analysis correctly predicted the correct critical failure mode and location, and the correct load distribution, but they are very expensive and insufficient if used alone.

Due to the expense, few (if any) replicates can be tested. This means that it becomes very difficult to *quantify* aleatory uncertainty since you can only obtain limited quantitative failure data (e.g., selected environments, and only a single critical failure mode). This type of testing relies on smaller building block element testing and analysis to provide supporting data and to adjust the results to other relevant environments. It is generally only used to provide a final validation that the analysis and data from the small-scale testing is correct.

Combining data from multiple sources (Heterogeneous Data): From the previous discussions, the need for a coherent methodology for integrating various sources of information with their own uncertainty pedigree is clear. In the most general sense, the various elements of the developed data pooling methodology can be graphically represented as in Figure 9.25.

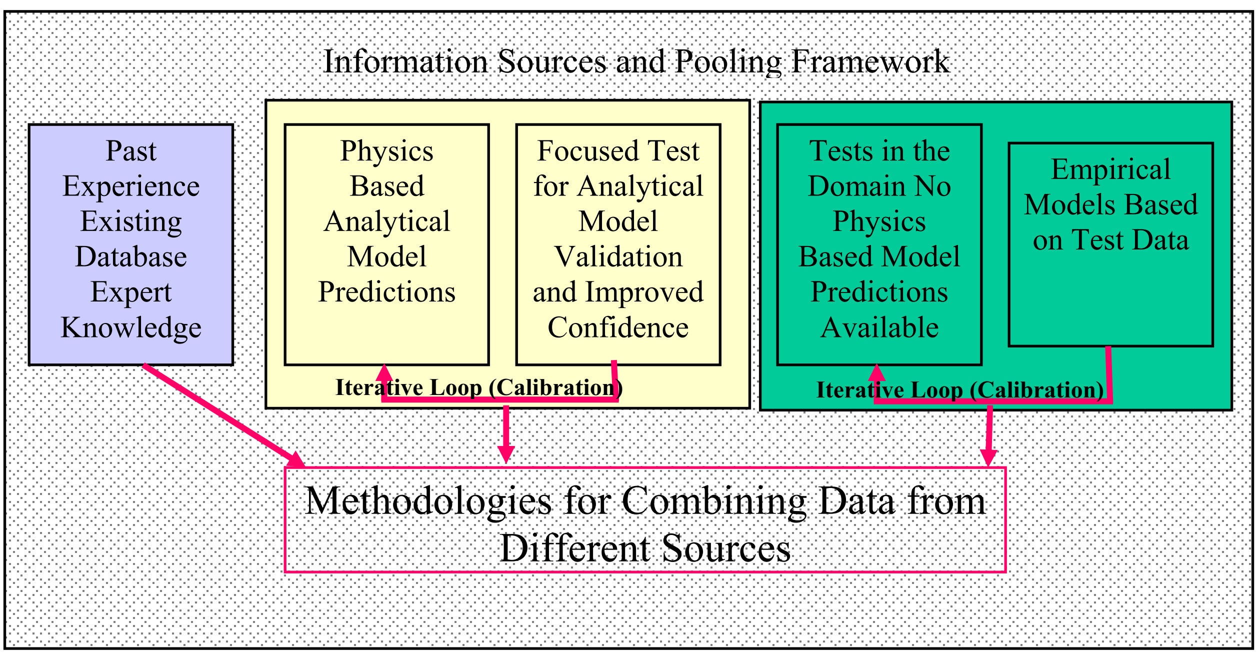


Figure 9.25 Identification of Information Sources and Sub-iterations within Each

The various elements of the above methodology are acknowledging the following:

- Domain expert opinions and past database of similar materials are valuable but their applicability to a specific design problem is uncertain
- The physics models generally need to be calibrated since some of the inputs that go in to test conditions that are compared against are unknown or the model parameters themselves need to calibrated for the particular condition
- The current state of the art is such that there is domain space where adequate physics based model are not yet available. In this case empirical models are developed based on tests.
- From a practical design point of view, judicious combination of all the information sources needs to be made to make design decisions with least risk using a quantitative basis (not a subjective decision)

Considering the above and more specific to material allowable development, a more quantitative framework attributes can be stated as:

- Ability to make prediction of new materials/conditions leveraging from known past history that has test and analytical model predicted data. The predictive capability should include percentile values as the case of arriving at a B-basis or A-Basis allowable.
- Ability to produce an error metric associated with predictions. The algorithm for the error metric must reflect changes due to any new information consistent with the quality of new information (actual or based on "what if" scenarios).
- Ability to make predictions in the presence of small amount of test data with very few replications (5 to 100 samples). As a corollary, the methodology should be able to pool test data from different conditions but judged similar (e.g. different laminate lay ups from the same basic material) to form a sizable pool of data to improve the quality of predictions
- Ability of the methodology to address a potentially needed calibration step for the parameters of physics based models or parameters of the data fusion methodology model itself
- There are refined physics based models that demand severe computational resources and there are less accurate models but provide quick answers. The methodology should be able to provide the engineer with ability to trade off uncertainty and fidelity based on design stage (e.g. conceptual, preliminary and detailed).
- Ability to provide additional quantitative measures that can be used to improved decision making using mathematical optimization approaches.
- Ability to handle different types of uncertainty information in a mathematically consistent format. For example, aleatory uncertainty is normally quantified in a probabilistic format and epistemic uncertainty (lack of knowledge) is frequently portrayed as interval or discrete information or other forms with no probabilistic metric associated with it.
- All of the above needs to be wrapped in a rigorous mathematically sound approach

Pooling Model and Test Results:

Two potential approaches for pooling of model and test data were evaluated. They are a) the Hierarchical Bayesian Approach and b) Factor Models Using Percentile Regression Approach.

Hierarchical Bayesian Approach:

The primary benefit of hierarchical-modeling is it forces the user to think about how information should be sensibly combined because it requires the user to formulate a model that captures the "similarity" opinion about data sources being integrated. The hierarchical model approach was applied to open hole tension data with and without countersink for laminates with 4 different laminate stacking sequence. Predictions based on analytical models were also performed for the four laminates and for another laminate for which there was no experimental data. The predictions were very reasonable. The conclusions were somewhat limited due to the fact that at the time of this study, a limited number of computer runs were available to integrate with the test data. However, since then more numerical studies have been completed. This approach could be further studied now that we have adequate number of numerical and corresponding test data.

Phase-1 Factor Model Study:

Considerably more work compared to Bayesian, was performed on the Factor Model approach. The many mathematical details of this approach are described in detailed reports which are attached as appendices along with references. Attachment 1 summarized the Phase 1 and Phase 2 efforts.

The Factor model study was performed in two phases. The phase 1 study can be considered as an exploratory study of the methodology to material allowable application. The objective of the study was to consider the Factor model as a basis for development of a coherent methodology for integrating various sources of information in order to predict accurately the percentiles of failure load distributions. The key issue is that, it is highly desirable, that the methodology deal with percentiles in a direct manner that can be associated with traditional A-Basis and B-Basis material allowable. The approach involves the linear combination of factors that are associated with failure load, into a statistical factor model. This model directly estimates percentiles of failure load distribution (rather than mean values as in ordinary least square regression). A regression framework with CVaR deviation as the measure of optimality is used in constructing estimates. The CVaR deviation (is mathematically defined the enclosed reports) is the average measure of some fraction of the lowest percentiles. Estimates of confidence intervals for the estimates of percentiles were considered, and the most promising of these were adopted to compute A-Basis and B-Basis values. Numerical experiments with available test and model results dataset showed that the approach is quite robust, and can lead to significant savings in number of physical tests to qualify a material. The approach showed a capability to pool information from experiments and model runs, with newer experiments and model predictions, resulting in accurate inferences even in the presence of relatively small datasets. The model dataset that was used in this study was limited to two predicted data points for each stacking sequence and/or test condition.

Phase-2 Factor Model Study:

The Phase-2 study of the factor model application, expanded the Phase-1 effort to look at many other facets of the problems. The main conclusions were as follows:

- The accuracy of CVaR regression is relatively insensitive to the number of batches present, but fairly sensitive to number of test points per batch
- There are diminishing benefits in using more than 10 batches, or more than 10 points per batch, in any one application of CVaR regression
- The estimates of A-Basis and B-Basis are fairly robust, in the sense that they are not severely affected by miscalculation (biases or errors) in the analytical methods.

A brief overview of the studies, devoid of mathematical equations is as follows. One of the important studies was to better understand the error associated with the computed CVaR deviation metric. In order to compute the true error, a simulated scenario is necessary. The use of actual datasets from experiments cannot be used to compute absolute error as the true complete information from tests is an unknown in the statistical sense. However, one of the notable features of the study was to create the numerical test conditions to be as close as possible to the material allowable generation as practiced today with relevance to composites. That is, there are very limited *samples from test as well as from model analysis results*. Thus an understanding of the sampling error both in model and test and its relation to CVaR was considered valuable and critical. This was achieved in many steps as described below.

Since Weibull distribution is most commonly used to characterize composite material variation, a statistical model fitting study was conducted on the available test data for several stacking sequences such as open hole tension, open hole compression, un-notched tension and un-notched compression. From this study, the range of Weibull parameters (two parameters) that could be used in Monte Carlo simulation study was obtained. The ranges were then used as the basis for generating samples for the controlled statistical experiments study. From the parameter ranges, the study randomly generated parameters of the Weibull distribution in addition to samples from within a randomly generated distribution.

On the model prediction side, a Weibull distribution was used to predict the error due to error/biases in the analytical model data.

With the above information, absolute errors associated with CVaR while predicting percentiles with limited data was possible. Many realistic combinations of limited number of datasets on the CVaR deviation were studied. It included the effect of limiting the number of stacking sequence tests, the number of tests with in a stacking sequence and sensitivity studies.

The second part of the study considered the scenario of availability of model results from two or three models with varying predictive accuracy and with varying number of test results. The goal was compare the CVaR deviation measure when information from various sources was pooled. The analytical model results for one model contained only nominal, a predicted high and low values for failure loads. The other two model results contained estimated mean and standard deviation of failure loads. Since test results with more than five samples (replications) were available for a number of stacking sequences, the predictive capability of the factor model was studied more extensively by eliminating one of the actual test results while generating the factor model and comparing the predictive results with the data set that was not used in factor model generation. This was done in a round robin manner. A representative set of obtained results is discussed below.

A subset of data totaling twenty two from all stacking sequence with at least 5 replicates was chosen for this study. Considering pooling of information from models only is depicted in Figure 9.26. The details of what represent M1, M2 and M3 are in enclosed report.

	regression coefficients								
Setup	**mean**	**st.dev**	**mean**	**st.dev**	**mean**	**st.dev**	**Mean**	**st.dev**	**CVaR**
M1			**1.098**	**-4.303**					**16.86**
M2					**0.571**	**0.005**			**24.656**
M3							**0.594**	**- 0.314**	**27.161**
M123			**0.510**	**-6.005**	**0.660**	**-1.243**	**0.0409**	**0.040**	**13.822**
T5	**1.000**	**-1.435**							**10.287**

Figure 9.26 Predicting 10th Percentile from Model Results Only

The regression coefficients for each model give a qualitative picture of the influence of individual elements in predicting the 10^{th} percentile failure load predictions. The CVaR error is metric on quality of predictions using the Factor Model. It can be seen for this particular case of model results, the predictive error in model 3 is the highest. It is also seen that perditions using Model 1 by itself is better that the other two. However, when information is pooled with other models, the predictions are better than predictions based on individual models, highlighting the complementary nature of model predictions and the final results are comparable to predictions using tests with 5 replicates.

Next, considering next pooling of model results with test results, various studies were conducted in which test data was introduced in incremental manner to the pooling methodology (Figure 9.27).

	regression coefficients								
Setup	**Test mean**	**Test st.dev**	**Model 1 mean**	**Model 1 st.dev**	**Model 2 mean**	**Model 2 st.dev**	**Model 3 mean**	**Model 3 st.dev**	**CVaR**
M123,T1	**0.303**		**0.105**	**-5.131**	**0.825**	**-1.058**	**-0.081**	**0.072**	**12.609**
M123,T2	**0.437**	**0.215**	**-0.264**	**-5.714**	**1.161**	**-1.029**	**-0.179**	**0.091**	**12.365**
M123,T3	**0.624**	**-0.268**	**-0.136**	**-3.881**	**0.713**	**-0.718**	**-0.088**	**0.046**	**11.821**
M123,T4	**0.875**	**-0.876**	**-0.101**	**-1.640**	**0.333**	**-0.371**	**-0.059**	**0.032**	**10.786**
M123,T5	**0.966**	**-1.428**	**0.155**	**0.163**	**-0.110**	**-0.178**	**-0.002**	**0.039**	**9.725**
T5	**1.000**	**-1.435**							**10.287**

Figure 9.27 Combining Three Models and 1 to 5 Actual Measurements

The uncertainty trade off between increased cost and the performing additional tests can be made using the last column CVaR measure.

A note regarding the results form Model -3 is needed. Because of the schedule constraints, the model-3 that was used in prior studies was sub-optimal with respect to its predictive capability. Had the Model-3 parameters have been calibrated before its use with the factor model (as identified in methodology in Figure 9.25), its influence on reducing the CVaR error measure would have been significant. The calibration of Model-3 was done except that it was not on time to be incorporated into the above factor model study. The model calibration studies that were performed are described below.

Calibration of Models:

The Probabilistic (Stochastic) Optimization Methodologies used to calibrate the input parameters for Model-3 is one of possible many applications of this technology. This technology provides a capability to define statistical parameters as design variables in a probabilistic optimization process. The technology allows the use of mathematical optimization techniques to operate in a probabilistic space by the ability to define probabilistic objective functions and constraints. This infrastructure can be potentially combined or independently used with other technologies described above.

The various steps in the model calibration are be summarized as

Step 1 - Identify and incorporate in the model all the potential uncertainty parameters
Step 2 - Perform probabilistic sensitivity analysis to determine the major drivers for the probabilistic response quantities (e.g. mean, standard deviation, 10th percentile etc) for each laminate
Step 3 - Reduce the dimension of the problem to major drivers for which the statistical parameters are most uncertain considering all laminates
Step 4 - Calibrate the unknown statistical parameters using probabilistic optimization for minimum violations considering all laminates. It is possible to use weighting functions which represent number of test data points is possible
Step 5 - Verify the approach using round robin out of sample approach
Step 6 - Use the calibrated model to predict response for new conditions
Step 7 - Recalibrate as new information becomes available

The probabilistic optimization process that was used is graphically represented in Figure 9.28. Considering the specific AIM-C application, the methodology can simultaneously consider the observed failure loads of six stacking sequences in four test conditions: open hole tension, open hole compression, un-notched tension and un-notched compression. The notations are TNX, CNX, TUX and CUX, wherein X represents a specific stacking sequence. The results of probabilistic sensitivity analysis in step 2 for this application are shown in Figure 9.29. The common top drivers that affect failure load scatter were selected from this list which are volume fraction, fiber elastic modulus –direction 1, fiber elastic modulus direction 2, fiber failure stress – direction 1, resin elastic modulus, resin shear strength and resin ultimate tensile strength. The resin tensile yield strength, resin compressive yield strength, and compressive ultimate strengths were assumed to be fully correlated to resin ultimate tensile strength by fixed factors provided by domain experts. In the probabilistic optimization process the statistical parameters of these identified random variables were treated as design variables as shown in Figure 9.30. The objective function was mean square values of the differences between analysis and test that included differences in mean as well as differences in standard deviation. The reduction in errors before and after model calibration is shown in Figure 9.31 and the new calibrated modified parameters are shown in Figure 9.32. The accuracy of the final results was verified using Monte Carlo simulation using the revised statistical parameter values.

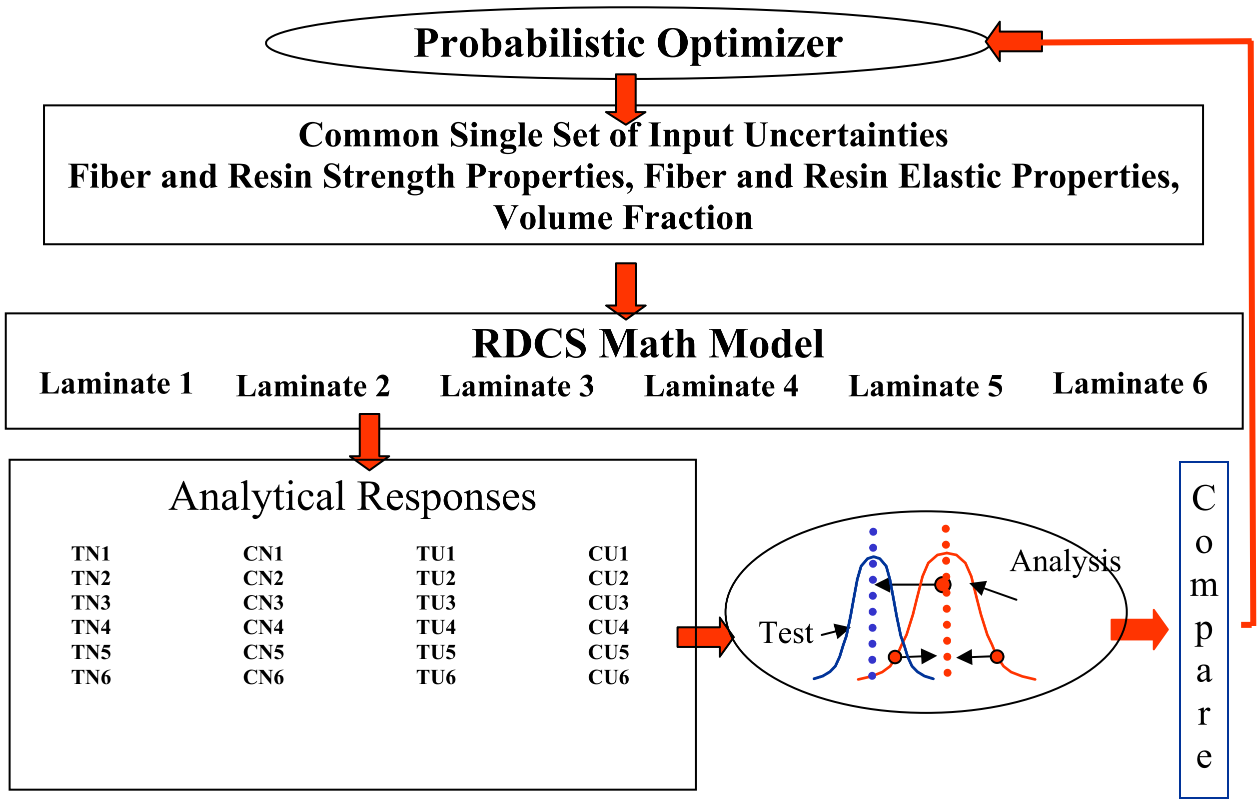
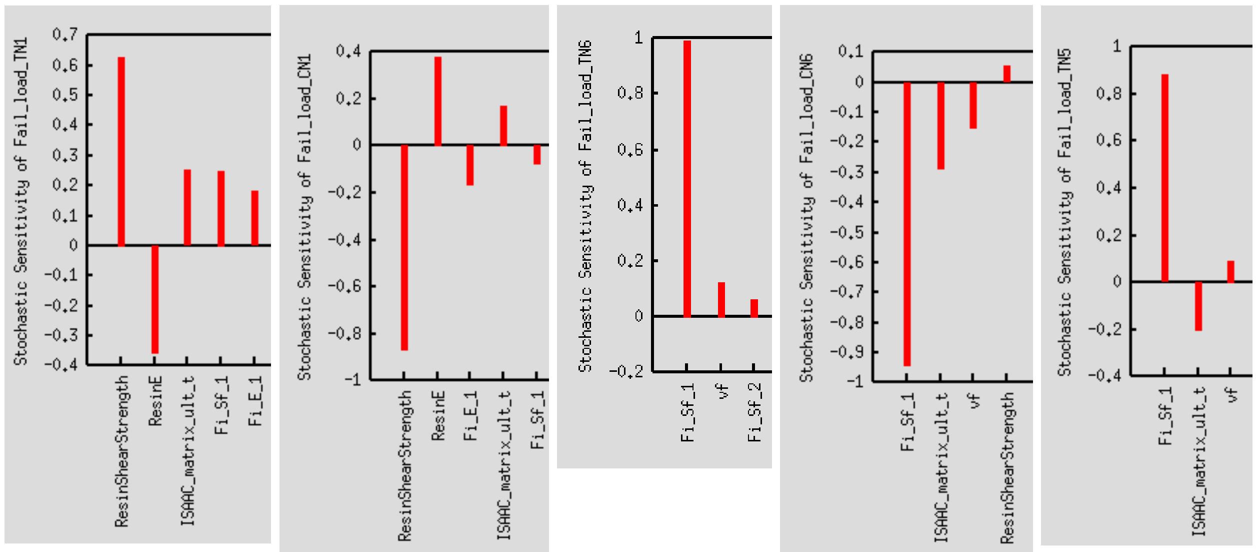


Figure 9.28 Probabilistic Optimization Process Employed in the Model Calibration Process



6/82/12 Tension | 6/82/12 Comp | 60/32/8 Tension | 60/32/8 Comp | 48/48/4 Tension

Figure 9.29 Probabilistic Sensitivity Analyses to Identify the Top Drivers

Input Variable	Minimum	Nominal	Maximum	Initial	Scale Factor
vf.m_mean	0.5	0.6028	0.7	0.6028	1.0
vf.m_stddev	0.003	0.006	0.012	0.006	1.0
Fi_E_1.m_mean	38000000	40100000	42000000	40100000	1.0
Fi_E_1.m_stddev	450000.0	950000.01000(	1500000	950000.010	1.0
Fi_E_2.m_mean	2000000	2110000	2300000	2110000	1.0
Fi_E_2.m_stddev	10000.0	20000.0	30000.0	20000.0	1.0
Fi_Sf_1.m_mean	575000.0	610000.0	775000.0	610000.0	1.0
Fi_Sf_1.m_stddev	30000.0	61000.0	120000.0	61000.0	1.0
ResinE.m_mean	420000.0	516440.0	630000.0	516440.0	1.0
ResinE.m_stddev	15000.0	25000.0	45000.0	25000.0	1.0
ResinShearStrength.m_mean	4000.0	4616.0	5300.0	4616.0	1.0
ResinShearStrength.m_stddev	150.0	230.0	400.0	230.0	1.0
ISAAC_matrix_ult_t.m_mean	10000.0	15000.0	20000.0	15000.0	1.0
ISAAC_matrix_ult_t.m_stddev	500.0	1500.0	3000.0	1500.0	1.0

Figure 9.30 Statistical Parameters That Were Treated as Design Variables in the Probabilistic Optimization Process

Number	*Layup*	*OHC*						
		Test			*Before Calib.*		*After Calib.*	
		# Tests	*Average*	*Std.Dev*	*Average*	*Std.Dev*	*Average*	*Std.Dev*
1	*6/82/12*	*333*	*35.26*	*1.60*	*34.99*	*2.15*	*34.46*	*1.749*
2	*12/48/40*	*10*	*38.75*	*1.34*	*41.03*	*2.02*	*40.27*	*1.708*
3	*28/48/24*	*13*	*56.92*	*3.95*	*48.65*	*4.79*	*52.32*	*4.657*
4	*32/64/4*	*13*	*59.57*	*3.96*	*44.93*	*3.99*	*48*	*3.871*
5	*48/48/4*	*10*	*68.12*	*5.20*	*62.73*	*5.58*	*66.75*	*5.376*
6	*60/32/8*	*N/A*	*N/A*	*N/A*	*80.97*	*7.5*	*86.25*	*7.185*
					Error	*0.5188*		*0.1646*

Figure 9.31 Optimization Process Reduced the Mean Square Error for Probabilistic Results from Analysis and Test

Item	*Before Calib.*		*After Calib.*	
	Mean	*Std.Dev*	*Mean*	*Std.Dev*
Vf	*0.6028*	*0.006*	*0.6179*	*0.006*
Fi_E1	*4E+07*	*950000*	*4E+07*	*927284*
Fi_E2	*2110000*	*20000*	*2E+06*	*19995*
Fi_Sf1	*610000*	*61000*	*633568*	*56773*
Resin_E	*516440*	*25000*	*548256*	*23856*
Resin_shear	*4616*	*230*	*4746*	*186*
Resin_Ult_t	*15000*	*1500*	*14946*	*1461*

Figure 9.32 Modified Statistical Input Parameters that Provide a Better Match between Analysis and Test.

The probabilistic optimization methodology that was applied for model calibration has a much wider application than the specific case illustrated above. For example the percentile values could be used in the optimization process as opposed to the higher statistical moments that was used in this application. An example of this will be the optimization of the process variables that can provide the maximum B-Basis allowable. Further, the optimization problem definition could include probabilistic constraints. A practical application of this in a new material introduction scenario can be arriving at processing allowable variations specifications for assured minimum B-Basis allowable.

The developed tools can handle complex probabilistic events in the objective as well as in the constraint functions. An example of such an application not exercised above is a system reliability problem wherein probabilistic constraints in the form of percentile values for multiple probabilistic events in the form "and/or" conditions could have been stated. A scenario of this application could be satisfying strength, fatigue, and fracture allowable based on percentile values. It is of value that the factor models along with probabilistic optimization process should further be applied to AIM-C methodologies to further validate their application.

10. Cost, Schedule and Technical Risk Assessment

Cost, schedule, and risk are the primary metrics for the AIM-C Program. Integrated Product Team (IPT) leaders will measure their performance and success using the parameters and the AIM Program needs a way to objectively develop these parameters, clearly, concisely, and consistently. With that end in mind, these parameters and the means for their determination are presented in this section. Not only are these parameters developed within the AIM toolset, they were also used by the Design Knowledge Base DKB re-creation teams, during the AIM-C Phase 1 program, to assess the capability of the system. It was the acceleration demonstrated by these DKB re-creation teams that gave credence to the potential for acceleration shown by the AIM-C process, examples of which are used herein to demonstrate the use of these parameters by IPTs.

10.1 Cost – Cost is not the primary metric used to assess the capability of the AIM methodology, but it is the one that is often the most difficult for IPTs to deal with and some of the better tools generated in the AIM-C program were focused on cost. The primary goal of the cost metric development activity was to provide to the IPT a tool to both assess the life cycle cost benefit of one materials system (or one application) versus another, but also to provide a means to determine if one method for achieving certification was more cost effective than another. To do that required that we assemble a tool that could develop realistic cost comparisons between systems from the non-recurring costs, through recurring costs, to operations and support costs. We were aided in this endeavor by the work previously performed under the Air Force Composites Affordability Program (CAI) and some work done internally by the Air Force on operations and support costs. The next few sections outline the non-recurring, recurring, and operations and support costs that make up the life-cycle cost models developed for AIM-C.

10.1.1 Non-Recurring Costs – Non-recurring costs are all those costs associated with the risk reduction efforts leading to authority to proceed with production of a product. These costs include the gathering of existing knowledge, testing from coupons to certification tests, and the cost of the analyses performed to support those tests. In the methodology the costs can be developed easily by examining the exit criteria for each Technology Readiness Level. Since each readiness level has a gate review associated with it that defines the knowledge required to exit the TRL, one can define and quantify the costs required to mature the technology through certification. This method is shown in Figure 10-1 that shows the elements of cost by TRL level and the source of money as it transitions from the development team to the applications team. The costs for the full scale test articles and their tests are assumed to be outside of this cost modeling effort and part of a project certification plan.

Cost Allocation	Technology Development Costs			Shared Costs					Non-Recurring Costs		
Development Cycle	Technology Development			Concept Defintion			Risk Reduction		RDT&E		
TRL	0.25	0.5	0.75	1	2	3	4	5	6	7	8
Application Cycle Definition	Technology Discovery	Technology Verification	Technology Ready to Offer	Assembly Concept	Assembly Plan Definition	Key Assembly Detail Definitions	Key Assembly Details Tested	Sub-components Assembled & Tested	Components Assembled & Tested	Airframe Assembled & Tested	Vehicles Assembled & Flight Tested
Materials Development	2 Panels	20 Tests	200 Tests	Req. Def.	Mat'ls for KFA	Sup Mat'ls					
Manufacturing & Tooling Development		3 Panels	30 Panels	Req. Def.	Tool Con KFA	Tool Fab	Fab KF Article	Fab Subcomp			
Assembly Simulation and Planning				Analyses	Plan Def.	Assembl. Def.	KF Article	Assemb Sub			
Certification Testing				Req. Def.			Crit. Details	Allowables	Full Scale	Static	Fatigue
Structural Concept & Sizing			5 Tests	30 Tests	KFA Init Size	KFA Final Size	KFA Test	Design Values			
Design Engineering				Concept Def.	Def. KFA	Assem. Def.	Redes. If Nec.	Sizing			
Supportability				Req. Def.	Repair Conc	Repair Plan		KFA Repair	Subc Repairs	Comp Repairs	A/F Repairs
Durability				Init. Screening			KFA Test	Details Tests	Full Scale	Prep for A/F	Repair Dur
Survivability				Req. def.			Eval				
Cost Benefit Analysis				Req,. Def.	Rom Costs	Plan Costs	Act. Costs				
Intellectual Property Rights				PIA etc.	Purchasing		Downselect				
Management, Scheduling and Planning		Info	Pre Eval	SRR	PPR	PDR	CDR	IDR	A/F PDR	A/F CDR	APR
Man Level	1	2	3	5	7	7	7	6	4	3.5	3
Development Costs	150	450	900	1350	1640	1190	640	300			
Application Costs				150	450	900	1450	1450	900	675	600
Total Costs	150	450	900	1500	2090	2090	2090	1750	900	675	600

Figure 10-1 AIM-C Cost Model for Estimating Non-Recurring Costs

After the IPT has developed their plan for meeting the certification requirements, the testing and analyses and knowledge gathering efforts required can be quantified right down to the costs of individual tests, their numbers, and their complexity to determine costs. The same can be done for analytical and knowledge gathering efforts. The total non-recurring costs are then a simple roll up. Charts like that shown in Figure 10-2 allow the IPT to determine whether they will meet exit criteria by existing knowledge, analysis, or test. Once that plan has been determined and the number of tests at each level is defined, it is a pretty easy matter to roll up the costs for the non-recurring portion of the plan. This represents a significant risk reduction for the cost portion of the analysis as well.

2.1		**TEST TYPE/PROPERTIES - FIBER**	**0.25**	**0.5**	**0.75**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
		Fiber Form and Type (Uni and Cloth, ie 5hs or plain or 8hs etc.)				x	x									
2.1.1	➢	Tensile Strength			x	x	x	x	x							Analysis
2.1.2	➢	Tensile Modulus E11 (longitudinal)			x	x	x	x	x							Analysis
2.1.3	➢	Tensile Strain to Failure			x	x	x	x	x							Analysis
2.1.19		Compressive Strength						x								Analysis
2.1.20		Cost			x	x	x	x	x							Specified Value
2.1.21		T(g)				x										Test
2.1.22		wet T(g)				x										Test
2.1.23		Health and Safety				x										MSDS
2.1.10		CTE - Radial					x									Analysis
2.1.11	➢	Filament Diameter			x	x	x	x	x							Test
2.1.12	➢	Filament Count			x	x	x	x	x							Test
2.1.13		Transverse Bulk Modulus					x									Analysis
2.1.14		Youngs Modulus, E22 Transverse					x									Test
2.1.15		Shear Modulus, G12					x									Analysis
2.1.16		Shear Modulus, G23					x									Analysis
2.1.17		Poissons Ratio, 12					x									Analysis
2.1.18		Poissons Ratio, 23					x									Analysis
2.1.4	➢	Yield (MUL)			x	x	x	x	x							Analysis
2.1.5	➢	Density			x	x	x	x	x							Test
2.1.6		Heat Capacity (Cp)					x									Test
2.1.7		Thermal Conductivity Longitudinal					x									Analysis
2.1.8		Thermal Conductivity Transverse					x									Analysis
2.1.9		CTE - Axial				x										Analysis
2.2.1	➢	Sizing Type			x	x	x	x	x							Specified Value
2.2.2		Fiber Surface Roughness				x										Test
2.2.3		Surface Chemistry				x										Specified Value
		Defect Identification				x										
		Defect Limits					x									
2.2.4		Fiber CME beta1 (Longitudinal)					x									Test
2.2.5		Fiber CME beta2 (transverse)					x									Test

Figure 10-2 The IPT Conformance Plan Identifies Test, Analysis, and Existing Knowledge That Can Be Used to Define the Costs to Mature the Technology

There are other portions of non-recurring costs that go beyond the qualification and certification plan. Tooling costs are a portion of the costs included in non-recurring costs. Re-qualification costs for materials are also computed in the non-recurring portion of the cost model because of the nature of the testing and analysis involved. One might consider re-qualification costs due to material changes during the course of production to be any of the three types of cost elements: non-recurring, because it is not a regular event in production or operation; recurring, because it does happen often during production; or, operations and support because it really done to verify that a new material formulation is equivalent to that used in the production of the vehicle as parts get replaced due to wear or damage, and operation and support (O&S) cost. However, the test types used for re-qualification are most closely associated with non-recurring costs and that's what is used to develop these costs and that's why they are booked there.

Non-recurring costs are those costs most impacted by the AIM-C process and so this is where one can develop the greatest visibility into the benefits of AIM-C.

10.1.2 Recurring Costs – Recurring costs are those costs incurred while fabricating, assembling, and producing the product. These costs include materials, processing, fabrication, joining and assembly, and any testing done to qualify a particular part for delivery. The summary cost model for recurring costs is shown in Figure 10-3.

Cost Allocation	Recurring Costs							
Development Cycle	Production							
TRL	9							
Application Cycle Definition	Long Lead Item Purchases	Part Purchases	Fabrication of Parts	Tooling Replacement / Repair	Assembly	Quality Assurance	Pre-Flight Qualificaiton	Delivery
Materials Development								
Manufacturing & Tooling Development								
Assembly Simulation and Planning								
Structural Concept & Sizing								
Design Engineering								
Supportability								
Durability								
Survivability								
Cost Benefit Analysis								
Intellectual Property Rights								
Management, Scheduling and Planning								

Figure 10-3 AIM-C Recurring Cost Estimation Model

A large effort was expended under the Air Force funded Composites Affordability Initiative (CAI) to develop recurring cost models for composite products and these have simply been incorporated into the cost models used in the AIM-C program. No effort was expended in this program to expand, validate, or verify these models. They were simply extracted from the work done on CAI and incorporated into the process used by AIM-C. The model shown in Figure 10-3 can be used to estimate recurring costs rapidly, but a more robust analysis like SEER-DFM should be used to determine costs for articles like the Key Features Article or subcomponent and component articles. However, under CAI funding these models were shown to be very accurate for those processes for which data exists, Figure 10-4. In this validation effort performed under CAI funding, the costs estimated from SEER-DFM for over 200 component and subcomponent parts were compared with actual costs. Results for all were within 3.5% and 95% were within 2% of the actual costs.

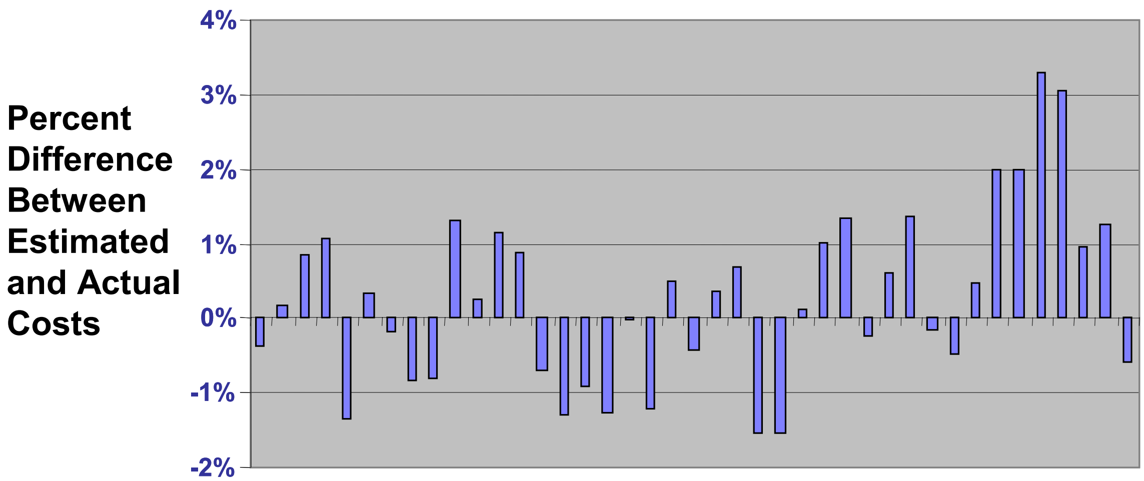


Figure 10-4 Comparison of Costs Estimated Used SEER-DFM and CAICAT Cost Model with Actual Costs Collected Shows Accuracy

The decisions made during the development of process limits, design values, and the key features fabrication and test article can make a great difference in the costs required to produce the product. The recurring cost module can be used to evaluate the impact of these decisions on the recurring costs of the product.

10.1.3 Operations and Support Costs – In some cases, operations and support costs can be drivers for the use of new materials in a system, especially when the material system provides a significant reduction in replacement costs. While the AIM-C methodology has little impact on the operations and support part of the costs for a given system, it has the disciplines that know those costs and they can be computed using the O&S cost model.

The biggest impacts that AIM-C has on O&S costs is the ability to select a material that minimizes O&S costs and the ability of AIM-C to potentially minimize the certification test costs required to implement the material, manufacturing, or structural change into the system. These costs are often major inhibitors to the introduction of new materials into existing systems or products.

The operations and support cost model developed for AIM-C came from Air Force data on such costs, but allows for modification based on the knowledge gained during the maturation process of AIM-C. The basic model is shown in Figure 10-5.

Cost Allocation	Operations and Support Costs									
Development Cycle	Operation through Disposal									
TRL	10									
Application Cycle Definition	Vehicle Operations	Mission Personnel	Consumable Materials	Maintenance Personnel	Depot Level Repairables	Depot Maintenance	Vehicle & Pollution Control	Replacment Parts	Installation Support	Part Disposal
Materials Development			1	1	1	1	1	1	1	1
Manufacturing & Tooling Development			1	1	1	1	1	1	1	
Assembly Simulation and Planning			1	1	1				1	
Structural Concept & Sizing			1	1	1				1	
Design Engineering		1	1	1	1				1	
Supportability	7	1		14	9	5	5	1	3	1
Durability		1		1	1					
Survivability		1		1	1					
Cost Benefit Analysis	1	1		1	1	1		1	1	1
Intellectual Property Rights		1		1	1					
Management, Scheduling and Planning	1	1		1	1	1	1	1	1	1
	9%	7%	5%	24%	19%	9%	8%	5%	10%	4%

Figure 10-5 Operation and Support Model Follows Air Force Data to Define Ratio of Effort in Each Category.

The overall AIM-C Cost model is defined most effectively in Figures 10-1, 3, 5. These figures show the relationship of each cost element to the technology readiness levels (TRL) where they are most often incurred. These Elements of Cost are rolled up to a higher summary level as shown in Figure 10-6.

AIM-C Cost Model					
		Low Value, High Rate	**Low Value, Low Rate**	**High Value, Low Rate**	**High Value, Very Low Rate**
		$K	**$K**	**$K**	**$K**
Non-Recurring		**$9,265.00**	**$9,265.00**	**$9,265.00**	**$9,265.00**
	Concept Definition & Development	$3,973.33	$3,973.33	$3,973.33	$3,973.33
	Risk Reduction	$940.00	$940.00	$940.00	$940.00
	Engineering, Manufacturing & Design	$2,175.00	$2,175.00	$2,175.00	$2,175.00
	Tooling and Long Lead Items	$1,706.67	$1,706.67	$1,706.67	$1,706.67
	Certification Testing	$470.00	$470.00	$470.00	$470.00
Recurring per Unit		**$115.20**	**$115.20**	**$11,520.00**	**$11,520.00**
	Materials & Purchases	$25.00	$25.00	$2,500.00	$2,500.00
	Fabrication (Incl. Tooling Replacement)	$50.00	$50.00	$5,000.00	$5,000.00
	Assembly	$25.00	$25.00	$2,500.00	$2,500.00
	Testing	$15.00	$15.00	$1,500.00	$1,500.00
	Delivery	$0.20	$0.20	$20.00	$20.00
Operation & Support		**$100.00**	**$100.00**	**$100.00**	**$100.00**
	Operations	$21.00	$21.00	$21.00	$21.00
	Maintenance	$60.00	$60.00	$60.00	$60.00
	Replacement	$15.00	$15.00	$15.00	$15.00
	Disposal	$4.00	$4.00	$4.00	$4.00
Unit Production Costs		**$133.73**	**$300.50**	**$11,705.30**	**$12,446.50**
	Number of Amortization Units	500	50	50	10
	Total Number of Units	5000	500	500	100
Unit Life Cycle Costs		**$133.75**	**$300.70**	**$11,705.50**	**$12,447.50**

Figure 10-6 Cost Model Summaries Provide Identification of the Cost Drivers for Insertion

The life cycle cost model shown in Figure 10-6 has been under development within Boeing for some time. It has been, and continues to be a valuable evaluation tool and a means for guiding engineers through the compilation of cost data required to compute life cycle costs for their concepts. It also provides good data for starting more detailed cost assessments done by cost accounting personnel for the IPT.

10.1.4 Unit Production Costs – The cost models developed for AIM-C allow the user to determine total product costs by rolling up the recurring costs with amortized non-recurring costs on a per part basis. Figure 10-6 shows the summary computation for such an analysis. Varying the number of units over which one amortizes the non-recurring costs can change the cost per unit significantly in some cases. In other cases, where the ratio of non-recurring to recurring costs are low, the number of amortization units has very little effect.

10.1.5 Life Cycle Costs – The cost models developed for AIM-C also provide a computation of the life cycle costs that are the unit costs plus the operations and support costs averaged per unit. This computation is also shown in Figure 10-6 for the same variations described above.

10.1.6 Cost Risk Assessment – Cost risks are determined by how much data and knowledge are available to support the cost estimates provided. At early TRLs in which the cost numbers are developed using previous knowledge and analytical projections, the risk is high. Once the IPT has assembled its plan for how it will develop the knowledge base required to certify the product cost risks come down significantly. As the maturation process progresses and the plan is modified or rework cycles take place, the plan becomes more robust and better defined and the cost risks are again significantly reduced. Once the key features test has been conducted and the plan for certification has been defined cost risks are negligible for the non-recurring portion of the cost model.

In the same way, as the processing limits and tooling requirements become defined the cost risk decreases for recurring costs elements. As the key features test article becomes defined and completed, further cost risk reductions take place. Production planning reduces the risk further and production itself reduces the risk to negligibility.

Operations and support costs have some risk reduction as certification and production are achieved, but the operations and support costs are all projections until the product is actually fielded. Then as knowledge comes in, these costs begin to see real risk reduction. Figure 10-7 shows the general trend for risk reduction as a material system passes the TRL gate reviews toward becoming part of a fielded product. Of course, the general reductions shown herein are revised based on knowledge gained on the specific material system as each review is held.

Cost Allocation	Technology Development Costs			Shared Costs					Non-Recurring Costs		
Development Cycle	Technology Development			Concept Defintion			Risk Reduction		RDT&E		
TRL	0.25	0.5	0.75	1	2	3	4	5	6	7	8
Application Cycle Definition	Technology Discovery	Technology Verification	Technology Reproducible	Assembly Concept	Assembly Plan Definition	Key Assembly Detail Definitions	Key Assembly Details Tested	Sub-Components Assembled & Tested	Components Assembled & Tested	Airframe Assembled & Tested	Vehicles Assembled & Flight Tested
			TRR	SRR	PPR	PDR	CDR	IDR	A/F PDR	A/F CDR	APR
Non-recurring Costs	Very High	Very High	Very High	High	Med-High	Med	Med-Low	Low	Very Low	Very Low	Very Low
Recurring Costs	Very High	Very High	Very High	Very High	Very High	Very High	High	Med-High	Medium	Med-Low	Low
Operations and Support Costs	Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High	High	High-Med	Med

Figure 10-7 Insertion Cost Risk Reduction and Technology Maturity

10.1.7 Benefits of AIM-C to Cost Control – AIM-C has been able to document cost reductions greater than 45% over the cost of the conventional Building Block approach using its coordinated analysis supported by test approach. Conditions under which AIM-C might not be able to save cost for insertion have not yet been identified.

The AIM-C methodology and cost models offer rapid estimation of costs right from the outset of the insertion path. We have included historical data from composite insertion cases that offer resident, existing data from which to make those estimates until the knowledge gathered during the course of the AIM-C process has developed more robust estimates using actual data on cost.

One of the benefits of offering the IPT a detailed test, analysis, existing knowledge guide is that the IPT can look at alternative paths, alternative tests, and alternative analyses to determine what the cost / risk payoffs or penalties might be. And with the AIM-C System having this database and process resident, these evaluations can be performed with the speed of a spreadsheet computation. Since risk assessments are part of the process, the IPT does not need to take a high risk approach unless it is being driven by schedule, cost, or performance requirements to do so. Even in those cases, they can identify what that risk penalty for 'skipping' steps will be.

The AIM-C Cost models offer direct computation of the cost for insertion from TRL of 1 through TRL of 6, ready for certification. But in addition to these direct computations, AIM-C includes a validated model for examining the costs of performance capability or manufacturing limitations on cost or performance in the product itself. The System uses the CAICAT model from the Composite Affordability Initiative to perform these computations. The IPT can also assess the effects of their decisions or the performance of the material system on the potential operations and support costs. These estimates are obviously the least mature of those offered, but the knowledge base increases, these estimates will gain in reliability and robustness. Because the AIM-C process has only indirect effect on the costs of the product or the operations and support costs, these portion so the cost model might be expected to mature a little slower than the non-recurring models which will receive feedback during the use of the AIM-C System and process right from its implementation.

Finally, the cost modeling capability in AIM-C allows the user to examine costs based on unit costs for acquisition or on life cycle. This capability is a key to being able to relate the cost payoffs or penalties for one material system versus another for the IPT at the system level to assess the cost risk, schedule and performance payoffs for various material systems – one of the keys to successful insertion.

10.2 Schedule – Schedule is the primary metric used in assessing the value of the AIM-C program. But it is also the metric that helps the IPT to determine what path they will follow for developing the design knowledge base – whether by previous knowledge, test data, or by analysis. The conformance matrix is the guide used to determine the schedule and elapsed time required to implement any conformance plan selected by the IPT. By selecting the method by which each element of the conformance plan will be met, the IPT can get instant feedback on the length of time required to generate the knowledge base required and investigate, via 'what if,' alternative conformance plans. The IPT can also decide to eliminate portions of the recommended conformance plan to reduce schedule, but the risk associated with the plan increases when this is done. The intent was to link cost, schedule, and risk through the Conformance Plan, so that the IPT could get instant feedback on the impact of decisions made on whether to perform test or analyses to gather data, or whether to rely on analysis with previously developed data.

It must be mentioned here that the AIM-C System was never completed to the extent that cost, risk, and schedule were linked to the Conformance Plan. While the calculations can be done off-line, this remains one key element of the process that really needs to be implemented in the system at some later time.

10.2.1 Using the Conformance Plan to Develop Schedule – In the same way that the conformance plan is used to determine cost, as described previously, by looking at a baseline plan assembled by the recommended guidelines for conformance, a baseline schedule can be provided to the IPT. The times for tests to be documented, estimated by the lab, funds allocated, setups performed, systems checks made, tests performed, data reduced, and the test data documented, including lessons learned, can be developed from historical data. However, in this case, we relied on the baseline IM7/977-3 database development performed under the F/A-18 E/F program to define these time and elapsed times. Then by using the conformance guidelines developed under the AIM-C program, we set out the times associated with each test series and used the same amount of parallel testing that was performed under the F/A-18 program.

These assumptions allowed us to take the F/A-18 schedule experience and prepare a 'best case', version of that test program. A summary of that schedule is shown in Figure 10-8. In this development, "best case," means that no time was allocated for machine down time or calibration times, no time was set aside for unnecessary waiting for specimen fabrication or machine availability other than when the schedule said that the fabrication or testing was being delayed by other AIM-C related fabrication or testing. "Best case," therefore, refers to the best possible schedule that could be developed using the fabrication, instrumentation, and test times available on the machines used to do the F/A-18 testing.

The goal of this portion of the AIM-C effort was to tie the conformance plan to Microsoft Project and drive the schedule creation from the conformance plan. Today this must be done by hand. While not a serious technical problem to incorporate this element into the system, it was not completed because the other technical elements of the system took precedent over this one.

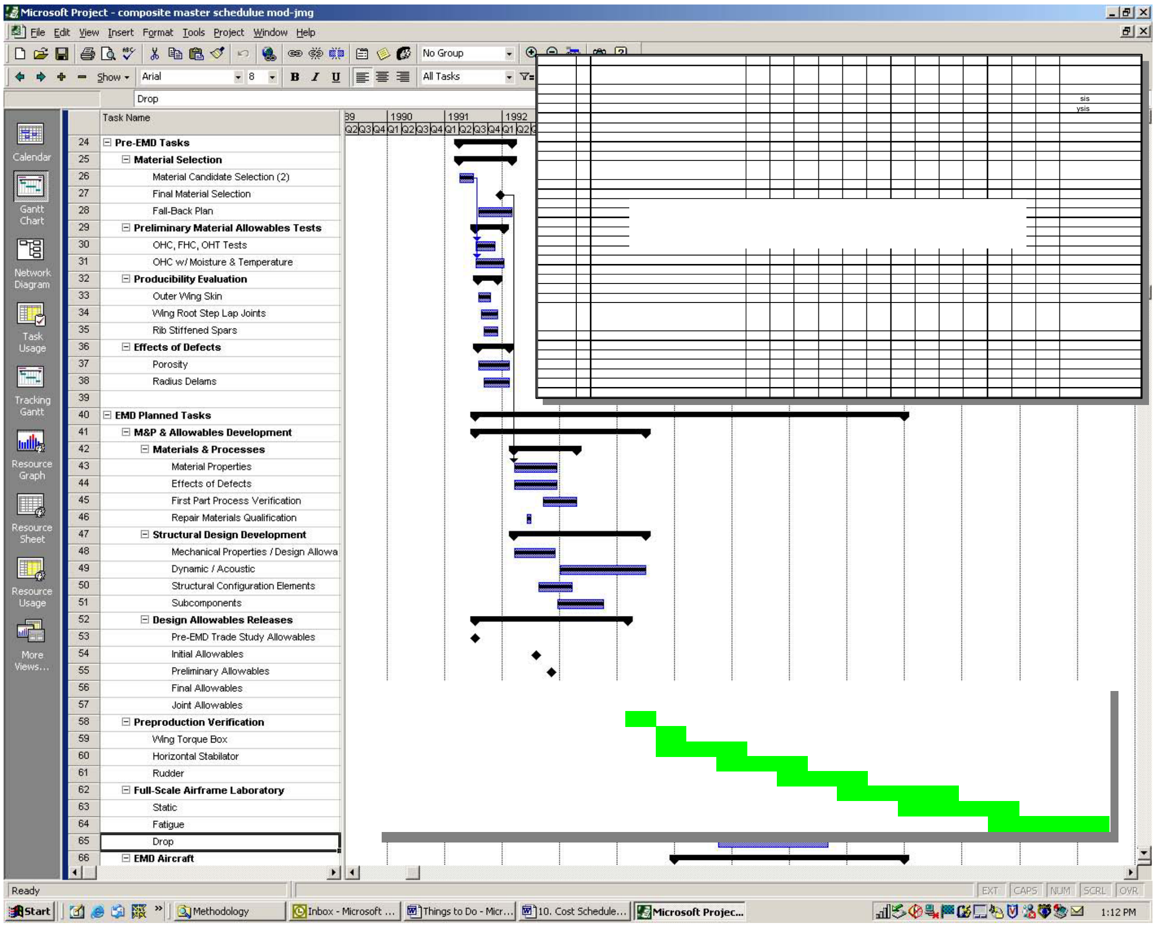


Figure 10-8 Development of the 'Best Case' Baseline Schedule for AIM-C

10.2.2 Schedule by TRL / Discipline / Knowledge, Analysis, Test

Because the schedule elements are tied to the conformance plan, these elements can be parceled any way the user demands. They can be developed by TRL level since the TRL levels are defined by IPT maturation reviews which are definable on the schedule. All work elements that must be completed prior to a given TRL maturation review can be summed to determine the amount of effort required to meet a given review milestone. The work effort can also be summed by discipline so that the staffing plan for that discipline can be readily determined. This can be a real advantage for program management. And the elements can be divided by how the team intends to develop the knowledge base, by analysis, test, or existing knowledge. This information is probably of greater interest to certification agents than to other management or team members, but it is available.

10.2.3 Schedule Risk Assessment –

Schedule risk parallels cost risk in that risks are mitigated as TRLs increase. One of the benefits of the AIM-C methodology is that problems are uncovered at each maturation review by the team and must be dealt with at that meeting before work on subsequent maturation levels can be started. Now the AIM-C team knows that there will be temptations to short cut this discipline and to forge ahead on risk reduction efforts while problems and potential show stoppers identified in earlier maturation steps have not yet been rung out. However, an honest assessment of the maturity of the technology will readily show the level of risk the team has accepted by moving forward in some areas while leaving unanswered questions open in the wake of the effort. The AIM-C methodology puts a premium on the discipline exercised by the IPT team leader in its implementation.

In the same way that cost risk is affected by technology maturity level, so is schedule risk. A similar chart can rather easily be formulated to depict this truth, Figure 10-9. But the reality of this chart is very real from a program management point of view. If the technology is not at a given level when delivered to the program, it cannot be matured in time to meet program milestones. So there are some hard and fast rules for when and at what TRL levels (from a program perspective) technologies can be accepted and when they must be rejected as too high a risk. These levels of risk are depicted in Figure 10-9.

			Product Development Phases			
Technology Readiness Level	Readiness Level Definition	Concept Exploration & Definition	Demonstration / Validation	Engineering / Manufacturing Development	Production / Deployment	Operations / Support
10	Operation and Support	No Risk				Very Low
9	Production Flight Proven				Very Low	Low
8	Flight Test Qualified			Very Low	Low	Med-Low
7	Ground Test Certified		Very Low	Low	Med-Low	Med
6	Component Ground Test Valdiation	Very Low	Low	Med-Low	Med	Med-High
5	Subcomponwent Ground Test	Low	Med-Low	Med	Med-High	High
4	Key Features Comp Test	Med-Low	Med	Med-High	High	Very High
3	Processing Validation Testing	Med	Med-High	High	Very High	
2	Materials Validation Testing	Med-High	High	Very High		Unacceptably
1	Material Concept Documented	High	Very High			High

Figure 10-9 Schedule Risk Linked to Technology Maturity

10.3 Technical / Performance Risk

The AIM-C methodology uses a divergence/risk assessment to determine the technical/performance risk at any technology maturation level in the process. The term "divergence/risk analysis" was coined for one of the qualification elements in a recent effort funded by Office of Naval Research "New Materials, New Processes and Alternative Second Source Materials Data Base Generation and Qualification Protocol Development," (Reference[1]). A shortened designation for the program will be "ONR Protocol." Divergence risk is intended to be a measure of the degree of similarity between the issue under consideration and other issues in the experience base of the integrated product team. Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how different the new material or process is from known and understood materials or processes. Risk analysis is also performed to determine the consequence of reduced testing, testing under different sequences, and so forth.

The consequences of the identified risks are also evaluated using the a concept developed at Boeing's Rocketdyne Division for assessment of the technical maturity of rocket engines. This concept is based on the number of rework cycles required to overcome problems as they are encountered at each level of maturity in the system development. It reflects the fact that the more mature the system development at the time the problem is identified, the higher the number of rework cycles required to overcome the problem and the higher the cost associated with this rework. These assessments drive the AIM-C methodology to make every attempt to make problems visible to the team as early in the development cycle as possible so they can be dealt with before they become costly show stoppers.

10.3.1 Technical / Performance Risk Assessment

The first step in establishing the level of risk is to define the magnitude of divergence between the baseline and the alternate material or process. This is done by listing all the properties, characteristics, descriptors, and attributes associated with the baseline composite materials and processes, then assessing the differences for each of the items on the list.

The list can be top level or detail in nature. Divergence areas could include (1) a change in the raw material source: (2) a change in the processing site or equipment; (3) a change in fiber sizing; (4) a change in fabric style; or (5) a change in resin. The difference could also include a change in the part fabrication process, such as going from hand collation to fiber placement, or from hand collation to resin transfer molding. There could be a material change associated with the fabrication process change or there could be no changes in the material. There may also be equipment changes within the fabrication process. The magnitude of divergence between the material and process combinations defines the starting level of risk.

For example, one of the items on the list could be "resin." In one case, the baseline material is a 350°F curing epoxy such as Hexcel's epoxy resin, 3501-6. To be rated as "no divergence," the alternate material need only be a 350°F curing epoxy resin such as Hexcel's 8552. In another situation, however, the definition of "no divergence" is an alternate resin mixed at an alternate site, but chemically equivalent to the 3501-6.

An assessment is made for each item on the list to determine the level of divergence between the baseline material and alternative material. By definition there will be acceptable levels of divergence for some items (such as the qualification of a new prepreg line) and there will be some items where no divergence is allowed (for example, the resin formulation for qualification of a licensed resin).

Relevant testing requirements are defined and identified with respect to these areas of divergence. At times the testing is used to validate that the divergence does not negatively impact the material or the end use of the material, while at other times testing is used to validate that there is no divergence.

A key element of the divergence assessment is to define the accept/reject criteria to be used in analyzing the test data, audit findings, and processing trials. Establishment of criteria requires a clear understanding of the divergence requirements: equivalent versus equal, similar versus identical, statistically based versus typical values, and so forth..

Risk is directly associated with the uncertainties that stem from the level of divergence. The objective is to manage the risk and reduce it to an acceptable level by effectively structuring and conducting the qualification program. The qualification program focuses on the testing of the alternate material, but risk is also reduced through other activities such as audits, processing trials, and drawing on previous experience.

Risk assessments may also be subjective. What is viewed as high risk to one person could be viewed as a medium risk to another. Past experiences and familiarity with the new material or process will influence a person's perception of the risk level. For these reasons, it is important that the level of material or process divergence be quantified and that a systematic risk assessment process is documented.

Figure 10-10 shows the results of one such analysis. The results for a number of parameters that define the maturity of the material system have been identified and their likelihood of occurrence has been determined. Secondly, the impact of that occurrence has been determined as well and the likelihood versus impact has been plotted on the chart. Note that the points for each parameter of the technology differ in size. There is uncertainty in the determination for these parameters and that uncertainty is reflected in the size of the symbol used to show the risk evaluation. Highest risk on this chart is in the upper right corner where the probability occurrence is very high and the impact of the occurrence is also very high. Rationally designed structures will attempt to do whatever is necessary to get risk evaluations in the lower left hand corner where certification is easiest.

The consequences or impact of the risk parameter can also be developed using the rework versus risk analysis developed by Rocketdyne. In this case, once the risk has been established, one can use a chart like that shown in Figure 10-11. This chart which is based on historical data and experience shows that the relationship between risk and rework cycle, impact, or cost consequences is not linear, but highly non-linear. Problems found early in the risk reduction effort can be reworked at small cost, but rework required at high risk, high maturity of the system can be very expensive. As always cost, schedule and risk are all linked to the maturation of the system. The purpose of the AIM-C methodology is to address system development risk so that the consequences to cost and schedule are minimized until the risk reduction has been completed to the level that the material system can be used with user defined confidence.

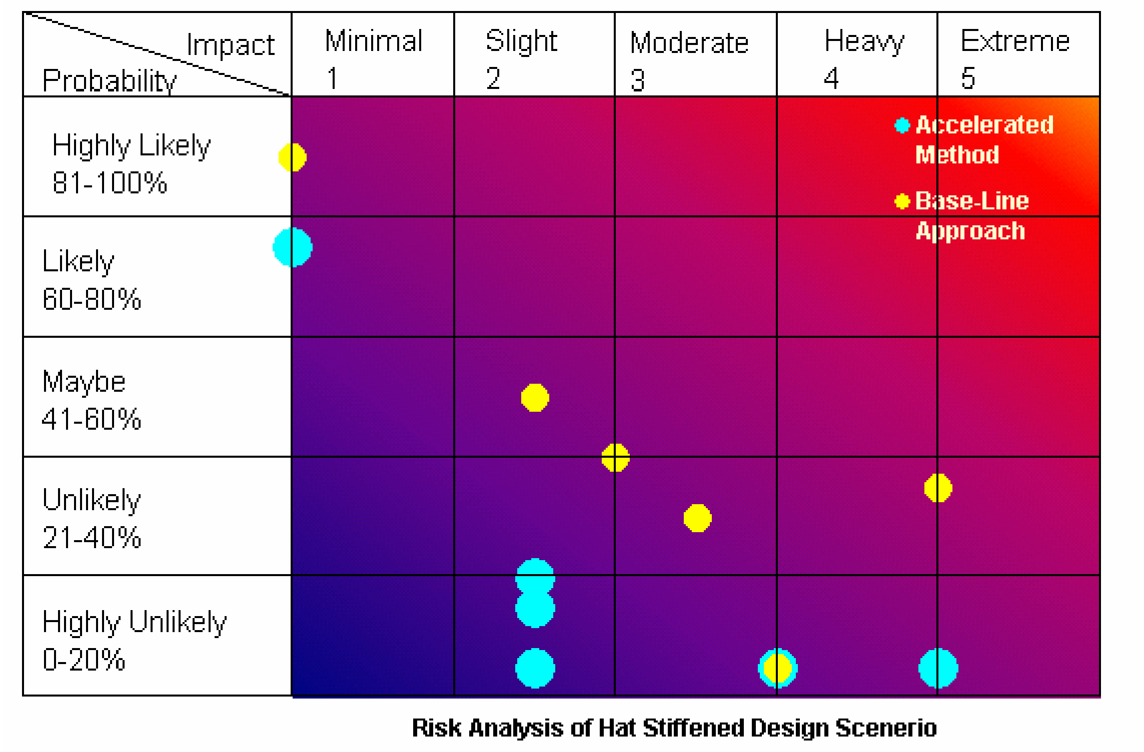


Figure 10-10 Risk Analysis

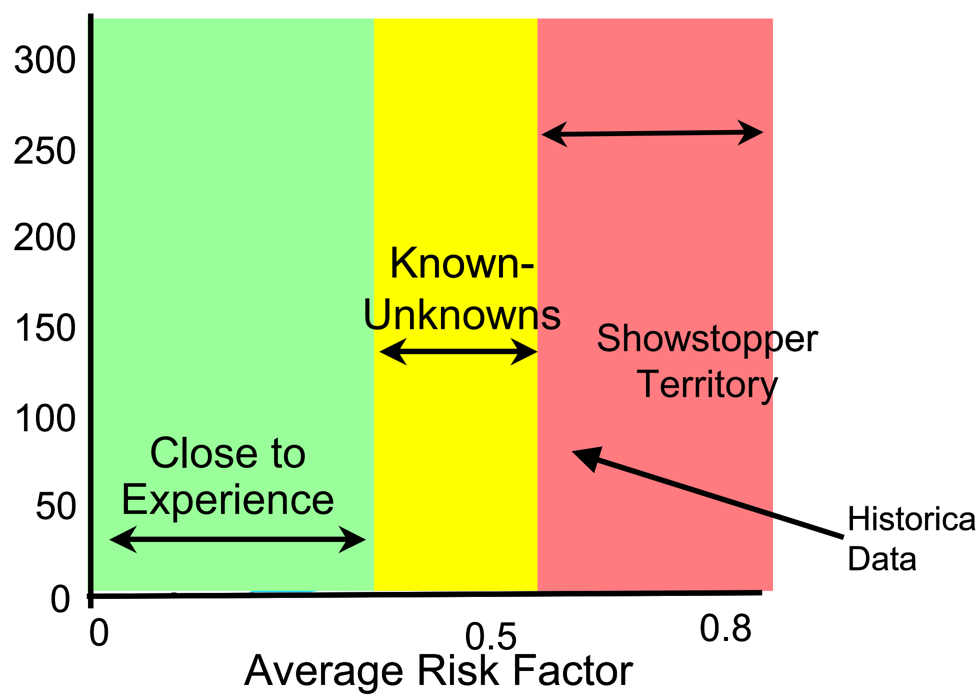


Figure 10-11 Rework Cycles Link Cost and Schedule to Risk Reduction and Maturation

10.4 Demonstration of the Use of Metrics for Acceleration in AIM-C

In order to demonstrate how the metrics for accelerated insertion are developed and how they are used to evaluate the value of acceleration provided by the AIM methodology, we have chosen to look at a baseline that is a conventional building block approach to certification and the AIM accelerated insertion methodology. For the purposes of this evaluation we chose to use an outer wing as the example case. The experience of the F/A-18 E/F development and some of the schedule experience from the program is used to develop the data herein. But this example (for both the building block approach and the AIM approach) is an idealized case; it assumes no rework, no interruptions, and no changes in requirements during the course of the development and certification program. No program has ever had it that good.

Since component development on an aircraft program is just part of an overall development program there are holds while data for other elements of the system are developed. In this example, we eliminated these holds and treated the development as if it could continue at its own pace independent of any other needs in the program. No component development ever had it this good either. However, our goal was to determine how well AIM serves to improve the insertion time, cost, and risk relative to a building block approach applied in its best-case scenario.

10.4.1 Baseline Schedule – The baseline schedule is developed using the AIM software and schedule process, but is based on the baseline building block approach toward component development and certification. Thus the time and costs of identical tests are the same between the two cases. A high level schedule for this effort might look something like that shown in Figure 10-12. We chose to identify the elements of the building block approach as major headings in this chart even though a program would group these with other elements of the plan and avoid duplication among components. But our goal was to treat the two cases as close to the same rules and conditions, as possible.

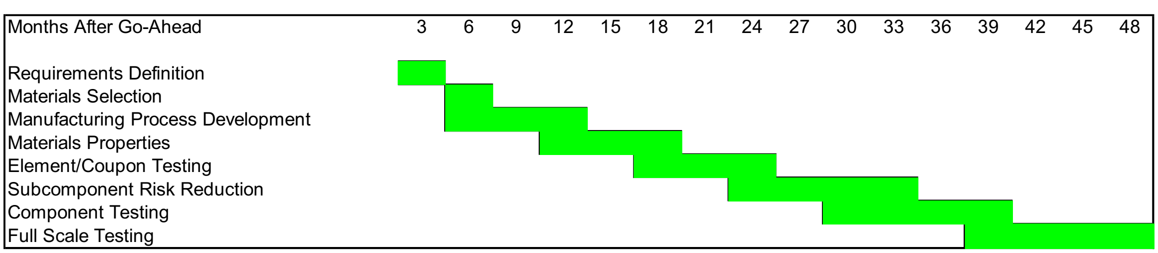


Figure10-12 Baseline Schedule for Conventional Building Block Certification Approach

10.4.2 Baseline Cost – The baseline cost was computed according to the same ground rules used for the schedule determination. We used the cost modules within the AIM-C system to compute these costs so that the same costing algorithms are used for each scenario. Thus the only difference in cost shown between these two scenarios is that produced by the difference in the Building Block Approach and the AIM-C methodology.

Figure 10-13 shows the cost breakdown for the building Block approach applied to this component.

	Lab Cost				Mfg Cost				Lab + Mfg	
	A	C	M	Total	A	C	M	Total	Total	
2	0	7130	0	7130	619	5601	212	6432	13562	Fiber & Resin Prop
3	8784	14205	128	23117	1237	11203	424	12864	35981	Material System Pr
4	575	11731	6045	18351	600	17830	8718	27148	45499	Process Impact
5	0	41705	11449	53154	0	33563	8160	41723	94877	Structural Propertie
6	200	39112	8315	47627	300	71846	18143	90289	137916	Structural Elements
7	2523	26331	14661	43515	6000	55158	7085	68243	111758	Subcomponets/Co
8	111144	28887	0	140031	527087	10000	0	537087	677118	Full-scale Ground T
Total	123226	169101	40598	332925	535843	205201	42742	783786	1116711	

Figure 10-13 Baseline Costs for a Conventional Building Block Approach

10.4.3 Baseline Risk – In the Building Block approach risk is minimized by providing a broad qualification of material and manufacturing systems that sequentially and methodically increases structural size and complexity to the full scale physical hardware. In our experience this has provided a safety of flight reliability that exceeds .999999. The elements that feed this reliability are those that make up the building block approach and the environments and fabrication repetitions that a part of that approach. Figure 10-14 shows the relative contribution made by each portion of the building block approach toward meeting the reliability experienced by our aircraft.

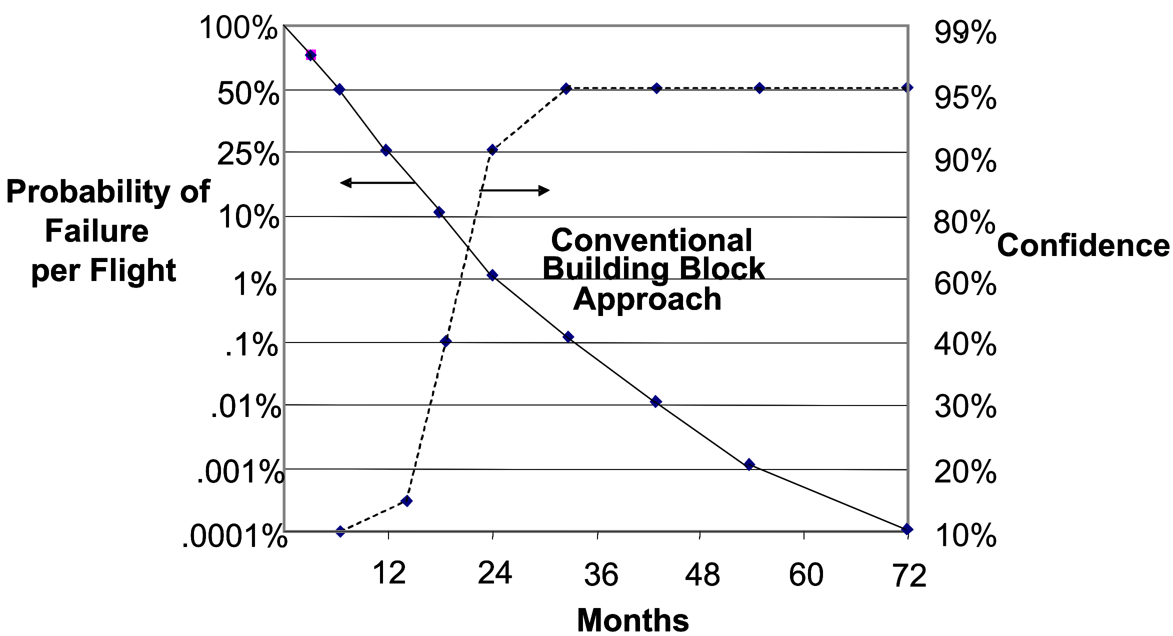


Figure 10-14 Risk and Confidence Levels Developed Using the Building Block Approach

10.4.4 Accelerated Schedule – The schedule for the AIM accelerated insertion methodology is a compilation of the elements shown in Figure 10-15. The qualification testing is spread through the fabrication maturation activity that leads to the full scale key features test article. But the types of tests are limited to those predicted to most influence the fabrication, and failure modes and loads expected in the key features test. So even though the key features fabrication and testing is by itself an expensive portion of the certification readiness effort, the amount of testing saved by focusing the testing toward this demonstration more than makes up for that additional expense.

But more important, the key features fabrication and test article focuses the certification testing on those loads and failure modes that truly impact the design. This cuts between 25 and 75 percent of the testing out of the certification test plan which no longer has to be all encompassing for allowables as the building block plan had to be. Moreover, the key features test article removed the risk reduction articles from the building block approach (since these really happen too late to impact either the allowables or the design. In the AIM approach the key features test article and its testing impact both the allowables produced and potentially the design should a problem be found in the fabrication or testing of the article. In this case, as in the building block approach evaluation, we’ve assumed that the entire process went off on schedule and without any required rework. This accelerated methodology is scheduled as shown in Figure 10-15.

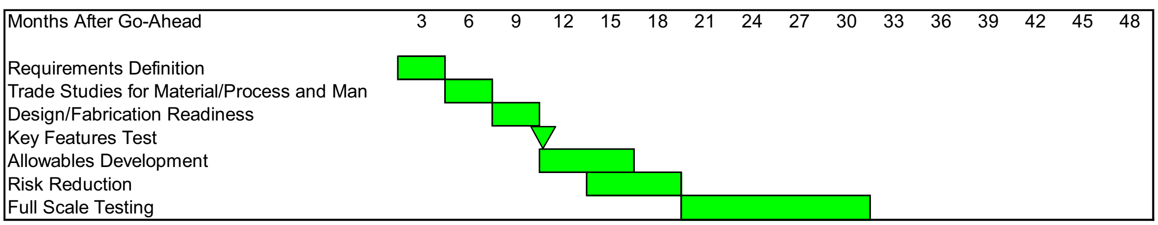


Figure 10-15 Projected AIM-C Accelerated Insertion Methodology

The AIM-C best case schedule reduces the time to readiness for full scale testing by more than 50% from 39 months to 18 months. However, we want to point out that the AIM-C methodology was developed to include planned rework cycles that not only can be accommodated, but are planned to occur early enough that a redesign can be incorporated into the configuration before allowables are developed and the design locked in place. This is crucial to the value of the AIM-C methodology – this built in ability to accommodate change before CDR and allowables development there is time built in (or the potential for a hold if you will), to incorporate lessons learned from the key features fabrication and test demonstration article.

10.4.5 Accelerated Cost – In the same way, the cost for the IPT and its activities leading to component certification were predicted using the same routines and same costs per test as those used in the evaluation of the baseline approach. All the costs by activity are shown in Figure 10-16. You can see that the cost of the key features fabrication and test article is large, but the payoff in qualification and certification testing is larger and moreover, you leave that test knowing you can build, at full scale, the parts you’ve designed, you can predict their behavior under load (and maybe environment if that's a concern).

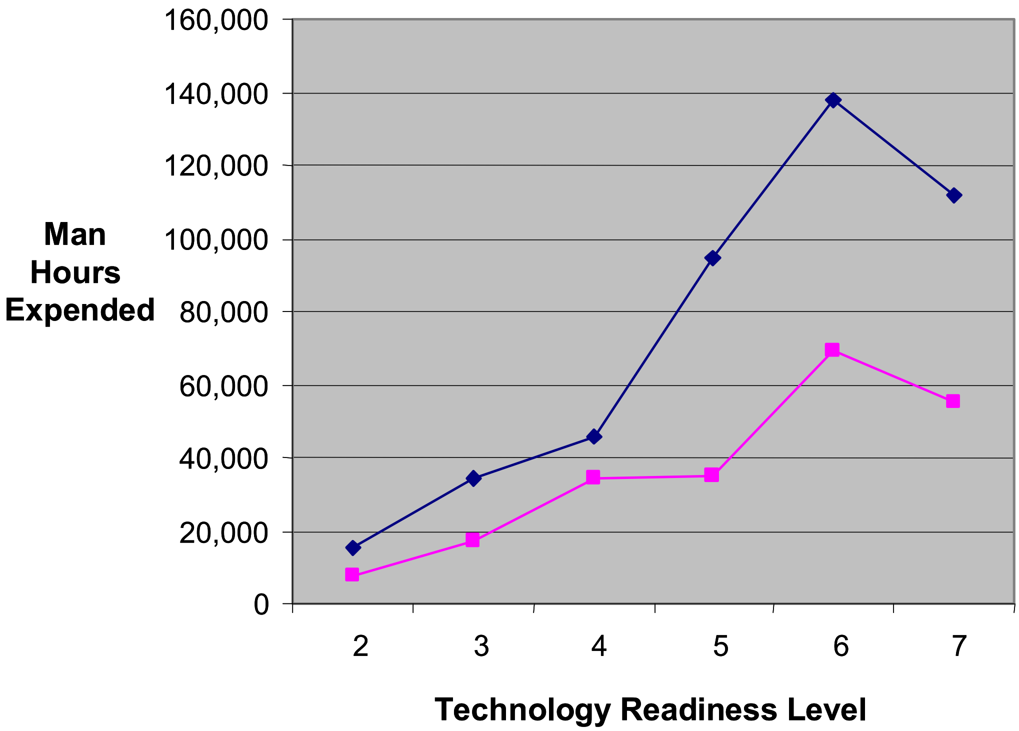


Figure 10-16. Comparison of Conventional and AIM-C Costs to Readiness for Full Scale Testing

10.4.6 Risk Due to Acceleration – One would think that reducing the number of tests performed and the number of risk reduction articles would increase the overall computed risk of the component at the end of the process, but this methodology puts all the risk into the process and its potential for rework, not in the delivered component. As shown in Figure 10-17, most of the risk is tied up in the early fabrication and testing of the key features article. But once that article has been fabricated and tested, its failure modes and loads predicted and verified, and allowables developed from that test knowledge base, the reliability is not only greater than that produced by the building block approach, but it renders the full scale test almost redundant since we could already have run a full scale outer wing test as the key features test.

Confidence levels shown in this chart assume that analysis of previous tests can be used to develop confidence in the predicted design values before any testing is performed. The assumption was that the greater the number of prior tests, the greater the confidence in those results. However, the results of the work in AIM-C Phase 1 have shown that tests plus analysis develops confidence faster than either alone. And thus we do not show real acceleration in confidence until the number tests becomes equivalent to those performed under the Building Block Approach. We get improved confidence when we can use analyses to project results with confidence and this depends entirely on the level of validation of the models through previous testing.

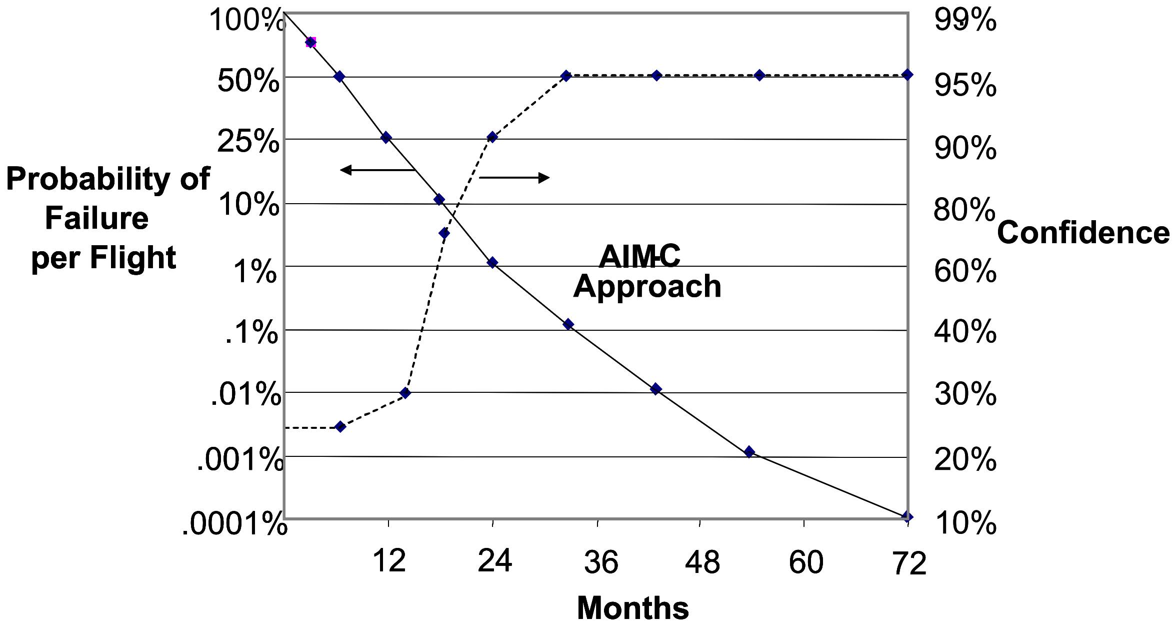


Figure 10-17. Risk and Confidence Levels Developed Using the AIM-C Approach

10.4.7 The Benefits of Acceleration – Using the formats previously presented to summarize the benefits of the AIM-C methodology, we produce the data shown in Figures 10-15 to 10-17, for schedule, cost, and risk respectively. Based on the baseline conventional building block approach and the project AIM-C optimized building block approach, the time to implement the new material has been reduced by 55%, the cost by 45%, and the risk has been reduced by an order of magnitude for the already high values obtained by the conventional building block approach. The experience gained with teams of people running through the methodology both using conventional tools and approaches, as well as using the AIM-C methodology has resulted in comparable results although the total acceleration varied depending on the scale and complexity of the component selected for study. In general, the smaller and simpler the component, the less the savings (sometimes there is even a penalty for very small and simple parts), and greatest with the larger and more complex parts that so often have caused new technologies to be left on the table when they could have provided significant cost or weight savings.

Figure 10-18 compares the risk reduction afforded by the AIM-C approach in comparison to the conventional building block approach. While it is often hard to realistically compare risk reduction schemes by the amount of risk reduced, this analysis based on performing and focusing on early risk and scale-up risk reduction provides payoffs throughout the development program.

Figure 10-19 summarizes the benefits of the AIM-C methodology on cost and schedule for accelerated insertion of materials and Figure 10-18 summarizes the more rapid risk reduction capable using the AIM methodology. All these evaluation metrics are linked and changes in any affect the other two, but the AIM methodology offers continuous evaluation of these parameters throughout the technology maturation process. The AIM team feels that the methodology described herein is applicable to nearly any technology and not just to materials or structures technologies.