DOT/FAA/AR-06/25

Air Traffic Organization
Operations Planning
Office of Aviation Research
and Development
Washington, DC 20591

Preliminary Guidelines and Recommendations for the Development of Material and Process Specifications for Carbon Fiber-Reinforced Liquid Resin Molded Materials

May 2007

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-06/25		

4. Title and Subtitle	5. Report Date
PRELIMINARY GUIDELINES AND RECOMMENDATIONS FOR THE DEVELOPMENT OF MATERIAL AND PROCESS SPECIFICATIONS FOR CARBON FIBER-REINFORCED LIQUID RESIN MOLDED MATERIALS	May 2007
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Gregg Bogucki, John Bayldon, Larry Gintert, Stephen Ward, William McCarvill, and John Tomblin	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
National Institute for Aviation Research Wichita State University 1845 North Fairmount Wichita, KS 67260-0093	11. Contract or Grant No.

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Air Traffic Organization Operations Planning Office of Aviation Research and Development Washington, DC 20591	Final Report
	14. Sponsoring Agency Code AIR-100

15. Supplementary Notes

The Federal Aviation Administration Airport and Aircraft Safety R&D Division Technical Monitor was Curtis Davies.

16. Abstract

This document recommends guidance and criteria for the development of material and process specifications and material acceptance documents for liquid resins and continuous carbon fiber reinforcement materials used in liquid molding processes to manufacture structures for aircraft and space structures. The guidelines and recommendations are meant to be a documentation of current knowledge and application of sound engineering principles to the development and implementation of composite material procurement and process specifications. This document can also be used to develop common industry specifications. This report is limited to recommendations and guidance on the development of material and process specifications. The guidelines and recommendations contained in this document should not be viewed as Federal Aviation Administration policy or as the only acceptable method for composite material specifications and qualification procedures. They are meant to be a documentation of current knowledge and application of sound engineering principles to the development and implementation of composite material procurement specifications specific to the liquid resins and continuous fiber reinforcements used in liquid molding processes. The goal of any material procurement document is to provide the necessary controls to ensure the material used to establish the qualification data and certification data has not changed beyond its normal variability. The goal of any process specification is to ensure that the process remains in control and produces material consistent with specified requirements.

17. Key Words	18. Distribution Statement
Composite, Specification, Liquid resin, Preform, Carbon fiber, Epoxy, Test methods, Testing, Qualification, Certification	This document is available to the U.S. public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	124	

ACKNOWLEDGEMENTS

The following report was assembled with help from many individuals across many areas of expertise. The following Federal Aviation Administration personnel are acknowledged for their individual contributions to this document:

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Larry Ilcewicz
Peter Shyprykevich

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LIST OF ACRONYMS AND SYMBOLS

α level	Alpha level. The risk or error associated with rejecting conforming material
T_g	Glass transition temperature
3D	Three-dimensional
ACMA	American Composites Manufacturers Association
ACO	Aircraft Certification Office
AGATE	Advanced General Aviation Transport Experiment
AMS	Aerospace Material Specification
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
EBE	Equivalency baseline enhancement
FAA	Federal Aviation Administration
FAI	First article inspection
HPLC	High-pressure liquid chromatography
IR	Infrared
KC	Key characteristic
KPP	Key process parameter
LRM	Liquid resin molding
MIL-HDBK	Military Handbook
NASA	National Aeronautics and Space Administration
NDI	Nondestructive inspection
NIST	National Institute of Standards and Technology
PCD	Process Control Document
QA	Quality assurance
RH	Relative humidity
SACMA	Suppliers of Advanced Composite Materials Association
SAE	Society of Automotive Engineers
SPC	Statistical process control

EXECUTIVE SUMMARY

A widely acknowledged validation process used within the composite aircraft industry for the substantiation of composite structure is called the building block approach. This approach is a process using analysis and associated tests of increasing structural complexity. The building block approach is integrated with supporting technologies and design considerations. Military Handbook-17F, Volume 3, contains a complete description of the building block approach. A key element supporting the building block approach is material and process specifications.

The material and process specifications are interwoven throughout the certification validation process. Material specifications are used to define the material's attributes and define the qualification characterization tests. Materials used within the building block tests are purchased in accordance with the material specification. The same material specification is used for the procurement of production material. This ensures the delivered materials are of the same quality and performance standards used in the certification and validation process. Process specifications define and control the processes used for the fabrication of materials into structural components. It is widely known that the performance properties of composites are directly affected by the specific process used for their fabrication. It is critical that the test specimens fabricated through the various levels of the building block approach use the same process, which is representative of the one that will be used in the fabrication of production aircraft and rotorcraft.

This report establishes preliminary recommendations to guide the development of new and revised composite liquid molding resin and continuous fiber reinforcement material and process specifications and material acceptance documents. This is intended to advance the work that has been done through previous Federal Aviation Administration and National Aeronautics and Space Administration programs such as the Advanced General Aviation Transport Experiment. These programs have established the methodology for developing design-allowable data, control of the data, and sharing the resulting database. It is intended to expand on those general aviation methods to allow a broader market to use the shared database.

This report recommends guidance and criteria for the development of material and process specifications and material acceptance documents for liquid resins and continuous carbon fiber reinforcement materials to be used on aircraft structures. Similar recommendations for prepreg tape and fabric materials can be found in DOT/FAA/AR-02/109, "Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Unidirectional Prepregs;" DOT/FAA/AR-02/110, "Guidelines for Development of Process Specifications, Instructions, and Controls for the Fabrication of Fiber-Reinforced Polymer Composites;" and DOT/FAA/AR-06/10, "Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Fabric Prepregs." The guidelines and recommendations are meant to be a documentation of current knowledge and application of sound engineering principles to the development and implementation of composite material procurement specifications. This document can also be used to develop common industry specifications.

1. INTRODUCTION.

1.1 OBJECTIVE.

This document contains preliminary guidance and criteria for the development of material procurement specifications, process specifications, and material acceptance specifications for liquid resins and continuous carbon fiber reinforcement materials processed by liquid molding processes for the manufacture of composites to be used on aircraft primary load-bearing structures. For purposes of this document, liquid molding processes are classified as any process where liquid resin is infused into a dry continuous fiber preform. Examples of the liquid molding process include Resin Transfer Molding, Resin Film Infusion, and Vacuum Assisted Resin Transfer Molding. For purposes of this document, preform is defined as a fabric intended for subsequent use in the resin infusion process. The preform structure may be a textile fabric, noncrimp fabric, braid, or an assembly of these and other materials.

These recommendations were prepared by a team of industry experts who have extensive experience with material specifications, part processing, qualification programs, and design allowables. Prior to final publication, a thorough review process was used to gain the insights of other industry, government, and academic experts.

The purpose of this report is to establish preliminary recommendations to guide the development of composite liquid resins and continuous carbon fiber reinforcement material procurement specifications, process specifications, and material acceptance documents. This is intended to advance the work that has been done through previous Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) programs such as the Advanced General Aviation Transport Experiment (AGATE). These programs have established methodologies for developing design-allowable data, control of the data, and sharing the resulting database. The specifications described in this document are intended to allow the development of such shared databases.

The guidelines and recommendations contained in this document should not be viewed as FAA policy or as the only acceptable method for composite material specifications and qualification procedures. They are meant to be a documentation of current knowledge and application of sound engineering principles to the development and implementation of composite material procurement specifications specific to the liquid resins and continuous fiber reinforcements used in the liquid molding processes. The goal of any material procurement document is to provide the necessary controls to ensure the material used to establish the qualification data and certification data has not changed beyond its normal established variability. The goal of the process specifications is to ensure the process remains in control and produces materials consistent with specified requirements.

1.2 BACKGROUND.

Steady growth in the use of composites has continued in transport aircraft and rotorcraft. General aviation has emerged recently with the growth of new composite aircraft and composite material applications in primary structures. Several new composite aircraft are undergoing the certification process. Many more aircraft are currently undergoing the design and development

processes that take advantage of composite materials for primary structure applications. In addition, fabrication processes are being advanced beyond the traditional prepreg material-based processes. One such emerging process is the liquid resin molding process. With this growth of liquid resin molding composite applications in aircraft, certification procedural issues have emerged with respect to the philosophy of quality control and quality assurance (QA) methods needed to guarantee a safe and consistent material supply.

The material properties of a composite are manufactured into the structure as part of the fabrication process (process intensive material). Therefore, it is essential that material and process specifications used to produce composite materials contain sufficient information to ensure that critical parameters in the fabrication process are identified to facilitate production and adherence to standards in the final engineered part. Due to the wide variety of composite aircraft structures now emerging for certification, control of the materials is rapidly becoming a vital issue with respect to the overall assurance of safety.

In recent years, the aerospace industry, NASA, and the FAA have worked together to develop a cost-effective method of qualifying composite material systems by sharing material qualification databases such as Military Handbook (MIL-HDBK)-17 [1] and AGATE. By using shared databases, a manufacturer can select an approved composite material system to fabricate parts and validate adequate control with a smaller subset of tests for a specific application. For materials to be accepted into these shared databases, the raw materials are required to be manufactured in accordance with a material specification, which imposes control of key characteristics (physical, chemical, and mechanical properties) and be processed in accordance with a process specification that controls key characteristics (processing parameters).

1.3 RELATED DOCUMENTS.

The following documents provided related information:

- DOT/FAA/AR-02/109, "Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Unidirectional Prepregs," April 2003

- DOT/FAA/AR-02/110, "Guidelines and Recommended Criteria for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Fiber-Reinforced Polymer Composites," April 2003

- DOT/FAA/AR-03/19, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure," (supercedes DOT/FAA/AR-00/47), September 2003

- DOT/FAA/AR-06/10, "Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Fabric Prepregs," June 2006

1.4 CERTIFICATION PROCESS.

The objective of the composite aircraft structure certification process is to validate that the design meets the applicable configuration requirements. In this context, the design validation process (to establish by proof) is accomplished through verification (to prove by evidence) and qualification (to define attributes or characteristics) of the materials, processes, and analysis tools. Verification is simply to prove by evidence, usually by test data, that the proposed design is acceptable. Material qualification is the verifying of materials' attributes and characterizations, typically through testing.

Material qualification is a key element of the validation process, which occurs during the coupon level of the building block approach. It is during qualification that the composite material is fully defined and characterized. Qualification tests are planned and conducted to

- establish key material attributes,
- establish material performance properties,
- verify that material characteristics will work in the intended application, and
- create a statistical basis for requirements used in subsequent material quality assurance.

The objective in defining material attributes is to establish the constituent material property limits. Examples of attributes applicable to liquid resin molding (LRM) processing in which limits are set are more easily explained by segregating those associated with the preform from those associated with the liquid resin. Examples of preform attributes include:

- Fiber properties (linear weight, density, tow count, and mechanical properties)
- Ply dimensions, alignment, and stacking sequence
- Shaped preform contours
- Debulked preform fiber volume
- Preform permeability
- Preform bulk

These attributes define the preform material and control its resulting performance properties. Other attributes, often overlooked, are those related to the physical structure of the material, which affects processing characteristics. Example attributes of this type include:

- Fiber-sizing level and type
- Quantity of tackifiers or binders used
- Distribution of tackifier or binder through the preform thickness
- Compatibility of constituent materials with each other

Examples of liquid resin attributes include:

- Initial mix viscosity (at a defined temperature)
- Initial mix heat of reaction (ΔH_{ult}).
- Mix chemistry (e.g., ratio of epoxide: amine groups in some epoxy chemistries).

These attributes define the liquid resin material and control its resulting performance properties.

Other attributes, often overlooked, are those related to the physical structure of the liquid resin material, which affects processing characteristics. Example attributes of this type include:

- Amount of entrained air or solvent
- Thermal conductivity
- Viscosity as a function of temperature and time at temperature

Performance properties are established through statistically significant amounts of testing. It is imperative that the material's natural variability is captured during material qualification. The objective is not to meet a desired level of performance, but rather, establish the true performance range of the material. Unfortunately, mechanical properties are typically thought of as the only performance properties.

There are other performance-related properties that have a direct bearing on the more familiar mechanical properties, which include handling characteristics, kinetic behavior, rheological behavior, sensitivity to ambient moisture and temperature, effect of storage conditions, and resistance to fluids and solvents. Multiple material batches (typically a minimum of three) are tested to establish the combined material variability. Results obtained from these tests are used to establish tolerance limit values within the constituent material specifications.

1.5 LIQUID RESIN MOLDING MATURITY LEVEL.

At present, the use of LRM methods in aerospace is relatively limited compared to its use in marine and land transport applications. One reason for this is that although processing methods have been developed to a great extent, the methodologies for validation and verification lag somewhat. For instance, LRM is very effective for producing composite structures based on nonlaminar textile preforms (e.g., three-dimensional (3D) weaves or braids); however, these do not fit easily into the conventional building block approach for design validation. As a result, the use of this type of structure in certified aerospace applications is often limited by the cost of certification. Other areas where standard LRM methods may cause additional difficulties in certification include:

- The use of resin systems where the resin chemistry is varied from part to part to assist in production (e.g., control of viscosity in vinyl ester resins by variation in styrene content).

- In line-mixing systems where resin is continuously mixed and fed into the mold.

Additional verification of the process is likely to be required in these cases, and due to the wide variety of possible processes and the rapid advances that are being made, it is not appropriate to set hard and fast guidelines. In all cases, good engineering judgment (backed by appropriate evidence) is the most important guideline, and as in any certification process, early involvement of the Aircraft Certification Office (ACO) will assist in choosing the most cost-effective processes and materials. In some cases, the potential variability in raw materials and processes and the lack of adequate analysis tools may make an apparently cost-effective process considerably more expensive.

1.6 ORGANIZATION OF INFORMATION IN REPORT.

Sections 2 and 3 discuss, in general, the attributes and characteristics of LRM.

Sections 4 through 7 provide guidelines for the development of resin (or other reactive materials) reinforcement and cured materials specifications.

Section 4 provides guidelines specific to the LRM resin material procurement specification.

Section 5 addresses the reinforcing fibers material procurement specification (for discussion purposes, the nonreactive reinforcing fiber will be in the form of a textile fabric).

Section 7 addresses the total material system, resin, and fiber combined into a cured composite, through an acceptance specification.

Sections 8-10 of this report deal with other critical aspects of the material and process specification.

Section 8 refers to development of materials controls and in particular the possibility of development of shared materials databases and industry material specifications.

Section 9 deals with the development of a qualification plan and how to deal with subsequent changes to materials and processes.

Section 10 deals with productability and fabricator/facility qualification.

2. LIQUID MOLDING PROCESSES AND MATERIALS.

2.1 LIQUID RESIN MOLDING PROCESSES.

The LRM process differs significantly from the prepreg process in that the reinforcement constituents (fiber) are processed independently from the resin, and are generally located on the mold or tooling before the resin is introduced. The reinforcement is sometimes trimmed, formed, and assembled outside the mold and is referred to as a preform. The preform is generally located on the mold, infused with liquid resin, and then cured according to the specified cure cycle for the liquid resin. A flow chart for the LRM process is provided in figure 1.

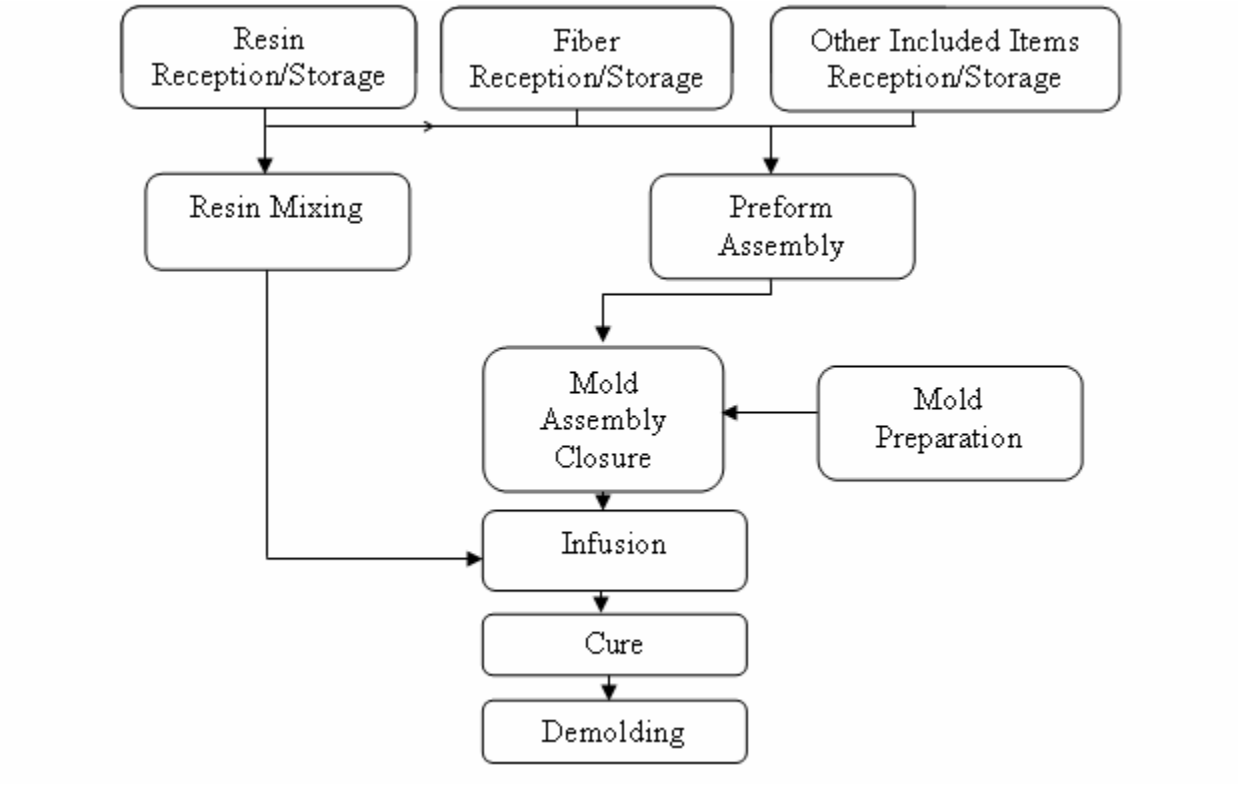

Figure 1. Typical LRM Process Flow

The various combinations of reinforcement type and forms and resin types for the LRM process are too numerous to cover in this document. Likewise, LRM process tooling options are numerous. The infusion process may take place in a closed-cavity mold, whereby all surfaces of the final molded part are defined by the surfaces of the rigid tooling, or the tooling may be such that it only defines a portion of the part and the other surfaces are controlled by bagging material of some sort as in a vacuum-bagged prepreg part. These options are illustrated in figure 2.

The part manufacturer creates the final material properties as a part of the fabrication, and thus requires a well-controlled process. In addition, to ensure that the final engineered parts match the performance of the materials tested during qualification, it is essential to demonstrate that the process control for manufacture is equivalent to the process control for qualification. This can only be done through the use of a well-defined process specification. If the process specification for manufacture differs from the process specification for qualification, the manufacturer must demonstrate that the properties of the materials produced remain equivalent. This is effectively carried out using the change control procedures outlined in section 9.

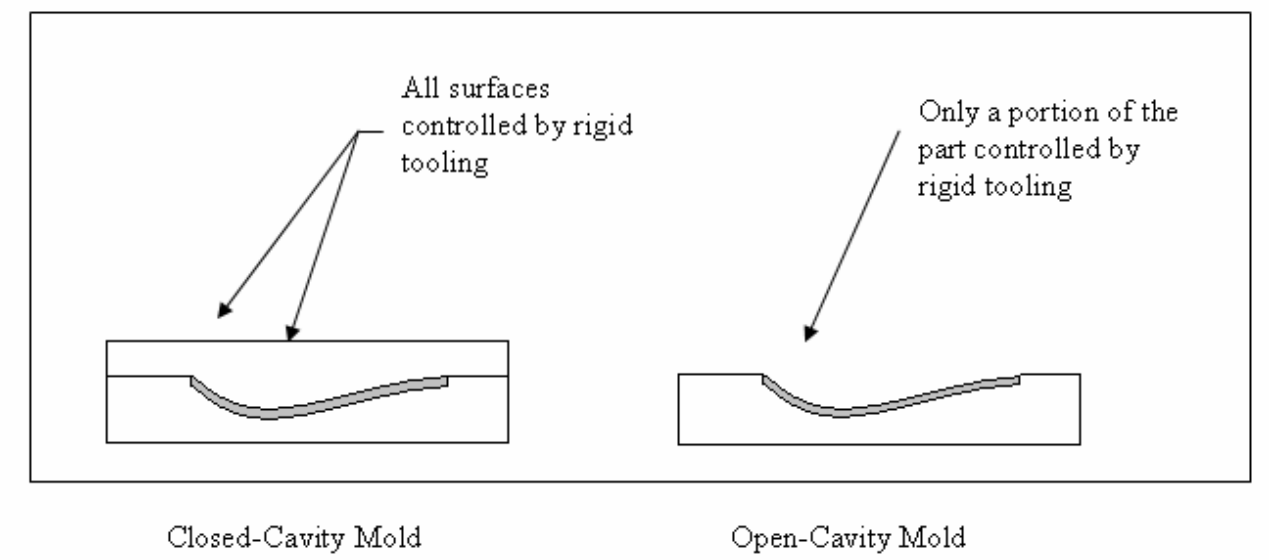

Figure 2. Typical LRM Mold Options

2.2 LIQUID RESIN MOLDING MATERIALS.

In the liquid molding process, as with all composite processes, many materials are used to fabricate components; the matrix and fiber reinforcement are the two major constituent materials. The guidelines contained within this document specifically address polymer resin matrix and continuous carbon fiber reinforcement materials (though with appropriate engineering judgment, they can be applied to other material systems.) Materials used by the LRM process can be divided into four categories:

- Resin materials: The resin is a reactive material, which may be a one- or two-part system. In addition, the resin can be used as a tackifier, which is applied to the carbon fiber reinforcement. Because both the resin and tackifier undergo polymerization reactions during the cure process, they are referred to as reactive materials.

- Reinforcement materials: The reinforcing carbon fibers are nonreactive materials, i.e., they do not polymerize during the cure process. The carbon fibers can be in the form of textile fabrics, braided structure, or noncrimp fabrics. The preforms (fabrics) can be purchased or made with or without an applied tackifier. The application of a tackifier can change the usually nonreactive material into a reactive material, similar in nature to a prepreg. Tackifiers can be either applied by the preform material supplier or by the part producer just prior to placement into the mold. It is critical that the tackifier be chemically compatible with the matrix resin and fiber sizing.

- Assembled materials: Preforms, where the various layers have been assembled together, are referred to as assembled materials. A common assembled preform material is the combining of noncrimp fabrics. The noncrimp fabrics are stitched or warp-knitted together to form a single preform. Textile fabrics can also be stitched together to form

3D preforms. Other material forms assembled into the part include precured composites, metallic fittings, honeycomb core, and foam core. Materials assembled into the part should be controlled with their own material procurement (and possibly process) specification(s).

- Consumable and ancillary materials: A variety of additional materials are used by the liquid molding process. These materials include mold release agents, adhesives, bagging films, release films, flow media, damming materials, vacuum bag films, vacuum bag sealants, breather materials, resin distribution materials (such as porous tubes or tightly wound springs), and tapes. While it is not standard practice to control these materials by their own material procurement specifications, consideration should be given to controlling their sources and characteristics via a qualified products list.

With LRM processes, the resin and fiber are typically purchased from different suppliers and are only brought together at the time of part fabrication, making it very difficult for the material suppliers to test the total material system at the composite level. The part fabricator is now required to communicate with a variety of material suppliers and generate individual material procurement specifications for the constituent materials. In addition, a specification is required that combines the matrix resin and reinforcing fiber into the total composite material system. This is the level at which the primary design-related properties are evaluated and controlled.

One approach for material control of liquid resin molded parts is the use of material procurement specifications for the constituent materials (resin and reinforcement) in combination with a process specification and the material acceptance specification for the cured parts, as shown in figure 3. The constituent materials are tested by the supplier. Depending on the material, the purchaser (part producer) may or may not elect to test the constituent materials upon receipt. The combined system is then controlled at the cured composite assembly (resin combined with reinforcement) through an acceptance specification by the part producer. This document validates that the composite final assembly yields performance properties equivalent to those developed during qualification, design-allowable property development, and certification. This same document can define the process for qualifying the material system. This acceptance document will be very similar in content to a traditional prepreg material specification, with one major difference being that the requirements at the cured part level are levied by the part producer on themselves rather than on a material supplier.

It would prove impossible to test every possible combination of resin lot and preform (fabric) lot. As a rule, a part supplier would have received multiple lots of resin and preform (fabric) batches. A prudent approach for a material acceptance-sampling plan would be to test every preform (fabric) lot received. It would not be necessary to test every lot of resin as part of the acceptance tests. The resin lot is released for production use based on tests performed at the resin level.

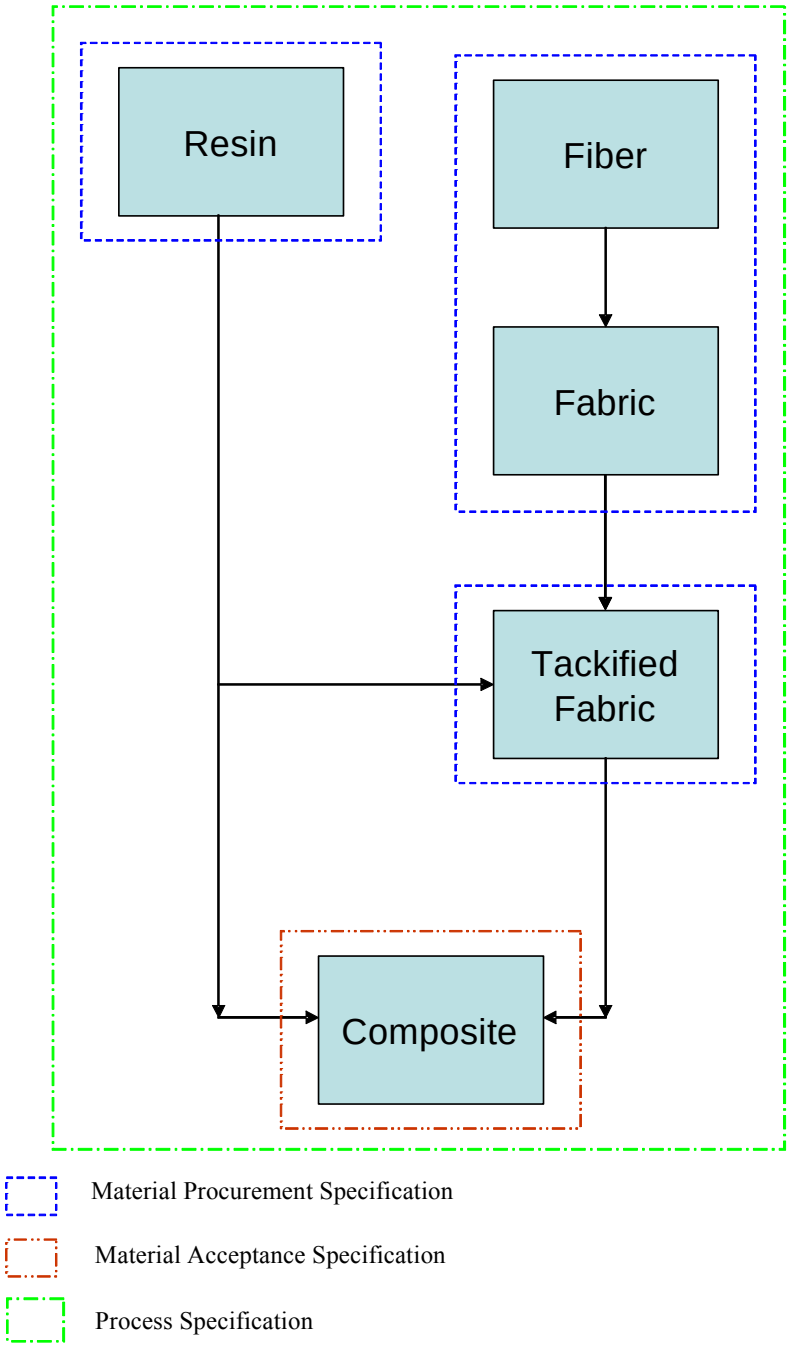

Figure 3. Liquid Resin Molding Material Procurement and Acceptance Documents

3. RECOMMENDED LRM SPECIFICATION STRUCTURE.

3.1 RECOMMENDED SPECIFICATION STRUCTURE.

Generation of material specifications for the LRM process is not as simple and straight forward as with traditional prepreg materials. With prepreg materials, the resin and fiber are combined at the material supplier and can be processed into laminates by the supplier to validate performance properties. The prepreg procurement specification can then control all aspects of the prepreg

manufacturing process from receipt of fiber, through resin mixing and filming, to impregnation of the fibers with the resin film, and ending with testing of the total material system by the fabrication and testing of laminates (or parts).

With liquid resin molding processes, the resin and fiber are typically purchased from different suppliers and are only brought together at the time of part fabrication, making it very difficult for the material suppliers to test the total material system at the laminate level. The part fabricator is now required to communicate with a variety of material suppliers and generate individual material procurement specifications for the constituent materials. In addition, a specification (referred to as the material acceptance specification in figure 3) is required that combines the matrix resin and reinforcing fiber into the total composite or part material system. This is the point at which the primary design-related properties are evaluated.

The three major material procurement specification categories required for LRM are reactive resins, nonreactive reinforcing fibers and fiber preforms, and combined cured material system. This document provides guidance for the generation of material procurement and acceptance specifications for these three classes of LRM materials.

One approach is the use of material procurement specifications in combination with an acceptance specification. The constituent materials (resin and reinforcement) are controlled through material procurement specifications. The constituent materials are tested individually by the supplier and purchaser. The combined system is then controlled at the cured composite assembly (resin combined with reinforcement) through an acceptance specification by the part producer. This document validates that the final composite assembly yields performance properties equivalent to those developed during qualification and design-allowable property development. This same document can define the process for qualifying combinations of constituent material to produce the cured parts.

3.2 SECTIONAL ARRANGEMENT OF MATERIALS SPECIFICATIONS.

For consistency and standardization purposes, a general format for composite material specifications should be followed. The following is a recommended format for subjects to be included that follows the standard format of SAE AMS specifications; other formats with the same content are acceptable to the FAA. Please see "Editorial Style Manual for the Preparation of Aerospace Material Specifications (AMS)" prepared by SAE International for additional information on specification structure. Only those subjects applicable to the material should be included in the specification.

1.0 Scope
2.0 Applicable Documents
3.0 Technical Requirements
  3.1 General Material Requirements
    3.1.1 Formulation or Constituent Materials
    3.1.2 Product Characteristics
    3.1.3 Chemical, Electrical, and Mechanical Properties
    3.1.4 Environment Conditions
    3.1.5 Stability

3.1.6 Environmental, Health, and Safety
3.1.7 Identification
3.1.8 Workmanship
3.2 Qualification Requirements
3.3 Process Control Document Requirements
4.0 Quality Assurance
4.1 Responsibility for Inspection
4.2 Classification of Tests and Inspections
4.2.1 Qualification Tests
4.2.2 Quality Conformance Tests
4.2.3 Receiving Inspection Tests
4.2.4 Sampling
4.2.5 Retest
4.2.6 Storage Life Extension
4.2.7 Material Distributors
4.3 Certification of Conformance
4.4 Statistical Process Control
4.5 Test Methods
4.6 Records
5.0 Preparation for Delivery
5.1 Material Identification
5.2 Packaging and Preservation
5.3 Packing Requirements
5.4 Shipping Requirements
5.5 Receipt at Procuring Organization
6.0 Acknowledgement
7.0 Rejection
8.0 Notes
8.1 Intended Use
8.2 Definitions
8.3 Ordering Data
8.4 Approved Products

3.3 SECTIONAL ARRANGEMENT OF PROCESS SPECIFICATIONS.

As with materials specifications, for consistency and standardization purposes, a general format for composite material process specifications should be followed within any organization. Section 6 describes the subjects that a process specification should follow, based on the sections described below. Due to the maturity level of LRM processes, this section is necessarily less prescriptive than the materials specification sections; however, this places a greater onus on the manufacturer to ensure that good engineering judgment is exercised and sufficient controls are in place to ensure that the process will produce consistent final material properties. The manufacturer is also responsible for demonstrating that such controls are adequate through direct demonstration in process trials or through validated data.

1.0 Scope
2.0 Applicable Document
3.0 Requirements
    3.1 Personnel
    3.2 Required Materials
    3.3 Required Equipment
    3.4 Facilities Control
    3.5 Tooling
    3.6 Required Procedures
        3.6.1 Process Instructions
        3.6.2 Tool Preparation
        3.6.3 Material Preparation
        3.6.4 Lay-up Procedures
        3.6.5 Injection Procedure
        3.6.6 Cure Procedure
        3.6.7 Panel Identification
4.0 Quality Assurance, Inspection and Process Monitoring
5.0 Preparation for Delivery
6.0 Acknowledgement
7.0 Rejection
8.0 Notes

4. GUIDELINES FOR SECTIONS OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section provides guidelines specific to a material procurement specification applicable to reactive materials. Reactive materials would include the matrix resin or preform tackifier resin. The guidelines provided in the following subsections are structured around epoxy-based resin systems. However, the requirements and process can be adapted for any resin system.

4.1 THE SCOPE SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section should include a general description of the resin and its area of application to guide the prospective user. General temperature use limits and cure conditions should be stated. If the resin is to be supplied as a one- or two-part system, it should be stated within this section of the specification. Those products to be controlled by this specification are required to be listed here.

A classification system can be used to distinguish different resin forms or characteristics.

4.2 THE APPLICABLE DOCUMENTS SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section should include appropriate drawings, specifications, standards, and methods that will form a key part of the specification. The material supplier is encouraged to use existing documentation available to the public that was developed or approved by industry organizations. Test methods can come from ASTM and SACMA (available from American Composites Manufacturers Association (ACMA)). Government-recommended processes and procedures

should be referenced and followed, such as DOT/FAA/AR-03/19, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems" and MIL-HDBK-17, "Composite Material Handbook." Supplier internal documents, such as special test procedures, should be kept to a minimum. When used, they should be referenced and included in a Process Control Document (PCD).

Examples include:

- ASTM D 792 — Specific Gravity (Relative Density) and Density of Plastics by Displacement
- ASTM D 2471-99 — Standard Test Method for Gel Time and Peak Exothermic Temperature of reacting Thermosetting Resins
- ASTM D 3878-01 — Standard Terminology Composite Materials
- ASTM D 4065-95 — Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics
- ASTM D 5229-92 (1998)e1 — Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
- ASTM D 5279-99 — Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics in Torision
- ASTM D 5418 — Standard Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry
- ASTM E 168 — General Techniques of Infrared Quantitative Analysis
- ASTM E 1252-98 — Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis
- ASTM E 1356-98 — Standard Test Method for Assignment of the Glass Transition Temperature by Differential Scanning Calorimetry of Differential Thermal Analysis
- ASTM E 1640-99 — Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis
- ASTM E 2041-99 — Method of Estimating Kinetic Parameters by Differential Scanning Calorimetry Using Borchardt and Daniels Method

- ASTM E 2070-00 — Test Method for Kinetic Parameters by Differential Scanning Calorimetry Using Isothermal Methods
- ASTM E 4473-95 — Standard Practice for Measuring the Cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures
- SACMA SRM 20R-4R — High-Performance Liquid Chromatography of Thermoset Resins
- SACMA SRM 25R-94 — Onset Temperature and Peak Temperature for Composite System Resins Using Differential Scanning Calorimetry (DSC)

4.3 THE TECHNICAL REQUIREMENTS SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

The technical requirements section defines the characteristics and attributes required to ensure the resin procured to this specification is satisfactory for its intended use. The functional, physical, chemical, electrical, and mechanical requirements are to be defined in this section at a level of detail sufficient to assure reliability.

4.3.1 The General Material Requirements Section.

This section should include requirements that define the specific raw ingredients and processes for producing the resin (many of these requirements may be specified in the PCD, which is referenced by the specification).

4.3.2 The Resin Material Requirements Section.

This section should include requirements that define the specific chemical and physical properties of the resin.

Each designation of the resin must be specific and must refer to only one combination of ingredients processed via one mixing regime. The resin composition and mixing process should be defined prior to qualification. Limits of ingredient-weighing accuracy and process times and temperatures should be validated through physical and chemical testing. The mixing process includes premix step(s), final mix step(s), ingredient handling, mixed resin cooling, and mixed resin storage. The limitations of in-process tests must be understood. Current industry practice is to use resin viscosity and gel time as quick methods to validate the resin mixing step. These quick tests typically allow a wide range of acceptable values and may not be an accurate measure of resin consistency. If blending of mixed resin batches is to be allowed, the nature and type of blending should be validated through chemical analysis. Blending of mixed resins is discouraged unless it can be demonstrated that there is no impact on viscosity and cure kinetics. Process limits defined and validated by the physical and chemical testing must be documented in the specification or PCD. These limits should be defined and validated by tests performed in all extremes of the processing envelope; design of experiments may be used.

Resin components and their manufacturers must be specified in the specifications, qualified product list, or PCD. The material supplier should establish material specifications for all raw materials to be used in the resin. If multiple sources of an ingredient are planned, the use of each component must be validated through physical and chemical analysis. Raw ingredients can be blended as long as storage and handling requirements for the raw materials are met. Testing must establish that departures from the raw material manufacturer's recommendations for handling and storage are valid.

Resin test requirements that measure key attributes of the final mix or premix(es) should be identified. In some cases, this information may be considered proprietary and controlled in the PCD. These may include gel time, viscosity, degree of advancement, and analytical signature, such as infrared spectrophotometry (IR) or high-performance liquid chromatography (HPLC) peak ratios. In addition, the resin cure kinetics and rheology should be well characterized. It is valuable to conduct the kinetic and rheological studies on resins made to the limits of ingredient ratios allowed by the mix procedure and weighing errors. For example, in epoxy resins, at one extreme, the curative would be at its lowest concentration and the epoxy resin at their highest concentration. At the other extreme, the curative would be at its highest concentration and the epoxies at their lowest. With two or more part resins, the effect of ratio tolerances must be quantified.

The diffusion and absorption of moisture and environmental fluids in the cured resin should be evaluated via moisture uptake versus time and degree of plasticization, which leads to lowering of elastic modulus and glass transition temperature, T_g. The resistance of the cured resin to thermal microcracking over the range of use temperatures and cycles, both as cured neat resin and cured composite, should be assessed.

All the above-mentioned data should be documented by the material supplier, be made available to potential users of the material, and be made available to the industry committee responsible for the industry specification for the material, if applicable. Table 1 summarizes the resin property data discussed above. Tests in table 1 recommended for batch acceptance tests are as indicated.

Table 1. Recommended Set of Neat Resin Physical and Chemical Properties

Resin Property	Test Method
Density	ASTM D 1475
Viscosity (Brookfield)	ASTM D 2196*
Viscosity (Cure Behavior)	ASTM D 4473
Gel Time	ASTM D 1824*
Cure Kinetics by DSC Heat of Reaction Onset Temperature Peak Exotherm Temperature	ASTM D 3418*

Table 1. Recommended Set of Neat Resin Physical and Chemical Properties (Continued)

Resin Property	Test Method
Color	ASTN D 1544
Epoxide Equivalent Weight	ASTM D 1652*
Amine Content	Any agreed method*
High-Pressure Liquid Chromatography	Any agreed method*
Spectrophotometry (IR)	Any agreed method*

*Acceptance tests.

This section should include definitions and limitations for storage life under specified conditions and handling life under ambient conditions. These requirements should be based on specific test data and experience with similar materials. The material supplier can establish and document the storage life as a function of storage temperature. A portion of the material batches produced for the initial material database development should be placed in an appropriate storage facility. After the desired maximum shelf life is reached, the material should be tested and the results compared to the specification requirements.

It is recommended that a tracking policy be implemented by the material supplier to document storage of material from date of manufacture to arrival on dock at the part producer. Tracking should include resin intermediates and mixed resin.

Any testing to re-establish the acceptance of materials that have been subjected to storage upsets, such as a freezer breakdown, must demonstrate that key cure-related attributes are within the normal range. A distributor should practice the same documentation of storage life and conditions as the material supplier and part producer (see section 4.4.2.5).

4.3.3 The Cured Resin Mechanical Properties Section.

It is recommended that the material supplier establish a baseline resin cure cycle to be used to produce neat resin plaques for neat resin mechanical properties. Reasonable tolerances on heat-up rates and time-at-temperature should be established and documented. The cure process should be capable of producing cured resin plaques of consistent high quality. This cure cycle should be used for all batch acceptance testing by the material supplier and part producer (if required). It is possible that part-manufacturing processes will use a different cure cycle than the baseline resin plaque cure cycle.

It is recommended that the material specification include, as a minimum, requirements for the cured neat resin physical and mechanical properties listed in table 2. The limits and test methods for each property should be documented in the specification.

Table 2. Recommended Set of Cured Resin Physical and Mechanical Properties

Property	Test Method
Tensile Properties Strength Modulus Elongation	ASTM D 638
Flexural Properties Strength Modulus Elongation	ASTM D 790
Compressive Properties Strength Modulus	ASTM D 695
Shear Strength	ASTM D 732
Fracture Toughness	ASTM D 5045
Glass Transition Temperature (by TMA)	ASTM D 1545*
Coefficient of Thermal Expansion	ASTM E 831
Degradation Temperature	ASTM D 3850
Density	ASTM D 792
Water Absorption	ASTM D 570
Shrinkage	ASTM D 2566

*Acceptance tests.
TMA = thermo-mechanical analyzer

All the above-mentioned data should be documented by the material supplier, be made available to potential users of the material, and be made available to the industry committee responsible for the industry specification for the material, if applicable.

4.3.4 The Qualification Requirements Section.

Qualification requirements are defined in this section. Refer to sections 8 and 9.2 for additional information on minimum requirements for qualification.

4.3.5 The Process Control Document Requirements Section.

It is strongly recommended that the material producer establish a PCD that documents key aspects of the material fabrication, lists all raw material ingredients, defines key process parameters, and establishes statistical process control (SPC) procedures and requirements. The PCD should be maintained by the material supplier. While the PCD will typically be a proprietary document, it should be made available at the supplier's site for review by material part producers and certification agencies. It should be referenced by the material specification.

The PCD should contain, as a minimum, the following information. This information could be considered proprietary and, therefore, protected in accordance with disclosure agreements signed by the supplier and procuring organization.

- List the sources and exact raw materials used in the formulation of the resin system (generic and trade names).
- List the physical or chemical properties of each material or material component considered critical.
- List the tests conducted on each raw material at receiving inspection, noting the limits for acceptance or rejection.
- Describe the manufacturing process and in-process controls.
- Provide the tolerances on weight measurements for each manufacturing step. The exact formulation is required, and substantiation that the weight tolerances are appropriate for the quantities used is required.
- Provide the order and means of combining the subcomponents and give the time-temperature profile with the control tolerances employed.
- List the tests and control limit requirements on the finished resin system.
- Define the time-temperature history of the tackifier resin during the application of the tackifier to the fabric and the control tolerances employed.
- Describe acceptance inspection procedures used to evaluate the finished material and state the acceptance/rejection criteria.
- List the tests conducted on the finished material and test control limit requirements employed.
- Describe packaging, storage, and shipping controls.

4.4 THE QUALITY ASSURANCE SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section defines the tests and inspections required to verify the material complies with the technical requirements of the specification. In addition, it provides guidance for evaluation of manufacturing changes and provides procedures for determining equivalency.

4.4.1 The Responsibility for Inspection Section.

Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all quality conformance inspection and test requirements specified herein, and the procuring organization is responsible for the performance of all receiving inspection tests specified herein. The supplier and procuring organization may use their own facilities or any commercial laboratory acceptable to the purchaser. However, the purchaser reserves the right to perform any or all of the inspections/tests that are deemed necessary to assure the material furnished conforms to the prescribed requirements.

4.4.2 The Classification of Tests and Inspections Section.

4.4.2.1 Qualification Tests.

The qualification or preproduction tests performed for material qualification are those tests performed on representative samples of each specific form of material to establish a qualified product in accordance with this specification. Qualification testing should consist of all requirements and tests specified in section 7. This testing should be performed for each type of material.

4.4.2.2 Quality Conformance Tests.

The material supplier must perform material certification (acceptance) testing. The material specification should define the type and frequency of tests to be performed by the supplier.

Certification reports must be prepared for each batch of material. The test report must show that the batch meets all the uncured and cured material requirements. All records for each batch and the original baseline database should be kept on permanent file. Records of raw material receiving inspection, in-process materials testing, SPC required by the PCD, and full material batch traceability should be kept for a minimum period of 10 years, unless superceded by other requirements. The supplier quality department will review the certification test results prior to shipment to a part producer. Materials that fail the acceptance criteria can undergo a material review board process.

4.4.2.3 Receiving Inspection Tests.

The part producer (purchaser) quality department should perform acceptance tests for each batch of material. The material specification should define the testing frequency.

The part producer must review the test results and allow the material to be released to manufacturing only upon satisfactory demonstration that the material meets the specification requirements. The part producer should hold to the same record keeping requirements and retest criteria as the material supplier.

A part producer must conduct the acceptance testing whether the material is bought directly from the manufacturer or through a distributor. The original certification testing conducted by the material manufacturer will be made available by the distributor for a specific batch sold to the part producer.

In cases where the material has demonstrated a high level of SPC control and capability for the material, it may be possible to reduce or eliminate the purchase acceptance testing. If material is supplied by a distributor, it is recommended that purchaser testing be maintained as a safeguard against uncontrolled material. It is expected that the FAA will evaluate requests to reduce or eliminate part producer testing on a case-by-case basis (specific FAA policy for reduced testing approvals will be developed in the future). If part producer testing is reduced or eliminated, then provisions for monitoring the thermal exposure history of each shipment of material between the

supplier and part producer (including all transit periods and storage periods at a distributor) will be required.

The procuring activity reserves the right to perform additional testing to confirm the supplier's certification data, and to approve incoming material for use in the fabrication of production parts.

4.4.2.4 Retest.

Retest or replacement of test data is allowed only

- if an abnormality is observed or can be reasonably deduced to have occurred during testing,
- data is a statistical outlier, or
- the test has been conducted on materials that have not been prepared or conditioned properly (e.g., machining errors on test coupons).

Note: Any testing error should be identified and corrected prior to retest.

If a retest is required, a complete set of replicates for the property should be tested. If the retest results fail the acceptance criteria, the material batch covered by the failed test should be rejected and dispositioned through a material review board process (which should include engineering personnel). All part producers of a material batch for which retests were performed must be notified at the time of batch shipment.

4.4.2.5 Material Distributors.

Material distributors, either a facility of the manufacturer or an independent facility, must abide by all requirements of the material specification and the applicable portions of the process specification. The part producer should approve a distributor under their supplier surveillance system as described in their quality control manual. It is recommended that the material manufacturer will also have a role in authorizing distributors for proper control of the material. Material batches should remain traceable to the manufacturer's original batch and test reports. The distributor should provide copies of the original material certification and test reports to the user. The manufacturer's material, batch, and lot identification should be maintained.

A distributor should practice the same documentation of storage life and conditions as the material supplier. The distributor should be able to provide objective evidence of the material storage conditions. All shelf life should be determined from the date of material manufacture. Any extension of the shelf life allowed by the material specification should be performed by a source approved by the original manufacturer.

If the product is repackaged, the materials used to repackage should be the same as approved for use by the material manufacturer. When the material is repackaged, if refrigerated or frozen, it should first be allowed to reach room temperature in the unopened package such that moisture does not condense on the inside of the package. The repackaged material should be inspected for

visual defects and documented. All out-time accumulated during warming and repackaging must be subtracted from that specified by the manufacturer and documented for part producers, who assume responsibility after acceptance.

4.4.3 The Certification of Conformance Section.

The supplier should furnish with each shipment a Certification of Conformance, including certified test reports, confirming that all the material in the shipment complies with the requirements of this specification. For SPC, this should also indicate the values of key characteristics (KC) and key process parameters (KPP) agreed upon between the supplier and part fabricator.

4.4.4 The Statistical Process Control Section.

The supplier should maintain the procedures and requirements for SPC based on KCs and KPPs. The KCs are a subset of those properties detailed in the material requirement tables. KCs should be selected such that they ensure all properties of the material are within acceptable statistical limits. These are usually the set of requirements used for acceptance testing. KPPs are those process parameters that have a significant influence on the KCs. KPPs must be determined prior to qualification and be documented in the PCD. Average values, ranges, limits, and sampling frequency should be established and documented in the PCD.

The procedures used to conduct SPC analysis of the KCs and KPPs should be documented in the PCD. The PCD should also include the procedures used to establish and calculate the control limits. It is expected that control charts will be maintained on the KCs and KPPs and will be available for inspection by part producer and FAA personnel. It is strongly recommended that there be an effective program to collect, plot, analyze, and act on KC and KPP data. It is expected that action will be taken when the criteria for nonrandom data trends are met. Review should be initiated when the data is approaching the upper and lower control limits established during the initial database generation and subsequent production batches. Action should be taken when the data falls outside the upper or lower control limits.

If a KC is out of control, the cause of variation should be identified and eliminated, re-establishing statistical control. The supplier must document all corrective actions affecting the process and monitor if the corrective action has been effective.

Reduced acceptance testing may be established based on the stability demonstrated by the KCs and KPPs. Reduced testing will require approval by the FAA and the part producer(s) prior to being implemented. The reduced testing plan will be documented in the PCD. If KCs are found to be out of control, testing must return to the original level for a period of time until confidence in the control of the material is re-established. The reduced testing may take the form of a reduction of part producer testing or less frequent supplier testing. A prerequisite for reduced testing is adherence to monitoring and action based on control charts.

4.4.5 The Test Methods Section.

Recommended test methods for each property are given in Chapters 3 through 7 of Volume 1 of MIL-HDBK-17, Rev. F. In general, ASTM Standard Test Methods are recommended. However, in most cases, additional test specimen configuration requirements and test procedures will have to be defined to provide sufficient detail to avoid undesired variations. Deviations from industry standard methods must be clearly detailed in the specification. In the event that part producer testing is required by the specification, it is recommended that the material supplier and part producer conduct round-robin test evaluations to reduce test result differences.

It is recommended that all tests be conducted by a laboratory certified to conduct the tests to the specified methods; this certification applies to supplier, part producer, and independent test laboratories. A certified laboratory follows established policies and procedures such as training of test technicians, written procedures for performing tests, documenting the dimensional accuracy of test fixtures, and tracing calibration to the National Institute of Standards and Technology (NIST) standards. The requirements and procedures for certifying a test laboratory should be defined within the specification or other document as required to be in compliance with internal company procedures. It is recommended that for an industry specification, a national laboratory certification be required for facilities used.

4.4.6 The Records Section.

The supplier should retain records of the batch raw ingredients for a minimum of 10 years from date of manufacture. Records should contain date of manufacture, process control tests, certification tests, acceptance tests, and storage conditions.

4.5 THE PREPARATION FOR DELIVERY SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

The product must have suitable identification, and the packaging and handling during shipping must result in the product being capable of its full handling and working life when received by the part producer.

If repackaged by a distributor, the new packaging must be labeled properly and functionally equivalent to the original packaging and the labeling requirements met. Any decrease in storage life, working life, and handling life must be documented by the distributor and provided to all users.

4.5.1 The Material Identification Section.

The batch number should be on two labels, one on the container and the other on the outside of the shipping wrapper. The label should also include the material designation, name of manufacturer, specification number, and date of manufacture. The outside label should also clearly define the required material storage conditions.

4.5.2 The Packaging and Preservation Section.

The material should be placed into containers appropriate for the protection of the material during shipping and storage. Step-by-step procedures should be given for the packaging of the material.

4.5.3 The Packing Requirements Section.

The resin should be packaged in containers that meet federal regulations. Consideration should be given to container material selection to ensure the container material does not act as a catalyst and will allow the resin to be preheated while still in the container.

4.5.4 The Shipping Requirements Section.

The appropriate shipping and storage temperatures must be established for the material. If freezer temperatures are needed to maintain product quality, time-temperature recording devices should be used to document the temperature exposure history of the shipment. Materials that have exceeded recommended limits will require a disposition process.

4.5.5 The Receipt at Procuring Organization Section.

Instructions for receipt of the material at the procuring organization are specified in this section.

4.6 THE ACKNOWLEDGEMENT SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section of the specifications should contain the standard statement:

A vendor shall mention this specification number and the applicable detail specification number and their revision level in all quotations and when acknowledging purchase orders.

4.7 THE REJECTION SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section should contain the standard statement:

Product not conforming to this specification and modifications authorized by purchaser will be subject to rejection. Rejected batches by a purchaser should not be rerouted to other purchasers.

4.8 NOTES SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION.

This section is reserved for explanatory and other notes.

4.8.1 The Intended Use Section.

This section should define the intended use of the material.

4.8.2 The Definitions Section.

This section should include definitions for terms or abbreviations that are used. The definitions provide clarity between the supplier and the procurer. This is of major importance with respect to material batch definition and many times is not addressed. Material properties, quality, and defects must be defined such that batches made after the original qualification have the same level of quality and properties. Where possible, definitions from industry standards such as MIL-HDBK-17, SAE, and ASTM should be used.

The following resin batch definitions are recommended.

Batch (or Lot) (general)—n, A quantity of material produced essentially at the same time and under the same conditions from a well-defined collection of raw materials. The quantity of material must have minimal variation in properties throughout to be considered a unique batch.

Batch (or Lot) (resin)—n, For a batch of resin, the definition varies depending on the specific mixing process:

- In a batch mixing process, a large vessel is charged with the desired types and quantities of raw ingredients. After mixing is complete, the vessel is discharged. The material made from this single-mix process is defined as a single batch of resin.

- A continuous mixing process for producing resin typically involves incrementally feeding raw ingredients into a mixing device that blends them into a stream of resin. A batch of resin made by this process is defined as a quantity of material formed during one essentially continuous uninterrupted production run under the same process conditions using the same raw ingredients. Since start-up and shutdown usually require purging the equipment, a shutdown will signal the end of a specific batch. Material made after start-up is defined as a new batch. If a process shutdown does not require purging, an interruption in the process of up to 72 hours is permitted (or more if allowed by the PCD), provided that the production equipment settings are not modified or another material was not produced on the equipment during the interruption.

- In one version of a semicontinuous mixing process, a large vessel is charged with a portion of the raw ingredients (premix). After mixing, the vessel is discharged into several smaller containers, each of which acts as the vessel for subsequent mixing steps. The remaining raw ingredients are added to these smaller vessels and further mixing results in the final resin composition. The premix produced in the large vessel can be considered as a single batch of raw ingredient. The material produced during the final mixing in the small containers can be considered one batch if it is produced from the same raw ingredients batches without an interruption of more than 72 hours (or more if allowed by the PCD) or the production of another material in the interval, and until the premix is consumed.

- In another version of a semicontinuous mixing process, small complete mixes of raw ingredients are made without the premix step. A batch of resin then consists of any number of these small mixes if they are made from the same lots of raw ingredients, the

production run is not interrupted for more than 72 hours (or more if allowed by the PCD), and there is no other material made in the interval.

- For all mixing processes, blending of raw ingredient lots is permissible if the same blend ratio is found throughout all portions of the resin batch. Procedures that will cause blend ratio variations, such as resin batch blending, if allowed, should be controlled by the prepreg material specification or PCD. Traceability must be retained on the ingredient lots that were used. For all mixing processes, a single-resin batch may contain a maximum of three blended lots of each raw chemical ingredient.

The above definitions are generally applicable for use with material acceptance processes, including sampling plans for acceptance testing. For material qualification and allowables test programs, stricter definitions of a batch are often specified in order to control the amount of material variability to be evaluated in the test program. For example, specific resin batches are required to be combined with specific preform batches for evaluation of the combined composite system batch.

4.8.3 The Ordering Data Section.

Detailed information to be incorporated in purchasing documents should be contained in this section.

4.8.4 The Approved Products Section.

A listing of products that have qualified as defined within the specification is provided in this section.

5. GUIDELINES FOR SECTIONS OF A MATERIAL PROCUREMENT SPECIFCATION FOR FABRIC REINFORCEMENT.

5.1 THE SCOPE SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section should include a general description of the product and its area of application to guide the prospective user. If the product is to be supplied with various product forms, i.e., different fabric weaves, then a system must be defined to distinguish the various types, classes, grades, etc. Those products to be controlled by this specification are required to be listed here.

It is recommended that for part producer material specifications:

- Form—defines the basic material form.
- Style—defines the fabric weave style, fiber tow count, and areal weight of the fabric.
- Class—defines the specific fiber used in the fabric (fiber type, tow count, size type and content, surface treatment level, manufacturer, and facility).

For industry standard specifications, they would specify the form, areal weight, fabric, and specific fiber information for each specific fabric material covered.

5.2 THE APPLICABLE DOCUMENTS SECTION.

This section should include appropriate drawings, specifications, standards, and methods that will form a key part of the specification. The material supplier is encouraged to use existing documentation available to the public that was developed or approved by industry organizations. Test methods can come from ASTM and SACMA (Available from ACMA). Supplier internal documents, such as special test procedures, should be kept to a minimum. When used, they should be referenced and included in the PCD.

Examples include:

- ASTM D 3544-76 (1996) Standard Guide for Reporting Test Methods and Results on High Modulus Fibers
- ASTM D 3800-99 Standard Test Method for Density of High-Modulus Fibers
- ASTM D 3878-01 Standard Terminology Composite Materials
- ASTM D 4018-99 Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows
- ASTM D 4102-82 (1999) Standard Test Method for Thermal Oxidative Resistance of Carbon Fibers
- ASTM D 6507-00 Standard Practice for Fiber Reinforcement Orientation Codes for Composite Materials
- ASTM E 1309-00 Standard Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases
- ASTM E 1434-00 Standard Guide for Recording Mechanical Test Data of Fiber-Reinforced Composite Materials in Databases
- ASTM E 1471-92 (1998) Standard Guide for Identification of Fibers, Fillers, and Core Materials in Computerized Material Property Databases

5.3 THE TECHNICAL REQUIREMENTS SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section defines the characteristics and attributes required to ensure the fabric procured to this specification is satisfactory for its intended use. The functional, physical, and mechanical requirements are to be defined in this section at the required level of detail.

5.3.1 The General Material Requirements Section.

This section should include requirements that define the specific fibers and processes for producing the fabric (many of these requirements may be specified in the PCD, which is referenced by the specification).

5.3.2 The Carbon Fiber Property Requirements Section.

This section should include requirements that define the mechanical and physical properties of the fiber. The carbon fiber to be used in the fabric should be purchased to a separate fiber specification that uniquely defines the fiber type, manufacturer, and facility.

The carbon fiber must be capable of meeting the requirements of the composite acceptance specification when woven in accordance with the fabric specification and infused with the specified resin and processed in accordance with the specified cure procedure. If they are separate documents, both the fabric and composite acceptance specifications must define the specific fiber to be used. If multiple fiber sources are to be included in the composite acceptance specification, then each fiber source must correspond to a unique designation (e.g., class) and, in the case of an industry specification, must correspond to a unique designation (Note: Two or more facilities owned by the same company producing identical fiber can be considered a single item when it has been established by testing that the two materials are equivalent). It is not acceptable for a specification to refer to the carbon fiber and the fabric by a trade name without specifying the manufacturer and facility that produces the fiber, the fiber specification that controls the fiber, the fabric specification that controls the fabric weaving, and the manufacturer and facility that produces the fabric.

The fiber specification must define the average values and ranges for all critical fiber mechanical and physical properties including tensile strength, tensile modulus, and density. The fabric specifications must identify the fiber form, tow count (e.g., 12 K flat tow), and twist or no twist. The fiber-sampling plan and test methods for fiber properties and quality must be documented.

The fiber size material, method of size application, and size content are considered to be an integral part of the carbon fiber. The fiber sizing is to be unique and there should be a shelf life requirement if the sizing ages during storage. Changes to the size, application, or content will require equivalency testing or the establishment of a new material designation (see section 3).

The recommended definition of fiber batch is given in section 5.8.2. Fiber batch blending of up to three lots is allowed as long as there is traceability of each fiber batch, and the lots are randomly distributed across the fabric.

Table 3 summarizes the fiber property data discussed above. These tests should be performed by the fiber supplier on each lot of fiber supplied to the fabric weaver. None of the tests in table 3 are recommended for fabric batch acceptance testing by the fabric supplier or material part producer.

Table 3. Recommended Set of Carbon Fiber Properties

Fiber Property	Test Condition	Test Method
Form	N/A	ASTM E1309
Tow twist	N/A	Any agreed method[1]
Tow size content	N/A	ASTM D4018[1]
Tow tensile modulus	RTD	ASTM D4018[1]
Tow tensile strength	RTD	ASTM D4018[1]
Fiber density	RTD	ASTM D3800[1]

[1]Acceptance tests performed by the fiber supplier.
RTD = Room temperature dry.
N/A = Not applicable

5.3.3 Section 3.1.2—Fabric Construction and Description.

Fabric destined for the LRM processes should be purchased to a fabric specification that defines the manufacturer and facility. The fabric specification should establish the fiber type, tow filament count, sizing type and level, fabric areal weight, and the fabric style. Carbon-fiber fabric can include a contrasting glass or aramid fiber tow (tracer) to help in discerning tow alignment. These tracer fibers can be treated to enhance detection by nondestructive inspection (NDI) methods. It must be demonstrated that these tracer fibers do not affect the short- and long-term performance of the cured composite.

Carbon fiber fabrics which contain conductive fibers (aluminum, copper, phosphor bronze, nickel, and nickel-coated carbon) for lightning protection, electromagnetic interference shielding, or other purposes must be treated in the applicable fabric specifications as a separate fabric style from the basic fabric without the conductive fibers. A full set of fabric and composite qualification test data should be obtained on the fabric with the conductive fibers.

Table 4 shows the recommended set of fabric properties.

Table 4. Recommended Set of Fabric Properties

Fabric Property	Test Condition	Test Method
Width	RTD	ASTM D 3774
Tracer spacing*	RTD	Any agreed method
Alignment*	RTD	Any agreed method
Waviness	RTD	Any agreed method
Openness	RTD	Any agreed method
Yarn count/inch*	RTD	Any agreed method
Areal weight (g/m^2)*	RTD	ASTM D 3776

*Batch acceptance tests
RTD = Room temperature dry

5.3.4 The Fabric Workmanship Section.

This section should include limitations on visual defects in the fabric. Criteria for continuous defects, such as yarn alignment, width, tracer alignment, and edge alignment, must be established and documented. In some cases, this information may be considered proprietary and controlled in the PCD. Allowable defect limits can be based on generally accepted industry standards.

Procedures for closing fabric openness, e.g., through the use of rollers, can be used if documented in the PCD. Edge alignment can be corrected by tentering. Where reactive binders with low-temperature storage requirements are used, procedures must be established to control and document material out-time.

Criteria for discontinuous defects, e.g., puckers, fuzz balls, wrinkles, slubs, crimps, splices, foreign material, incomplete wet out, yarn twists and crossovers, broken yarns, fiber distortion, crushed yarns, and bowed fibers, should be defined in the specification or PCD (appendix A for recommended definitions of fabric defects). Where surface defects such as foreign material and fuzz balls can be removed by scraping or picking, these procedures can be used if defined in the specification or PCD.

Procedures for continuous inspection of the fabric should be defined in the specification or PCD. It was recognized that due to machine limitations, only the top surface can be inspected. Should the same defects be detected by the part producer on the bottom of the fabric when the part is being laid up, the same criteria for allowable defect limits and correction should be followed.

The specification should require that each defect outside the allowable limits be identified and marked by a flag positioned at the edge of the material. The type, location, and length of each defect should be recorded for each roll and attached to the roll. Defects can be removed by splicing, per documented procedures, and by criteria for maximum number and minimum spacing of splices. The splicing technique must be easily identified by the part producer to avoid incorporation of the splice into a part.

Recommended fabric defects and allowable limits are listed in table 5. See appendix A, Glossary for descriptions of various fabric defects.

Table 5. Recommended Fabric Defects and Allowable Limits

Subject	Defect	Allowable Limits
Gaps and alignment	a. Warp yarn deviation from a straight line.	0.18 inch wide by 3 feet long max.
	b. Fill deviation from a straight line.	1. 2.0 inches over width of roll max. 2. 1.0 inch in any 21-inch width of roll.
Single yarn defects	Broken filaments, fiber distortions, fuzz balls, and wrinkles.	Defects shall not be greater than three over a distance of 6 lineal feet.
Continuous defects	Multiplicity of defects; e.g., two or more single yarn defects closer than 6 inches, excess binder, binder gaps, blisters, and foreign materials.	Defects separated by at least 3 lineal feet of each other, excluding selvage.
Tow splices	Spliced on adjacent tows within 0.5 inch of each other.	None
Single and continuous defects	All	10 percent of roll length max.

5.3.5 The Qualification Requirements Section.

Qualification requirements are defined in this section. Refer to section 8 for additional information on minimum requirements for qualification.

5.3.6 The Process Control Document Requirements Section.

It is strongly recommended that the material supplier establish a PCD that documents key aspects of the material fabrication, lists all raw material ingredients, defines KPPs, and establishes SPC procedures and requirements. The PCD should be maintained by the material supplier. While the PCD will typically be a proprietary document, it should be made available for review at the supplier's site by material part producers and certification agencies. It should be referenced by the material specification.

The PCD should contain, as a minimum, the following information. This information could be considered proprietary and, therefore, protected in accordance with disclosure agreements signed by the supplier and procuring organization.

- List the physical or chemical properties of each fiber type considered critical.
- List the tests conducted on each raw material at receiving inspection. Note the limits for acceptance or rejection.
- Describe the manufacturing process and in-process controls.

- List the tests conducted on the fiber yarn prior to weaving the fabric and note the requirements for acceptance or rejection.

- Define the time-temperature history of the tackifier resin during the application of the tackifier to the fabric and the control tolerances employed (if applicable).

- Describe acceptance inspection procedures used to evaluate the finished material and state the acceptance/rejection criteria.

- List the tests conducted on the finished material and test control limit requirements employed.

- Describe packaging, storage, and shipping controls.

5.4 THE QUALITY ASSURANCE SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section defines the tests and inspections required to verify that the fabric complies with the technical requirements of the specification. In addition, it provides guidance for evaluation of manufacturing changes and provides procedures for determining equivalency.

5.4.1 The Responsibility for Inspection Section.

Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all quality conformance inspection and test requirements specified herein and the procuring organization is responsible for the performance of all receiving inspection tests specified herein. The supplier procuring organization may use their own facilities or any commercial laboratory acceptable to the purchaser. However, the purchaser reserves the right to perform any or all of the inspections/tests that are deemed necessary to assure that the material furnished conforms to the prescribed requirements.

5.4.2 The Classification of Tests and Inspections Section.

5.4.2.1 Qualification Tests.

The qualification or preproduction tests performed for material qualification are those tests performed on representative samples of each specific form of material to establish a qualified product in accordance with this specification. Qualification testing should consist of all requirements and tests specified in section 7. This testing should be performed for each type of material.

5.4.2.2 Quality Conformance Tests.

The material supplier must preform material certification (acceptance) testing. The material specification should define the type and frequency of tests to be performed by the supplier.

Certification reports must be prepared for each batch of material. The test report must show that the batch meets all of the uncured and cured material requirements. All records for each batch and the original baseline database should be kept on permanent file. Records of raw material receiving inspection, in-process materials testing, SPC required by the PCD, and full material batch traceability should be kept for a minimum period of 10 years unless superceded by other requirements. The supplier quality department will review the certification test results prior to shipment to a part producer. Materials that fail the acceptance criteria can undergo a material review board process.

5.4.2.3 Receiving Inspection Tests.

The part producer (purchaser) quality department should perform acceptance tests for each batch of material. The material specification should define the testing frequency.

The quality department must review the test results and allow the material to be released to manufacturing only upon satisfactory demonstration that the material meets the specification requirements. The part producer should hold to the same record keeping requirements and retest criteria as the material supplier.

A part producer must conduct the acceptance testing whether the material is bought directly from the manufacturer or through a distributor. The original certification testing conducted by the material manufacturer will be made available by the distributor for a specific batch sold to the part producer.

In cases where the material has demonstrated a high level of SPC control and capability for the material, it may be possible to reduce or eliminate the purchase acceptance testing. If material is supplied by a distributor, it is recommended that purchaser testing be maintained as a safeguard against uncontrolled material. It is expected that the FAA will evaluate requests to reduce or eliminate part producer testing on a case-by-case basis (specific FAA policy for reduced testing approvals will be developed in the future). The procuring activity reserves the right to perform additional testing to confirm the supplier's certification data and to approve incoming material for use in the fabrication of production parts. Each roll of material should be examined for appearance, color uniformity, imperfections that would be detrimental for use in the fabrication of parts and for quality of workmanship.

5.4.2.4 Material Distributors.

Material distributors, either a facility of the manufacturer or an independent facility, must abide by all requirements of the material specification and the applicable portions of the process specification. The part producer should approve a distributor under their supplier surveillance system as described in their quality control manual. It is recommended that the material manufacturer will also have a role in authorizing distributors for proper control of the material. Material batches should remain traceable to the manufacturer's original batch and test reports. The distributor should provide copies of the original material certification and test reports to the user. The manufacturer's material, batch, and lot identification should be maintained.

A distributor should practice the same documentation of storage life and conditions as the material supplier. The distributor should be able to provide objective evidence of the material storage conditions. All shelf life should be determined from the date of material manufacture (impregnation). Any extension of the shelf life allowed by the material specification should be performed by a source approved by the original manufacturer.

If the product is repackaged, the materials used to repackage should be the same as approved for use by the material manufacturer.

5.4.3 The Certification of Conformance Section.

The supplier should furnish with each shipment two copies of a Certification of Conformance including certified test reports, confirming that all the material in the shipment complies with the requirements of this specification.

5.4.4 The Statistical Process Control Section.

The supplier should maintain the procedures and requirements for SPC based on KCs and KPPs. The KCs are a subset of those properties detailed in the material requirement tables. KCs should be selected such that they ensure all properties of the material are within acceptable statistical limits. These are usually the set of requirements used for acceptance testing. KPPs are those process parameters that have a significant influence on the KCs. KPPs must be determined prior to qualification and be documented in the PCD. Average values, ranges, limits, and sampling frequency should be established and documented in the PCD.

The procedures used by the supplier to conduct SPC analysis of the KCs and KPPs should be documented in the PCD. The PCD should also include the procedures used to establish and calculate the control limits. It is expected that control charts will be maintained on the KCs and KPPs and will be available for inspection by part producer and FAA personnel. It is strongly recommended that there be an effective program to collect, plot, analyze, and act on KC and KPP data. It is expected that action will be taken when the criteria for nonrandom data trends are met. Review should be initiated when the data is approaching the upper and lower control limits established during the initial database generation and subsequent production batches. Action should be taken when the data falls outside the upper or lower control limits.

If a KC is out of control, the cause of variation should be identified and eliminated, re-establishing statistical control. The supplier must document all corrective actions affecting the process and monitor if the corrective action has been effective.

Reduced testing may be established based on the capability of the KCs and KPPs. Reduced testing will require approval by the FAA and the part producer(s) prior to being implemented. The reduced testing plan will be documented in the PCD. If KCs are found to be out of control, testing must return to the original level for a period of time until confidence in the control of the material is re-established. The reduced testing may take the form of a reduction of part producer testing or less frequent supplier testing. A prerequisite for reduced testing is adherence to monitoring and action based on control charts.

5.4.5 The Test Methods Section.

Recommended test methods for each property are given in Chapters 3 through 7 of Volume 1 of MIL-HDBK-17, Rev. F. In general, ASTM Standard Test Methods are recommended. However, in most cases, additional test specimen configuration requirements and test procedures will have to be defined to provide sufficient detail to avoid undesired variations. Deviations from industry standard methods must be clearly detailed in the specification. In the event that part producer testing is required by the specification, it is recommended that the material supplier and part producer conduct round-robin test evaluations to reduce test result differences.

It is recommended that all testing be conducted by a laboratory certified to conduct the tests to the specified methods; this certification applies to supplier, part producer, and independent test laboratories. A certified laboratory follows established policies and procedures such as training of test technicians, written procedures for performing tests, documenting the dimensional accuracy of test fixtures, and tracing calibration to NIST standards. The specification should define the requirements and procedures for certifying a test laboratory. It is recommended that for an industry specification, a national laboratory certification be required for facilities used.

5.4.6 The Records Section.

The supplier should retain records of the batch raw ingredients for a minimum of 10 years from date of manufacture. Records should contain date of manufacture, process control tests, certification tests, acceptance tests, and storage conditions.

5.5 THE PREPARATION FOR DELIVERY SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

The product must have suitable identification, and the packaging and handling during shipping must result in the product being capable of its full handling and working life when received by the part producer.

If repackaged by a distributor, the new packaging must be labeled properly and functionally equivalent to the original packaging and the labeling requirements met. Any decrease in storage life, working life, and handling life must be documented by the distributor and provided to all users.

5.5.1 The Material Identification Section.

The batch number should be on two labels, one on the container and the other on the outside of the shipping wrapper. The label should also include the material designation, name of manufacturer, specification number, and date of manufacture. The outside label should also clearly define the required material storage conditions.

5.5.2 The Packaging and Preservation Section.

The material should be placed into containers appropriate for the protection of the material during shipping and storage. Step-by-step procedures should be given for the packaging of the material.

5.5.3 The Packing Requirements Section.

The fabric should be packaged in containers that meet federal regulations. Consideration should be given to container configuration that will not allow the fabric to move during shipment.

5.5.4 The Shipping Requirements Section.

Any special shipping requirements should be identified in this section.

5.5.5 The Receipt at Procuring Organization Section.

Instructions for receipt of the material at the procuring organization are specified in this section.

5.6 THE ACKNOWLEDGEMENT SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section of the specifications should contain the standard statement:

A vendor shall mention this specification number and the applicable detail specification number and their revision level in all quotations and when acknowledging purchase orders.

5.7 THE REJECTION SECTION OF A RESIN MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section should contain the standard statement:

Product not conforming to this specification and modifications authorized by purchaser will be subject to rejection. Rejected batches, by a purchaser should not be rerouted to other purchasers.

5.8 THE NOTES SECTION OF A MATERIAL PROCUREMENT SPECIFICATION FOR FABRIC REINFORCEMENT.

This section is reserved for explanatory and other notes.

5.8.1 The Intended Use Section.

This section should define the intended use of the material.

5.8.2 The Definitions Section.

This section should include definitions for terms or abbreviations that are used. The definitions provide clarity between the supplier and the procurer. Material properties, quality, and defects

must be defined such that batches made after the original qualification have the same level of quality and properties. For example, fabric defects such as fuzz balls, creases, foreign material, fiber alignment, splices, and edge deviation from a straight line should have a specific definition (see section A.2 in appendix A for recommended fabric defect definitions). Where possible, definitions from industry standards such as MIL-HDBK-17, SAE, and ASTM should be used.

The following batch definitions are recommended:

- Batch (or Lot) (general)—A quantity of material produced essentially at the same time and under the same conditions from a well-defined collection of raw materials. The quantity of material must have minimal variation in properties throughout to be considered a unique batch.

- Batch (or Lot) (fibers)—For fibers, a quantity of material formed during one essentially continuous, uninterrupted production run under the same process conditions using one to three precursor lots. An interruption in the process of up to 72 hours is permitted, provided that the production equipment settings are not modified or another material is not produced on the equipment during the interruption.

- Batch (or Lot) (fabric)—For fabrics, a quantity of material woven from one to three batches (lots) of fiber. The weaving process can be interrupted for up to 72 hours if the loom settings are not changed and another material is not produced in the interim.

The above definitions are generally applicable for use with material acceptance processes, including sampling plans for acceptance testing. For material qualification and allowables test programs, stricter definitions of a batch are often specified in order to control the amount of material variability to be evaluated in the test program. For instance, a particular batch of fabric may be restricted to a single lot of fiber.

5.8.3 The Ordering Data Section.

Detailed information to be incorporated in purchasing documents should be contained in this section.

5.8.4 The Approved Products Section.

A listing of products that have qualified as defined within the specification is provided in this section.

6. PROCESS SPECIFICATION GUIDELINES.

The objective of process specifications is to provide a means by which engineering requirements and procedures can be documented and communicated to the various organizations involved in the fabrication of LRM composite. The intent is to flow down and specify any regulatory or engineering requirements and procedures that are necessary for the fabrication process. It is imperative that the process specifications be clear and complete to ensure that the resulting composites are consistent in quality.

For the purpose of this report, the term process specifications refers to documents such as process specifications, material specifications, planning, work instructions, or test plans. The guidelines found in the following sections can be applied to any of the above documents. These guidelines have been found to be helpful in the fabrication of continuous fiber-reinforced polymer composite test panels, but should not be viewed as the only means of control for a particular application.

Due to the relative novelty of liquid molding processes in certified aircraft, there is no generally agreed best approach for the processes described. Improvements in process controls may eliminate the need for some final quality inspections requirements, equally new processes with more limited controls may require additional inspection, or the introduction of additional process controls. The part producer must ensure that the process used will consistently produce parts whose materials properties are equivalent to the properties defined during qualification testing. A part producer should, therefore, at least consider for their specification process every aspect discussed in this section, and understand how they will affect the final part quality.

The guidelines for fabrication of continuous fiber-reinforced polymer LRM composite test panels are divided into the following sections:

- Work Instructions
- Personnel
- Materials
- Equipment Description
- Facility Description
- Tooling
- Panel Lamination
- Panel Acceptance
- Process Monitoring

6.1 THE SCOPE SECTION OF A PROCESS SPECIFICATION.

This section should include a general description of the process and its area of application to guide the prospective user. General descriptions of acceptable resin types (e.g., one,- two,- or three-part systems, solid or liquid at room temperature, solvent content, etc.) and tooling systems, as well as processing temperature limits, should be described. Also, the manufacturing facility for which the process specification was prepared should be stated.

6.2 THE APPLICABLE DOCUMENTS SECTION OF A PROCESS SPECIFICATION.

This section should include appropriate drawings, specifications, standards, and methods that will form a key part of the specification. This will include any calibration procedures for process equipment or tooling, may include related safety procedures, and will include any internal specifications referred to within the document. For example, the facility may be a multiuse facility used for more than one process, in which case, it is preferable for the process specification to refer to a separate facility control document. However, where such documents

are used, it is essential to refer to the revision status and date of the document so that changes in referenced documents are properly accounted for (see section 9.6).

6.3 REQUIREMENTS SECTION OF A PROCESS SPECIFICATION.

This section lays all the requirements to ensure that the process remains in control. As noted above, the specification may refer to other documents where appropriate, though care should be taken to avoid issues in maintaining consistency between document revisions.

6.3.1 The Personnel Section.

Highly skilled technicians are needed to produce quality composites. Fabricators are encouraged to establish a comprehensive training program for technicians directly involved with the fabrication of LRM composites. Training and employee certification are sometimes required as part of the fabricator's certified process. Both written and practical proficiency tests are recommended for the training program. Fabrication of test panels and production parts by trained technicians increases the probability of fabricating high-quality and repeatable test panels. The quality of the composite materials has a direct bearing on program cost (elimination of rework due to poor quality composites) and optimum structural performance (establishment of design allowables). Proper training may also enable an increased level of self-inspection versus inspection by an independent source, thus reducing the fabrication cost.

Table 6 lists suggested factors to be addressed in the selection of fabrication personnel.

Table 6. Recommended Personnel Selection Factors

Experience
Inspection personnel, ratio to manufacturing personnel
Level of training
Personnel status identified (qualified or unqualified)

It is strongly recommended that a mentoring relationship be established between the company's technicians and engineering personnel. This mentoring relationship is best if the flow of knowledge is in both directions, but engineering should always approve process changes.

6.3.2 The Materials Section.

All materials (and their sources) required for the fabrication procedures and requirements relevant to the materials should be listed within the process specifications. The listing includes both consumable and structural materials. In cases where equivalent materials may be used, specific alternate materials should be explicitly stated.

Materials that can come in contact with the LRM constituents, primarily the preform and the liquid resin, should be evaluated to verify they do not contaminate the constituents. It should be verified that all materials that have the potential to become a foreign object within the composite can be detected by NDI methods that will be used for the inspection of production parts.

The purchaser should inspect constituent materials upon receipt in accordance with the appropriate material specification. Test methods, types of tests required, sampling requirements, criteria (acceptance value), and retest provisions should be clearly defined. Supplier certification records should be reviewed and maintained with the LRM process instructions, and periodic audits of raw material suppliers should be conducted to ensure that proper controls and documentation are maintained. Material that does not meet the established quality requirements should not be processed into test panels or parts.

Reactive material (such as the liquid resin or tackified preform materials as well as fiber with sizing applied), freezer storage conditions (temperature), and shelf life limits should be defined (controlled in the material specification). Many tackified preform materials and some liquid resins require a storage temperature of 0°F or lower. A typical freezer storage life can be from 6 to 18 months, with 12 months the most common. Procedures for the disposition of out-of-date material also need to be defined. This could include shelf life extension based on the performance of reinspection tests.

Ambient working life (sometimes called out-time) limits should be defined. The time period should be associated with a defined temperature and relative humidity range. This time period should have been determined during the material qualification test program.

Within the industry, two approaches are used in defining ambient working life for tackified preforms. The first approach refers to the ambient working life as out-time. Out-time begins when the material is removed from freezer storage and ends when the resin infusion cycle begins. Depending on the material, out-time will typically be from 10 to 30 days. The second approach is to divide the ambient working life into two sections: handling life and staging life. Handling life begins when the material is removed from the freezer and ends with placement of the material onto the tool. The staging life begins at placement of the material on the tool and ends when the resin infusion cycle begins. Aborted injection cycles should also be documented as the cumulative heat history of preforms containing reactive materials must be acknowledged, documented, and addressed as part of the process.

Definition of the ambient environment is critical to producing quality parts and avoidance of scrapped material and parts. Figure 4 is a schematic of the relationship between storage life, handling life, and staging life.

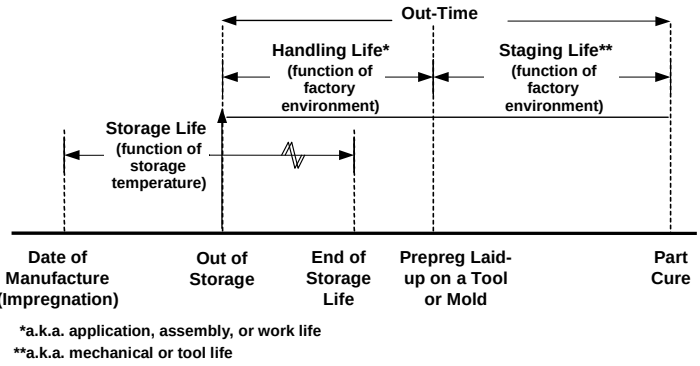

Figure 4. Recommended Definitions of Storage Life, Handling Life, Staging Life, and Out-Time

Liquid resins are typically perishable at ambient temperatures, i.e., they continue to react. This continuing reaction could, in time, reduce the resin kinetics and flow characteristics of the material, thus affecting producibility and properties.

Reactive materials (such as tackified preform fabrics and materials) handling properties are a function of temperature. If the temperature is too high, the material will be too tacky, making it difficult to position and handle the plies. If the temperature is too low, the material will be stiff, and again difficult to work with.

Some liquid resins are susceptible to moisture in that the absorbed water can affect cure kinetics. Therefore, controlling the relative humidity is important for ensuring the resin will obtain an optimal cure. High humidity will also increase the tack of the tackified material. Preform materials with high tack have been shown to inhibit the forming process, especially when numerous plies are simultaneously formed to a complex shape, resulting in wrinkles, distortions, or other defects in the final composites.

Complete records should be maintained that document traceability of the fiber, preform, liquid resin, adhesive, other constituents material, and the final composites. These records should also document the total shelf life and out-time of the reactive materials up to the time of liquid resin infusion. Provisions should be made within the work instructions to record material batch and lot numbers and ambient out-time at the time of resin infusion and cure. The part fabricator generally retains records for a period of 10 years.

6.3.3 The Required Equipment Section.

All equipment needed to perform the fabrication process with necessary requirements should be listed in the process instructions. Sources for the equipment should also be listed. A simple change, such as using a different heated clamp or press, can affect part quality due to variations in heat-up rates, clamping pressure, and platen deflection. Calibration and certification requirements should be defined (including frequency of calibration, limits, and remedial actions in case of calibration failure). Equipment requiring calibration and certification typically includes ovens, autoclaves, liquid resin delivery devices (such as pumps), thermocouples, vacuum gages, and ply-warming devices (e.g., hot-air guns). Provisions should be made within

the process specification to record the last date of calibration (as applicable) and equipment serial number.

6.3.4 The Facilities Control Section.

Collation (lay-up) of plies in the preform, including cutting and kitting, should be performed in a designated and segregated area, in some cases, a clean room may be used. The preform room should be an environmentally controlled facility where, in addition to the control and monitoring of temperature, humidity, air pressure, air distribution, and air velocity, conditions are established to minimize the introduction, generation, and retention of airborne particles. Good housekeeping procedures should be followed along with controlling the temperature, humidity, and airborne particles. A complete clean room discussion can be found in reference 2. Additional information on manufacturing facility controls can be found in reference 3.

Reactive material handling and curing characteristics are sensitive to both temperature and humidity, and therefore, it is critical to control and monitor temperature and humidity within the processing area. The temperature and humidity requirements should align with the material's ambient out-time requirements. After a preform is loaded into a tool or bagged, it should be properly sealed from the environment or otherwise protected before leaving the preform processing area.

The control of airborne particles is essential to maintaining a clean environment for the fabrication of LRM composites. Airborne particles are primarily controlled by restricting dirty operations within the preform processing area. The following actions also help to minimize the generation of airborne particles:

- Clean work areas on a regular basis and inspect for potential foreign objects.
- Do not allow mold releases or other (uncured) silicone-containing materials into the room.
- Do not allow sanding, machining, or any other operation that generates dirt, dust, or other debris in the room.
- Do not allow an air tool to be used without special precautions against contaminating parts with oil suspended in most shop air.
- If tools are heated using internal hot oil, take care not to contaminate the preform or the molding surfaces with the oil.

The inclusion of a positive-pressure ventilation system in the preform room is an effective method of preventing the introduction of airborne particles from other parts of the facility, such as machine shops.

Table 7 presents a checklist of items to consider when specifying requirements for a clean room.

Table 7. Recommended Preform Room Requirements Checklist

Limit access by other equipment (gas-powered fork lifts)
Limit access by non-lay-up personnel
Airflow through the room
Equipment for monitoring environmental control
No contamination by other processes (chemical processing, painting, and sanding)
Treatments and cleanliness of floors
Humidity (minimum and maximum)
Temperature (minimum and maximum)
Isolation from other contaminates
Lay-up area status (approved and unapproved)
Lighting (lumens)
Particulate count
Pressure (positive)
Proximity to molding area
Hose status (approved and unapproved)
Treatment and cleanliness of walls
Use of rubber gloves by personnel handling fabric or resin is recommended for the safety of the employee and to prevent possible contamination of the materials

Provisions should be made within the work instructions to record the temperature and humidity at the time of preform processing.

6.3.5 The Tooling Section.

For the fabrication of flat test panels, tooling consists of a flat base plate and a caul plate. For a closed-cavity LRM process, a flat closed-cavity mold with a uniform thickness cavity (usually rectangular shaped) is preferred. For an open-cavity LRM process, a flat base plate and a reusable bladder is preferred. They should be designed for the defined process conditions (e.g., assembly, infusion parameters/pressures, cure temperature, and packing pressure). Surface finish and flatness requirements should be defined (as applicable). Tooling should be designed to be sufficiently rigid to prevent excessive deflection under processing parameters (heat and pressure). It should also be noted that deflections and tolerances become even more critical when making relatively thin parts, as the affect on final fiber volume is more pronounced. All tools should be clearly identified. Tool storage conditions that ensure the tools are not damaged over time need to be defined.

A heat survey should be performed on all tools. The survey should verify the tool can meet required heat-up rates and that the temperature is uniform throughout the tool surfaces. This is generally done by molding a representative part and conducting thermal heat-up trials with thermocouples embedded throughout the part, correlating the heating profile of those with the permanent reference thermocouples within the tooling. Thermocouples should be placed at the

coldest and hottest locations. The cure time for the part starts when the coolest (or slowest) thermocouple, sometime referred to as the lagging thermocouple, reaches temperature.

For more complex shapes, tooling for forming of the preform may be necessary. These tools generally are required to withstand only the relatively lower temperatures necessary to soften the tackifier or binder. While these temperatures are relatively low, they contribute to the advancement of the reactive materials and need to be accounted for in documenting the thermal-processing history of the part.

A method for accurately positioning the plies is required. It is imperative that the ply orientation is within the engineering requirements, as strength and modulus properties are sensitive to orientation. A method must be used that allows for transfer of the tool zero direction to the panel and then to the machining equipment. Scribe lines on the tool and thin metal strips embedded along one edge of the panel are two methods that have been successfully used.

Detailed tool preparation procedures are necessary. Areas to cover include tool inspection, verification that all tooling details are available and in good working condition, mold release application procedure (acceptable mold releases should be listed in the materials section), and tool clean-up procedures. See table 8 for a checklist of tooling control items.

Table 8. Recommended Tooling Control Checklist

Method of cleaning, solvents, cleaning cloths
Mold release agents
Tool heat survey results (location of coldest and hottest thermocouples)
Scribe marking
Template inspection intervals
Template surface conditions
Template material
Templates, number of
Tool heat-up rate
Tool surface conditions
Tool, method of moving, transportation
Tooling condition (mold release applied, and no mold release)
Tooling configuration (flat and vertical)
Tooling status identified (approved and unapproved)
Tooling storage conditions and locations
Tooling, expansion and contraction rate
Tooling material
Location and number of vacuum ports

Table 8. Recommended Tooling Control Checklist (Continued)

Orientation rosette
Tool repair procedures
Tool inspection intervals
Tool (molding cavity) vacuum leak rate (must be measured at temperature)

6.3.6 The Required Procedures Section.

6.3.6.1 The Process and Work Instructions.

Work instructions (also referred to as planning) contain the requirements and procedures to be used in the fabrication process. Detailed step-by-step work instructions in conjunction with process specifications are found to be a successful approach for the fabrication of repeatable quality composites. Process specifications define the engineering requirements, while the work instructions convert the engineering requirements into detailed step-by-step process instructions.

The level of detail contained within the work instructions is subjective and varies from organization to organization. While the level of detail can vary, it should always be sufficient to ensure clear communication of the procedures and should be revision-controlled to ensure that traceability is maintained for the finished parts. Many instructions are best communicated through sketches or figures. Provisions should also be made within the work instructions for the recording of relevant observations, data, and quality assurance stamps.

6.3.6.2 Tool Preparation.

Tool preparation procedures and materials should be specified including:

- Release materials used and methods for application
- Tool sealing requirements and seal inspection
- Visual inspection for surface defects

Since the release materials may contaminate the resin or preforms, any tool preparation work should be carried out in an area isolated from preform preparation or preform loading. Steps should also be taken to prevent transfer of release agents on clothing or hand tools.

In some cases, the tool will be assembled as part of the preform assembly, (e.g., rib sections may be directly formed over tool inserts, and subsequently the tool insert and preformed fiber attached to the mold assembly). When this type of assembly is used, the inserts should be uniquely identified and should have some means to identify their state of preparation (e.g., a traveler document, or a transport assembly with an clear indicator to show that the inserts have been inspected and release-coated).

6.3.6.3 The Resin Preparation.

The resin should be stored and controlled to limit exposure to airborne moisture. In practice, this means that resins stored at room temperature should be held in airtight containers until ready for use. Resin stored in freezers or refrigerators must be warmed up to room temperature before opening.

The resin must be carefully controlled to ensure that on injection it conforms physically and chemically to the specified requirements.

- Premixed resins (supplied as a single component and stored in a freezer) will generally be controlled for chemistry by the resin manufacturer; however, the fabricator will need to ensure that the physical properties and degree of cure are within specified limits.

- Two-part formulated resins will generally be subjected to extensive controls by the supplier, and the fabricator will need to institute appropriate controls to ensure that the resin is thoroughly mixed in the correct ratios.

- Where the chemistry of the supplied resin is not controlled by the resin supplier, the fabricator will need to carry out appropriate levels of testing to ensure that its chemistry is within defined limits (e.g., through HPLC or through carefully instituted process controls).

Where automated mixing is used, the process capability should be measured carefully during installation (e.g., by taking samples for HPLC at regular intervals over the expected range of mix ratios and mixing speeds) and an SPC regime setup. This will define frequency of mix ratio tests and action/control limits for such tests. Resin samples should also be taken from the mix batch for QA testing. As a minimum, the ultimate T_g and the mix viscosity should be measured for each resin batch; the most effective test for viscosity is an isothermal hold test with limits set for the maximum viscosity reached within the expected injection time. Many resins are heated prior to injection to lower the viscosity. The time to heat up the resin also affects its viscosity and should be accounted for in the resin heat history. Some resins are packaged such that the leftover resin may be used for a subsequent injection provided that its heat history is acceptable.

The resin may require degassing to remove any air or volatile solvents, especially if the infusion process will be carried out under vacuum. The degassing should be carried out at the highest temperature possible without unacceptably advancing the resin cure, and the resin should be stirred slowly throughout the process. The possibility that degassing may remove volatile components must be assessed as degassing progresses. For example, vinyl ester resins are dissolved in styrene to create infusion resins, and under vacuum, the styrene preferentially evaporates. Therefore, some assessment of the loss of styrene over time is required, (e.g., by measuring the mass lost by the resin over time). Where significant changes in the resin composition are noted (e.g., removal of a volatile component), the degassing process must be modified and controlled to ensure that the composition stays within required limits. Again, an SPC approach should be used to ensure long-term control of the process.

In some liquid crystal materials, the resin viscosity may be controlled by variations in the mix ratios. Where this method is used, well-defined limits must be set, and a test plan developed to demonstrate that the final material properties remain within required limits. For minor variations, thermochemical testing may be sufficient to demonstrate that the final T_g and reaction chemistry remain within acceptable limits. For major variations, it may be necessary to evaluate neat resin mechanical properties across the range of variability (including effects of environmental exposure). Where there is significant variation in neat resin properties, the manufacturer will need to demonstrate that this does not significantly affect the composite properties.

6.3.6.4 Preform Fabrication and Assembly.

Frozen reactive materials (such as tackified preform materials and adhesives) in sealed containers must be warmed to room temperature prior to opening to prevent condensation from getting onto the material. The length of time required to warm the material to ambient temperature is a function of size; the larger the quantity, the longer the thaw time. Small quantities (5 to 10 pounds) can reach room temperature in 2 to 3 hours, while 30- to 50-pound quantities can take over 6 hours.

Materials should be cut on surfaces specifically dedicated to cutting. Materials should not be trimmed or cut on the molding tool to ensure the tool or underlying reinforcement materials are not damaged. If trimming of materials on the tool is required, a clean metal shim should be placed between the material to be cut and the underlying materials or tool surface. Care should be taken to ensure that foreign debris, resulting from the trimming operation, do not contaminate the panel materials. Individual materials should be identified and marked at the time of cutting. The cut materials may be put in a designated tray suitable for storage and transport provided that the orientation and identification of each unique constituent and shape is clearly identifiable and traceability is maintained.

Tackified preforms and complex shapes may require that interim processing using preform tooling, as discussed in section 6.3.5, be employed to stabilize and properly debulk the materials so that they may be located accurately onto the LRM molding tool. In these cases, it may be beneficial to mandate an inspection step with a translucent shaped caul that clearly establishes the limits of acceptability for trim lines. Those acceptable limits should be established as part of the certification process through analyses or testing, taking into consideration the worst-case scenarios. Complex parts typically require final part thicknesses to be achieved by debulking the preform before introducing it to the mold to avoid shifting or unintended distortion of the reinforcement materials. Preform teardowns may be required to ascertain that desired results are obtained during debulking steps, adding cuts, darts, and other reinforcement modifications as required.

The materials are located onto the tool as defined in the detailed work instructions. Care should be taken to accurately align the materials with respect to the tool 0° reference direction. See reference 4 for a description of the reference bar method used to maintain material (ply) alignment through the panel fabrication and subsequent specimen machining operations. Prior to collation, the materials are inspected for visual defects. Damaged materials are repaired or replaced as applicable. Layers of materials are debulked (compacted with vacuum pressure) as

applicable according to the detailed work instructions. After each layer of material is located onto the tooling, its surface is inspected for foreign objects.

The preform is assembled and located onto the molding tool and prepared for the resin infusion process as specified in the detailed work instructions. Provisions should be made to clearly mark the molded panel and to maintain orientation (0° and 90° reinforcement angles) to ensure traceability.

Mold assembly should be established as a repeatable process through positive location features and methods that ensure the preform is not distorted or damaged. This may be accomplished by establishing inspection features with acceptable limits for measured gaps in the case of closed-cavity molds, and thickness gages and templates in the case of open-cavity molds. Work instructions should clearly establish preform-tooling acceptance criteria so the resin infusion condition provides a good indicator of final part quality.

Thermocouples may be placed such that the panel temperature can be directly measured. The thermocouples may be placed against the preform or embedded in the preform to ensure the material is heated to the specified temperatures. A heat survey will establish the number of thermocouples required to ensure that the panel is evenly heated, typically at least two thermocouples are used for each panel. If the panel is large, one thermocouple per square foot should be sufficient (although the heat survey may indicate that less are required). In the case where the tool contains embedded thermocouples, a heat survey should be performed to validate that the embedded thermocouples are an accurate measurement of the panel temperature.

6.3.6.5 Resin Infusion.

The resin infusion should be carried out according to the applicable work instruction. This should define vacuum levels, tool temperatures and ramp rates, resin reservoir and delivery system temperatures, injection pressure or flow rate, and any externally applied pressures (e.g., on flexible tooling). The instruction should also define how to determine the completion of the infusion cycle and, hence, the start of the cure cycle.

When vacuum is used, a leak test is essential; the vacuum value should be recorded using a device able to measure better than 10% of the required vacuum level on an absolute scale (i.e., Torr, mBar). Thermocouples should be placed such that the tool temperature can be directly controlled. The thermocouples should be placed as close to the cavity as practical to ensure the material is heated to the specified temperatures. At least two thermocouples should be used for each panel. If the panel is large, one thermocouple per square foot of panel should be adequate. In addition, the resin thermal history must be controlled throughout the delivery system. At any point where the resin temperature is changed significantly, the resin stream must be designed to ensure the entire resin stream achieves the required temperature. During infusion, the resin flow rate/pressure may be directly or indirectly controlled. It is useful to be able to monitor resin flow rate, and a maximum flow rate should be set to prevent any movement of the preform within the tool. The maximum pressure at the end of injection should also be fixed to prevent distortion of the tool beyond its specified limits. The end of injection can be determined by direct observation of the vent points, sensors within the tool cavity, or measurement of the resin charge. A resin bleed is sometimes used to remove any trapped air. In some cases,

increased injection pressure is applied and held after the injection is complete. This final pressure forces air and volatiles into the solution during cure, and likewise, minimizes the effects of resin shrinkage. Injection parameters should be documented and used as part of the quality records for the part. Once the tool is filled, the cure cycle can be started.

6.3.6.6 Resin Cure (Control of Resin/Preform Thermal History).

The panel is cured to the applicable cure cycle. The cure cycle should define heat-up rate, temperature range, time, pressure, and cool-down rate. Although oven or press temperature is sometimes used, ideally, the cure time and temperature should be controlled by the lowest temperature-indicating (lagging) thermocouple in contact with the part. Temperature, vacuum, and pressure should be recorded as a function of time for the complete cure cycle.

6.4 THE QUALITY ASSURANCE, INSPECTION, AND PROCESS MONITORING SECTION OF A PROCESS SPECIFICATION.

This section defines the recommended examinations, inspections, and tests to be performed to verify that the processes, as well as the equipment, specified by the engineering requirements are used. Each inspection or examination given in this section should be tied directly to a requirement specified by the process instructions.

6.4.1 The Responsibility for Inspection Section.

Organizations or personnel responsible for the performance of the inspections and process monitoring examinations should be identified. When QA personnel are given the responsibility to perform inspection, they must be trained in the performance of the QA tasks and must be supported with complete documentation on the required inspection process.

6.4.2 The Inspection Section.

This section should contain all the requirements for inspection to ensure that the panel was processed correctly (within the specified guidelines) and is suitable for testing as part of the qualification. These requirements are also used in parts fabrication to ensure that the final manufactured parts conform to the same specification as the qualification coupons. In general, the section can be organized under the following subheadings:

- 4.2.1 Monitoring Procedures—Equipment
- 4.2.2 Monitoring Procedures—Materials
- 4.2.3 Monitoring Procedures—Facilities
- 4.2.4 Monitoring Procedures—Tooling

These sections will include inspection checks to confirm that the process is carried out as specified in the process instructions. (Note: It is possible to relax some of the checks once it can be demonstrated that the process remains in control without them.)

6.4.2.1 Process Monitoring and Control.

The data collected during the composite processing operations have typically been used for quality control purposes (i.e., to ensure that the process is operated within the limits set during the qualification process). This means that a record is kept to show that each critical process variable was in control during the processing of any particular part; however, no ongoing record of the performance of the process is recorded.

It is generally preferable to adopt an SPC regime, where critical process data are recorded and their variability measured. This allows the development of both control limits (which trigger the rejection of parts) and action limits (which indicate that the process is no longer in control and requires adjustment). A preform may be reworked, in some cases, to achieve design and quality requirements, thereby salvaging a potential scrap part. Any rework processes should likewise be qualified as a part of the fabrication process. By maintaining records of the process performance, the process capability can be continually reassessed and process control improved. SPC may also be considered as substantiation for reduced NDI requirements by recording data, which links control of processing parameters to part quality. A substantiation database of the processing limits correlated with acceptable engineering analysis or testing is required for this approach.

This approach also simplifies the process of assessing which process variables significantly affect key part performance characteristics. Typical variables that would be monitored in an LRM process include:

- Ply-cutting equipment data (time since last blade change, table cleaning, etc.)
- Quantities and types of consumable materials used (bleeders, flow media, breather, etc.)
- Physical characteristics/features of preforms (thickness, trim dimensions, weight, etc.)
- Out-time for time-sensitive materials (tackified fabrics and preforms)
- Vacuum level and leak rate for vacuum-formed preforms
- Times and temperatures for thermally formed preforms
- Torque readings for jack-screws and assembled tooling details
- Tooling gaps for assembled closed-cavity molds and die sets
- Number of cure cycles since previous mold-release stripping and reapplication process
- Resin reservoir temperature
- Resin degassing vacuum
- Resin degassing time
- Resin mix ratios
- Resin delivery pressure
- Resin delivery flow rate
- Shot size
- Time taken to reach maximum delivery pressure (flow-controlled systems)
- Resin delivery system temperature(s) (preheat temperatures)
- Tool temperature
- Tool vacuum and leak rate
- Time to fill (usually measured at each vent or at each monitoring point)

6.4.2.2 Panel Inspection.

After cure, it is strongly recommended that the test panel be inspected to ensure all engineering requirements have been met prior to machining test specimens. Inspections or tests are performed on each panel to verify that they are acceptable for submission to the machining step, which include:

- Panel thickness
- Surface flatness
- Resin content/reinforcement weight fraction
- Void content
- Composition variations (e.g., due to binder migration or resin filtration)
- Completeness of cure
- NDI for internal defects and embedded materials
- Test panels that fail to meet these requirements will result in test data that is not representative of the material.

The tests recommended are not necessarily applicable to production parts (though they are often used for developmental parts and first part qualification). They are used to verify that the panel is acceptable for further testing and are required to provide a complete database.

The panel should be visually inspected for surface defects that could be sources for premature test failures. Panel thickness is verified at a number of locations. The measurement locations should be equally spaced (within reason) around the panel. For closed-mold processes, the thickness measurements are used to verify that the mold deflection tolerance has been met (and to verify the process capability). For open-mold tooling, any systematic variation in the thickness between the inlet and outlet ends of the system must be assessed. In either case, the panel should not be tested if it fails to meet the required thickness and variation limits. Having assessed the typical variations found in parts, the test coupons used for material qualification should encompass the full range of variation. In open-tooled processes, this may be done by using similar geometry for the inlet and outlet galleries (ports) on test panels as are on the production tools. Acceptable process limits and ultimate quality requirements should be established for anticipated laminate imperfections and conditions, including reworked areas and repair techniques. Conditions such as surface scratches, foreign object debris, surface porosity, machined edges, resin-rich areas, and wrinkles, should be characterized, and acceptance limits, rework limits, and acceptance criteria should be established based on engineering substantiation. If possible, specimens should be machined from areas within, as well as outside observable defects. Panel density and resin content (fiber volume) should also be determined at several points on the panel. This requires that small samples (1/2 by 1/2 inch) be machined from the

panel. If possible, the edges of these samples should be inspected for voids, using optical microscopy.

It may be necessary to check that there is no variation of matrix composition through the panel. Variation of this type may occur through segregation of resin components or through migration of tackifiers or other materials added to the preform. The verification required depends on the nature of the component that may migrate or be filtered. To assess a test method for suitability, small panels of known composition should be made with a full range of variation of the component. These panels should be tested to determine how well the method can discriminate variations. Then a test panel of the same length scale as the production parts should be made and tested at a minimum 10 points. For instance, if a fire-retardant agent is included in the material as a solid, it may be appropriate to use a cone calorimeter test to ensure that the agent is evenly dispersed throughout the panel, or if some component of the tackifier may affect the final T_g of the cured resin, then dynamic mechanical analysis (DMA) could be used to ensure that this component has not migrated.

The material should be tested to ensure that the resin has reacted completely (e.g., by measuring the residual heat of reaction through DSC). In addition, the final T_g should be verified (e.g., through DMA).

Note: For T_g measurements, it is essential to establish a standard method for both the test and the data interpretation. The T_g definition should be included in the test report (e.g., the value should be quoted as T_g (DMA, peak tanδ)).

Each panel should be nondestructively inspected for internal defects, such as porosity, foreign objects, or delaminations. NDI standards should be fabricated as early as possible within the certification process. These NDI standards consist of panels fabricated with known defects so that the nondestructive methods and criteria can be calibrated relative to defect severity and panel thickness. It is imperative that NDI indications (such as sound loss for ultrasonic through transmission) be tied to a known physical defect type, location, and size. See SAE ARP 5605 for guidance in the fabrication of solid NDI references. In some cases, it is difficult or impossible to detect some types of defects. Two possible ways to deal with this are (1) to assume that the defects do exist and adjust the design allowables accordingly and (2) to design a process to eliminate the relevant defect. In the second case, the part producer must be able to demonstrate that the control system in place ensures that the defect can never occur.

6.4.2.3 Use of Prolongs/Cut-Outs.

Production part tests are frequently useful as both a quality control measure and a statistical process control. One way to ensure that the test material is equivalent to the fabricated part material and has undergone the same process is to extend the part slightly, or to retain salvage material, which will subsequently be tested. This extra piece (traveler) must be included at the earliest stage of the process design since it must be allowed for in the tool/preform design. The traveler can be tested for degree of cure, final T_g, flexural strength, and other properties. The data collected should be monitored as part of the statistical process control regime, and action/control limits established.

6.5 THE PREPARATION FOR DELIVERY SECTION OF A PROCESS SPECIFICATION.

This section details all the requirements to ensure traceability is maintained for the manufactured panel (linking the record of key process parameters to the final properties). In addition, any requirements to prevent deterioration of the panel before testing will be listed.

Each panel should be marked with a unique identification number. The identification number will provide traceability to the requesting document, resin batch number, preform identification number, cure cycle, and test type. Lines can also be drawn at an angle across the panel surface to aid in identifying specimen location within the panel.

6.6 THE ACKNOWLEDGEMENT SECTION OF A PROCESS SPECIFICATION.

This section should contain the standard statement:

Product manufactured according to this process specification should be identified as conforming in all details to the specification, and the specification number and applicable detail specification numbers and their revision level, if any, should be referred to in any documents referring to items manufactured according to this specification.

6.7 THE REJECTION SECTION OF A PROCESS SPECIFICATION.

If for any reason the process fails to conform to the process specification, for example, if a key process parameter is outside the limits set, the material must be clearly marked as nonconforming product and isolated from conforming product.

Subsequent use of this product will depend on the requirements agreed by the qualifying authority, which are usually defined in a nonconforming product procedure, or quarantine procedure. In any case, there must be a permanent record of the nonconformance and the action taken to resolve it.

6.8 THE NOTES SECTION OF A PROCESS SPECIFICATION.

This section is used for explanatory and other notes.

7. GUIDELINES FOR SECTIONS OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

This section provides guidelines specific to an LRM acceptance specification applicable to the cured composite material (epoxy resin reinforced with carbon fiber). This document is not a typical material procurement document, rather it defines the qualified constituent materials and the cured material property requirements that the part producer themselves are required to demonstrate for each production part. The guidelines contained within this section are specific to cured composite materials in the flat plate or part form containing textile fabric as the reinforcement and epoxy resin as the matrix.

7.1 THE SCOPE SECTION OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

This section should include a general description of the product and its area of application to guide the prospective user. General temperature use limits and cure conditions should be stated. A detail description is to be provided for the specific combination of resin and fiber reinforcement applicable to the requirements of this specification. A specific specification classification should include only a single resin formulation, a single fabric weave style (or specific preform design), and a single specific fiber (or specific combination of fibers in the preform). A specific classification is defined to be a unique form, type, style, class, etc. The specification document can include multiple forms, types, styles, and classes (fiber types).

The scope section should also clearly state that this document is to provide the performance properties of the combined material system and provide the requirements for the testing and release of the constituent materials into production usage.

7.2 THE APPLICABLE DOCUMENTS SECTION OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

This section should include appropriate drawings, specifications, standards, and methods that will form a key part of the specification. The part producer is encouraged to use existing documentation available to the public that was developed or approved by industry organizations. Test methods can come from ASTM and SACMA (available from American Composite Manufacturers Associations). Recommended processes and procedures should be referenced and followed, such as DOT/FAA/AR-03/19, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems," and MIL-HDBK-17, Composite Material Handbook.

Examples include:

- ASTM D 792 — Specific Gravity (Relative Density) and Density of Plastics by Displacement.
- ASTM D 2471-99 — Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins
- ASTM D 3878-01 — Standard Terminology Composite Materials
- ASTM D 4065-95 — Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics
- ASTM D 5229-92 (1998)e1 — Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
- ASTM D 5279-99 — Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics in Torsion

- ASTM D 5418 — Standard Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimety
- ASTM E 168 — General Techniques of Infrared Quantitative Analysis
- ASTM E 1252-98 — Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis
- ASTM E 1356-98 — Standard Test Method for Assignment of the Glass Transition Temperature by Differential Scanning Calorimetry of Differential Thermal Analysis
- ASTM E 1640-99 — Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis
- ASTM E 2041-99 — Method of Estimating Kinetic Parameters by Differential Scanning Calorimetry Using Borchardt and Daniels Method
- ASTM E 2070-00 — Test Method for Kinetic Parameters by Differential Scanning Calorimetry Using Isothermal Methods
- ASTM E 4473-95 — Standard Practice for Measuring the Cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures
- SACMA SRM 20R-4R — High-Performance Liquid Chromatography of Thermoset Resins
- SACMA SRM 25R-94 — Onset Temperature and Peak Temperature for Composite System Resins Using Differential Scanning Calorimetry (DSC)

7.3 THE TECHNICAL REQUIREMENTS SECTION OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

The intent of this section is to define the characteristics required of the composite plate or part. The required materials, equipment, and processing details necessary to ensure consistent quality material are to be specified.

7.3.1 The Materials Section.

Two classes of materials are used within this specification: (1) materials being tested and (2) materials used in the fabrication of composite test panels. The LRM materials being tested should be inspected upon receipt by the part producer, in accordance with the applicable material

procurement specification. Test methods, types of tests required, sampling requirements, criteria (acceptance value), and retest provisions should be clearly defined. Supplier certification records should be reviewed and maintained with the process instructions. Material that does not meet the established quality requirements should not be processed into test panels.

7.3.2 The Equipment Section.

Equipment guidelines for the preparation of composite parts by the liquid molding process can be found in section 6.3.3.

7.3.3 The Composite Preparation Section.

Guidelines for the preparation of composite parts by the liquid molding process can be found in section 6.

7.3.4 The Composite Mechanical Properties and Testing Section.

This section should include requirements for the cured composite. These requirements should be based on specific data obtained for the material. Whereas for the prepreg materials, batch acceptance tests are performed on the received prepreg material. With LRM processes, the part producer is responsible for three levels of material acceptance testing:

- Material batch acceptance tests for the constituent materials per the applicable procurement specifications are discussed in sections 4 and 5.

- Material batch release tests for the combination of resin, tackifier, and fiber preform per the material acceptance document. These tests are termed batch release tests to distinguish them from the constituent material batch acceptance tests. They are essentially equivalent to the batch acceptance tests performed on cured laminates for prepreg materials.

- Part acceptance or process control tests per the process specification and performed on excess resin, prolongation specimens, or traveler panels infused and cured at the same time as the part are discussed in section 6.4.

7.3.4.1 Baseline Infusion and Cure Process.

It is recommended that the part producer establish a baseline cure cycle to be used to produce panels for the initial material database (for qualification and design allowables) and for material batch release testing. The baseline cure cycle should be selected based on the expected applications and requirements for the material. Reasonable tolerances on heat-up rates and time-at-temperature should be established and documented. The cure process should be capable of producing cured plates or parts of consistent high quality. This cure cycle should be used for all material batch release testing by the part producer. It is possible that part manufacturing processes will use a different cure cycle than the baseline cure cycle. The part producer must demonstrate that the part cure cycle produces equivalent properties to the material database to use the allowables generated by the database for certification of the part (see final report

DOT/FAA/AR-03/19). If the part producer defines an alternate infusion and cure process, they should define additional acceptance testing with that process.

7.3.4.2 Cured Composite Physical Properties.

It is recommended that the specification include, as a minimum, requirements for the cured composite physical properties listed in table 9. The limits and test methods for each property should be documented in the specification.

Table 9. Recommended Set of Cured Composite Physical Properties

Cured Composite Physical Property	Test Condition	Test Method
Cured ply thickness[1]	TBD	Any agreed method
Fiber volume, % by volume [2]	N/A	ASTM D 3171
Resin content, % by weight [2]	N/A	ASTM D 3171
Void content, % by volume [2]	N/A	ASTM D 2734
Composite density	RTD	ASTM D 792
Glass transition temperature, T_g[2]	Precondition environments: • Dry • Wet (saturation under 85% relative humidity environment)	SACMA SRM 18, ASTM D 4065
Equilibrium moisture content	Equilibrium under elevated temperature and 85% RH environment	ASTM D 5229
Moisture absorption	Absorption vs time under elevated temperature and 85% RH environment	ASTM D 5229
Thermal induced microcracking	Cycles over expected range of usage temperatures; fast heat-up spikes, etc.	Any agreed method

[1] Batch release test.
[2] Equivalency baseline database test.
RH = Relative humidity
TBD = To be determined
N/A = Not applicable
RTD = Room temperature dry

7.3.4.3 Cured Composite Plate Mechanical Properties.

A minimum set of mechanical property data will be required to adequately characterize the material and to provide a database for future material equivalency evaluations. The tests should be able to detect changes in the fiber, resin, and the response of the material to variations in the cure process. A subset of these tests is required for material release testing for each batch.

In addition to the batch release tests, it is recommended that a second set of tests be run on a continuing basis to further populate the database, especially for use as a baseline in future

equivalency evaluations (see section 9.3). The results from these tests would be used to monitor the material acceptance and equivalency requirements in the specification. They would also assist in detecting material changes or an increase in variability.

The following paragraphs present a series of recommended tests for development of a material property database. It is expected that this database will be developed over time, as the market for the material expands and specific applications will require additional data. The first set of tests represents the minimum tests required to establish a material specification. This test matrix is very similar to the AGATE test matrix in final report DOT/FAA/AR-03/19 and is intended for applications that have simple lay-up configurations and do not involve mechanically fastened joints or highly loaded structure. An additional set of open-hole tests is recommended for inclusion in the specifications for materials intended for more general applications.

Further sets of recommended tests for an expanded database are also presented. These tests are optional with regard to inclusion in the material specification, but may be required for the design and certification of a part producer's product. There is a potential for cost savings if these additional tests could be shared amongst several part producers. Therefore, for marketing purposes, a material supplier developing a shared database may elect to perform tests to expand the shared database, either by themselves or in conjunction with one or more part producers. The expanded database could include the tests recommended below, other design-specific tests, or other environmental-related tests (e.g., flammability, moisture diffusion, thermal cycling). In each step of the database development, its utility is limited until more data is collected, but the intent is to let market conditions drive the expansion of the database.

It should be understood that while material specification acceptance values are not the same as B-basis design allowables, they are typically derived from the same test data. The calculation methods are different and they are intended for different objectives.

Material specification acceptance values are specifically intended for control of material. The values are calculated using statistical procedures that are a function of a risk level for rejection of a good batch of material and acceptance of a bad batch of material. The acceptance values are a function of the database mean and standard deviation and the batch sample size. Therefore, as data is added to the database, acceptance values will only change if there is a change in the data mean or variation.

Basis values (allowables) are intended to provide a certain level of statistical confidence for design strength calculations. B-basis values are established such that 90% of the population data falls above the basis value with 95% confidence. Basis values are a function of database mean and standard deviation and the number of data points in the database.

7.3.4.4 Recommended Cured Plate Tests.

Table 10 lists the specific fabric ply lay-ups for the tests recommended in tables 11 to 15. To establish a material specification, the tests in table 11 are recommended as a minimum set for material characterization and qualification. The additional open-hole tests in table 12 are recommended for materials expected to be used in more general applications that will contain

mechanical fastened joints or will be designed with notched plate properties. The requirements and the test methods for each property should be documented in the specification.

Table 10. Ply Lay-Up Sequences for Recommended Composite Tests

Lay-Up Name	Ply Lay-Up Sequence (starting from toolside)	Recommended Thickness Range for Selecting n (inches)
1. Warp Tension	[0*]n	0.060 to 0.100
2. Warp Compression	[0*]n	0.100 to 0.150
3. Fill Tension	[90*]n	0.060 to 0.100
4. Fill Compression	[90*]n	0.100 to 0.150
5. ±45 Shear	[45/-45/45/-45 // -45*/45*/-45*/45*]	
6. Warp Interlaminar	[0*]n	0.240 to 0.260
7. Quasi Plate	[(45/0/-45/0)n // (0*/-45*/0*/45*)n]	0.100 to 0.150
8. Soft Plate	[(45/-45/0/45/-45)n // (-45*/45*/0*/-45*/45*)]	0.100 to 0.150
9. Hard Plate	[(0/0/45/0/0)n // (0*/0*/45*/0*/0*)]	0.100 to 0.150
10. Warp Sandwich	[0*/0*/ core /0/0] (warp face next to core)	
11. Fill Sandwich	[90*/90*/ core /90/90] (warp face next to core)	
12. Quasi Sandwich	[45*/0*/ core /0/45] (warp face next to core)	
13. Warp Toughness	[0*]n	0.120 to 0.200
14. Quasi CAI	[(45/0/-45/0)n // (0*/-45*/0*/45*)n]	0.140 to 0.200

In the following lay-up sequences, the fabric ply orientations are defined as follows:
0 warp fibers in 0° direction, warp face down
0* warp fibers in 0° direction, warp face up
90 warp fibers in 90° direction, warp face down
90* warp fibers in 90° direction, warp face up
45 warp fibers in 45° direction, warp face down
45* warp fibers in 45° direction, warp face up
-45 warp fibers in -45° direction, warp face down
-45*warp fibers in -45° direction, warp face up
// = midplane of the lay-up
CAI = Compression after impact

Table 11. Recommended Minimum Set of Cured Composite Mechanical Properties

Lay-Up (see table 10)	Test Type and Direction	Property	No. of Batches x No. of Panels x No. of Tests/Batches/Panels			
			Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
1. Warp Tension	0 (Warp) tension ASTM D 3039	Ultimate Strength and Modulus	3 x 2 x 3	3 x 2 x 3 [2]	1 x 2 x 3	
2. Warp Compression	0 (Warp) compression ASTM D 6641	Ultimate Strength and Modulus	3 x 2 x 3	3 x 2 x 3 [2]	1 x 2 x 3	1 x 2 x 3
3. Fill Tension	90 (Fill) tension ASTM D 3039	Ultimate Strength and Modulus	3 x 2 x 3	3 x 2 x 3 [1]	1 x 2 x 3 [2]	3 x 2 x 3
4. Fill Compression	90 (Fill) compression ASTM D 6641	Ultimate Strength and Modulus	3 x 2 x 3	3 x 2 x 3 [2]	1 x 2 x 3 [1]	3 x 2 x 3
5. ±45 Shear	In-plane shear ASTM D 3518	Ultimate Strength and Modulus	3 x 2 x 3	3 x 2 x 3 [2]	3 x 2 x 3	3 x 2 x 3
6. Warp Interlaminar	Short-beam shear ASTM D 2344	Ultimate Strength	—	3 x 2 x 3 [1]	—	—

[1] Batch release tests.
[2] Equivalency baseline database tests.

Table 12. Recommended Additional Cured Composite Mechanical Properties for General Applications

Lay-up (see Table 7)	Test Type and Direction	Property	No. of Batches x No. of Panels x No. of Tests/Batches/Panels			
			Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
7. Quasi Plate	Open-hole tension [2] ASTM D 5766	Ultimate Strength	3 x 2 x 3	3 x 2 x 3 [1]	3 x 2 x 3 [1]	3 x 2 x 3
7. Quasi Plate	Open-hole compression [2] ASTM D 6484	Ultimate Strength	—	3 x 2 x 3 [1]	3 x 2 x 3 [1]	3 x 2 x 3

[1] Equivalency baseline database tests
[2] Open-hole test configuration: 0.25-inch-diameter hole, 1.5-inch width.

Table 13. Optional Cured Composite Mechanical Properties for Expanded Database

Lay-Up (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
7. Quasi Plate	Unnotched tension ASTM D 3039	Ultimate Strength	✓	✓		✓
8. Soft Plate	Unnotched tension ASTM D 3039	Ultimate Strength	✓	✓		✓
9. Hard Plate	Unnotched tension ASTM D 3039	Ultimate Strength	✓	✓		✓
7. Quasi Plate	Unnotched compression	Ultimate Strength		✓	✓	✓
8. Soft Plate	Unnotched compression	Ultimate Strength		✓		✓
9. Hard Plate	Unnotched compression	Ultimate Strength		✓		✓
9. Hard Plate	Open hole tension [1] ASTM D 5766	Ultimate Strength	✓	✓		✓
8. Soft Plate	Open-hole tension [1] ASTM D 5766	Ultimate Strength	✓	✓		✓
9. Hard Plate	Open-hole compression [1] ASTM D 6484	Ultimate Strength		✓		✓
8. Soft Plate	Open-hole compression [1] ASTM D 6484	Ultimate Strength		✓		✓
7. Quasi Plate	Filled-hole tension [2] ASTM D 6742	Ultimate Strength	✓	✓		
9. Hard Plate	Filled-hole tension [2] ASTM D 6742	Ultimate Strength	✓	✓		
8. Soft Plate	Filled-hole tension [2] ASTM D 6742	Ultimate Strength	✓	✓		
7. Quasi Plate	Filled-hole compression [2] ASTM D 6742	Ultimate Strength		✓		✓
9. Hard Plate	Filled-hole compression [2] ASTM D 6742	Ultimate Strength		✓		✓
8. Soft Plate	Filled-hole compression [2] ASTM D 6742	Ultimate Strength		✓		✓

Table 13. Optional Cured Composite Mechanical Properties for Expanded Database (Continued)

Lay-Up (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
7. Quasi Plate	Single-shear bearing [3] ASTM D 5961	Ultimate Strength		✓		✓
9. Hard Plate	Single-shear bearing [3] ASTM D5961	Ultimate Strength		✓		✓
8. Soft Plate	Single-shear bearing [3] ASTM D5961	Ultimate Strength		✓		✓
1. Warp Tension	Compression interlaminar shear	Ultimate Strength	✓	✓		✓

[1] Open-hole test configuration: 0.25-inch-diameter hole, 1.5-inch width.
[2] Filled-hole test configuration: 0.25-inch-diameter hole, 100° tension head countersunk fastener, 1.5-inch width.
[3] Single-shear bearing configuration: 0.25-inch-diameter hole, 1.5-inch width, one protruding head fastener, and stabilization fixture.

Table 14. Optional Cured Sandwich Panel Mechanical Properties for Expanded Database

Lay-Up[1] (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
10. Warp Sandwich	Sandwich long-beam flexure	Ultimate Strength		✓		✓
11. Fill Sandwich	Sandwich long-beam flexure	Ultimate Strength		✓		✓
12. Quasi Sandwich	Sandwich long-beam flexure	Ultimate Strength		✓		✓
12. Quasi Sandwich	Sandwich long-beam flexure, with open hole	Ultimate Strength		✓		✓
12. Quasi Sandwich	Sandwich long-beam flexure, with 30 in.-lb impact	Ultimate Strength		✓		

Table 14. Optional Cured Sandwich Panel Mechanical Properties for Expanded Database (Continued)

Lay-Up[1] (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
12. Quasi Sandwich	Sandwich long-beam flexure, with 120 in.-lb impact	Ultimate Strength		✓		

[1] If the material is designed to be self-adhesive to the core, then these tests should be conducted on cocured panels fabricated without adhesive. If the material requires an adhesive layer for bonding to the core, then the tests can be conducted on either (or both) cocured panels or precured skins secondarily bonded to the core, depending on the anticipated design and fabrication methods to be used with the material.

Table 15. Recommended Tests for Durability and Service Life Confirmation

Lay-Up (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
5. ±45 Shear Exposure to Solvent A (repeat for each potential exposure fluid)	In-plane Shear ASTM D 3518	Ultimate Strength and Modulus		✓		✓
13. Warp Toughness	Mode I fracture toughness ASTM D 5528	G1c	✓	✓		✓
13. Warp Toughness	Mode II fracture Toughness	G2c	✓	✓		✓
7. Quasi Plate	Open-hole fatigue[1], R=-1 (Tension/ Compression)	Fatigue Life [2]		✓		✓
8. Soft Plate	Open-hole fatigue[1], R=-1 (tension/ compression)	Fatigue Life [2]		✓		✓
9. Hard Plate	Open-hole fatigue[1], R=-1 (tension/ compression)	Fatigue Life[2]		✓		✓
14. Quasi CAI	Compression after impact, 270 in.-lb impact	Ultimate Strength		✓		

Table 15. Recommended Tests for Durability and Service Life Confirmation (Continued)

Lay-Up (see table 10)	Test Type and Direction	Property	Test Temperature/Moisture Condition			
			Lowest Temperature (Ambient)	70°F (Ambient)	Highest Temperature (Ambient)	Highest Temperature (Wet)
14. Quasi CAI	Compression after impact, 540 in.-lb impact	Ultimate Strength		✓		
14. Quasi CAI	Compression after impact, 1080 in.-lb impact	Ultimate Strength		✓		

[1] Open-hole test configuration: 0.25-inch-diameter hole, 1.5-inch width.
[2] Runout for fatigue life tests should be at least 1 x 10^6 cycles, unless the material is intended for use in severe fatigue environments, in which case the number of cycles for runout should be increased.

For fabrics where each warp or fill yarn crosses over more than one of the other direction yarn (e.g., an eight-harness fabric), one surface of the fabric will have more warp fibers (warp surface) and the other surface will have more fill fibers (fill surface). For these fabric materials, the orientation of the fabric relative to which surface is up in the preform stack can be important to avoid panel warping. For the tests using solid plates containing only one of 0°, 90°, or 45° oriented plies (tables 10 to 15), it is recommended to lay up the preform with all the fill faces down (if the warp and fill faces are alternated, a condition called warp face nesting can occur, which can lead to panel warping). For the tests using solid plates containing both 0° and 45° oriented plies (tables 10 to 15), it is recommended to lay up the lower half of the preform with the warp face down, and the upper half of the preform with the warp face up.

Process documents and controls for lay up of test panels and parts should ensure accurate alignment of both the warp and fill fiber directions (it is not sufficient to only align the warp fibers of the fabric). Fiber orientation tolerances (typically ±1° for test panels and ±3° to ±5° for parts) and fiber straightness requirements (such as ±2° over a distance of 12 inches for parts) should be specified. Exceptions are often required in highly contoured areas of parts.

All tests should be robust in that material variability, rather than test variability, is evaluated. Recommended test methods for each property are given in MIL-HDBK-17, Rev. F, Volume 1, Chapters 3 through 7. Moisture conditioning should be conducted per the procedures given in MIL-HDBK-17 and ASTM D 5229. The ASTM D 6641 combined loading compression test method is recommended for compression testing due to its superior performance (reduced variability) and lack of requirement for tabs on the test specimens.

Batch release tests are recommended in table 8 (as noted). These batch release tests are recommended based on the following rationale.

- The room temperature tension test is included to monitor the fiber and fiber-resin interface properties.
- The hot compression test is included to primarily monitor the resin properties.

- The apparent shear strength by short-beam test is included to monitor the fiber-resin interface properties.

The tests listed in table 13 are some optional tests for an expanded material database. These tests are intended to provide data for additional material design allowables that are commonly used to design and certify aircraft structures. The recommended test conditions for each test are shown with a checkmark. The number of batches to be tested will depend on the acceptable level of conservatism for the allowable values, on the criticality of the structure for which the data will be used, and on acceptance by the responsible FAA ACO.

Many aircraft applications involve more than solid plate construction. The tests listed in table 14 are recommended for honeycomb or foam sandwich panels. The tests are selected as sensitive indicators of any change in the constituent materials. This testing requires that separate specifications exist for the honeycomb or foam and the adhesive used to bond the prepreg to the core.

The optional tests listed in table 15 are some of those that may be required to show that the material will be suitable for the intended aircraft/rotorcraft application. These include testing of cured composites after exposure to solvents that the part will be subjected to in actual service. Recommended fluids for testing are:

- Extended Contact:

  - 100 Low-Lead Aviation Fuel
  - JP-4 Jet Fuel
  - MIL-H-5606 Hydraulic Oil
  - MIL-H-83282 Hydraulic Oil
  - Engine Lubricating Oil MIL-L-7808
  - Engine Lubricating Oil MIL-L-23699

- Short-Duration Contact:

  - Methyl Ethyl Ketone Washing Fluid ASTM D 740
  - Polypropylene Glycol Deicer (Type I) MIL-A-8243
  - Isopropyl Alcohol Deicing Agent (TT-I-735)

It is recommended that the test plates be exposed to the above fluids at room temperature conditions, unless the material is expected to be used in an application where fluid exposure occurs for significant time periods at a different temperature. For example, materials intended for use in integral fuel tanks should be exposed to fuel over the expected range of service temperatures for the fuel tank (typically -65° to 180°F). Tests for extended contact fluids should be conditioned by immersion for 500 ±50 hours; tests for short-duration contact fluids should be conditioned by immersion for 48 ±4 hours.

The test method to evaluate solvent effects must be sensitive to the expected effect on the composite. Shear tests are best for detecting the effect of solvent exposure on epoxy resins. The

solvent exposure and subsequent testing should be conducted at the temperatures expected during service.

It is recommended that fatigue testing of open-hole specimens be conducted to confirm that the parts will be durable over the expected service life. Postimpact residual strength evaluation for damage tolerance is recommended for primary structure applications. Fatigue testing of impact-damaged specimens may also be required for certification of certain primary structures; however, the detailed recommendations for these tests are beyond the scope of this document. See FAA Advisory Circular 20-107A for further guidance on these issues.

It is also recommended that any other unique environmental conditions, such as ultraviolet exposure and other weathering effects that may degrade material properties, be considered. These environmental conditions should be applied for the expected service conditions and life for the material and structural application.

The recommended test conditions for each test are shown with a checkmark in table 13. The number of batches to be tested will depend on the acceptable level of conservatism for the allowable values, on the criticality of the structure for which the data will be used, and on acceptance by the FAA.

All the tests shown in tables 13, 14, and 15 may not be applicable, depending on the physical limitations of the material (for instance, impact energy levels may have to be adjusted for different plate thicknesses and material characteristics).

7.4 THE QUALITY ASSURANCE SECTION OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

7.4.1 The Responsibility for Inspection Section.

Since the material acceptance document controls constituent materials assembled, infused, and cured at the part producers facility, the producer has the sole responsibility for the qualification, batch release, and part acceptance tests specified in this document.

7.4.2 The Classification of Tests and Inspections Section.

With LRM processes, the part producer is responsible for three levels of material acceptance testing: (1) material batch acceptance tests for the constituent materials; (2) material batch release tests for the combination of resin, tackifier, and fiber preform; and (3) part acceptance tests. Two approaches for conducting the required tests are diagramed in figure 5 and discussed in the following sections.

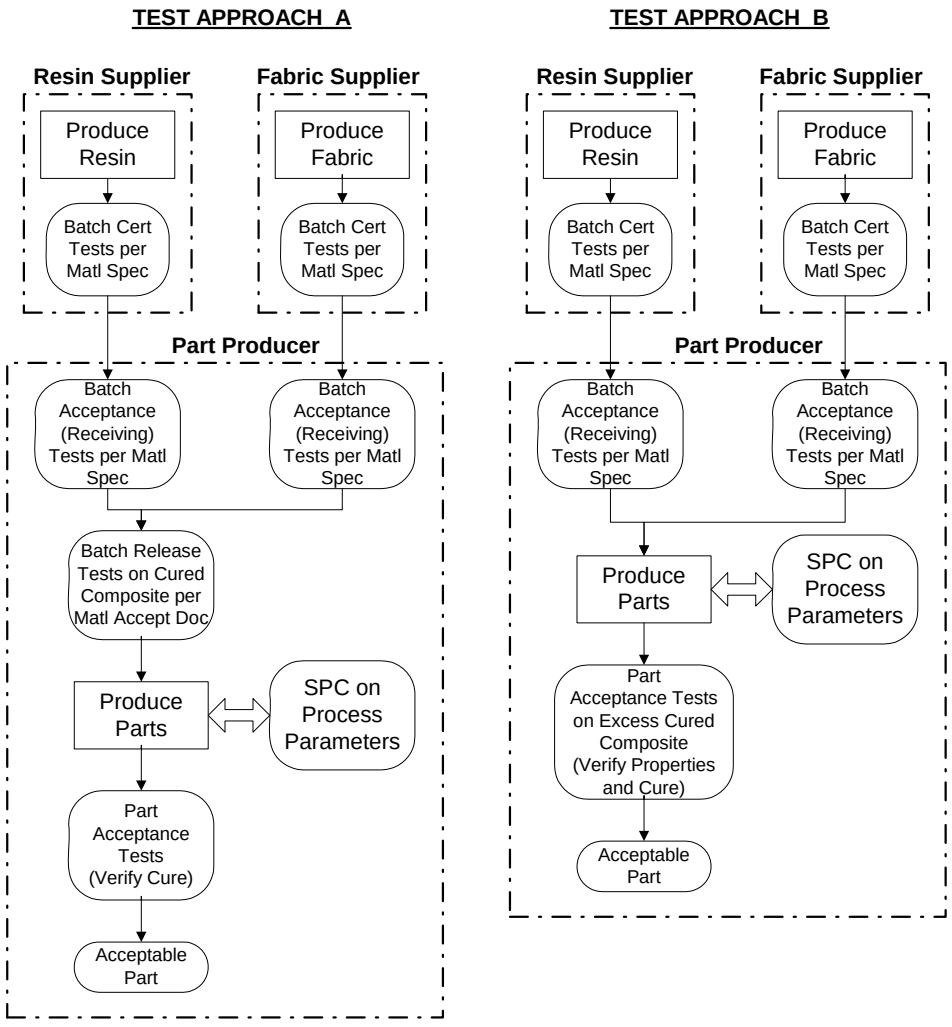

Figure 5. Liquid Resin Molding Material and Part Acceptance Testing Approaches

7.4.2.1 Qualification Tests Section.

The qualification or preproduction tests performed for the cured material qualification are those tests performed on representative parts, which contain each specific form of constituent material to establish a qualified material system in accordance with this specification. Qualification tests should consist of all requirements specified in section 3 of the acceptance document (section 7.3). This testing should be performed for each type of material.

7.4.2.2 Constituent Receiving Inspection Tests Section.

The part producer should perform the specified acceptance tests defined in the applicable material procurement specification (see sections 4 and 5 of this document) for each batch of material. The material specifications should define the testing frequency.

The producer must review the test results. The material shall be released only upon satisfactory demonstration that the material meets the specification requirements. The end-user should hold to the same record keeping requirements and retest criteria as the material supplier.

A part producer must conduct the acceptance tests whether the material is bought directly from the manufacturer or through a distributor. The original certification test conducted by the material manufacturer will be made available by the distributor for a specific batch sold to the part producer.

In cases where the material has demonstrated a high level of SPC control and capability for the material, it may be possible to reduce or eliminate the purchase acceptance tests. If material is supplied by a distributor, it is recommended that purchaser testing be maintained as a safeguard against uncontrolled material. It is expected that the FAA will evaluate requests to reduce or eliminate end-user testing on a case-by-case basis (specific FAA policy for reduced testing approvals will be developed in the future). If end-user testing is reduced or eliminated, then provisions for monitoring the thermal exposure history of each shipment of material between the supplier and end-user (including all transit periods and storage periods at a distributor) will be required.

The procuring activity should reserve the right to perform additional tests to confirm the supplier's certification data and to approve incoming material for use in the fabrication of production parts. Each roll of material should be examined for appearance, color uniformity, and imperfections, which would be detrimental for use in the fabrication of parts and for quality of workmanship.

7.4.2.3 Cured Material Batch Release Tests.

Once the constituent materials have passed the batch acceptance requirements of the applicable material procurement specification, the part producer must produce test panels and perform tests to demonstrate that the combination of resins, tackifiers, and fiber preforms, when combined into a cured composite part, meet the requirements of the material acceptance document. These tests are designated batch release tests since they are intended to provide the data required to release the materials for production use. Recommended mechanical property batch release tests are shown in tables 9 (panel physical properties) and 11 (panel mechanical properties).

Each potential combination of resin batch and fabric batch, which will be used in production parts, should be tested for the batch release tests. In some cases, this could lead to an excessive amount of batch release testing. There are two possible approaches for reducing the amount of required tests.

- Demonstrate that there is a very low risk of potential resin/fiber incompatibility. When this is achieved, the batch release tests need only be performed once for each unique batch of resin or fabric.

- Perform the batch release tests in tables 9 and 11 using excess composite material cut from each production part or group of parts infused and cured at the same time.

7.4.2.4 Part Acceptance Tests.

If the batch release tests are performed on the combinations of resin and fabric prior to using the material in production and provided that SPC systems are used to monitor the tackifier application, preform assembly, resin infusion, and cure processes, then the part acceptance tests can consist only of tests on excess cured resin (flash, infusion port plugs, etc.) to validate that an acceptable resin cure has been achieved.

If batch release tests on test panels are not performed, then more extensive part acceptance tests will be required. The tests designated as batch release tests in tables 9 and 11 should be performed on excess material representative of the part. These tests can use excess part material (e.g., prolongation) or test panel material infused and cured along with the part. Successful passage of all the tests will be required in order to accept the accompanying part.

The choice of which stage of the production process to perform the batch release tests will be driven by part complexity, preform complexity, the specific resin mixing and infusion process, along with test cost and part cost considerations. It should also be noted that later approach (performing release testing at part fabrication) is by far the highest risk approach.

7.4.2.5 Retest.

Retest or replacement of test data is allowed only if

- an abnormality is observed or can be reasonably deduced to have occurred during testing.
- data is a statistical outlier.
- the test has been conducted on materials that have not been prepared or conditioned properly (e.g., machining errors on test pieces).

  Note: Any testing error should be identified and corrected prior to retest.

If a retest is required, a complete set of replicates for the property should be tested. If the retest results fail the acceptance criteria, the material batch covered by the failed test should be rejected and dispositioned through a material review board (including engineering personnel) process. All end-users of a material batch for which retests were performed must be notified at the time of batch shipment.

7.4.3 The Statistical Process Control Section.

The part producer should maintain the procedures and requirements for SPC based on KC and KPP. The KCs are a subset of those properties detailed in the uncured and cured material requirement tables. KCs should be selected such that they ensure all properties of the material are within acceptable statistical limits. These are usually the set of requirements used for batch release testing. KPPs are those tackifier application, preform assembly, resin infusion, and cure process parameters that have a significant influence on the KCs. KPPs must be determined prior to part qualification and be documented in the process specification applicable to the part.

Average values, ranges, limits, and sampling frequency should be established and documented in the process specification.

The procedures used by the part producer to conduct SPC analysis of the KCs and KPPs should be documented in the process specification. The process specification should also include the procedures used to establish and calculate the control limits. It is expected that control charts will be maintained on the KCs and KPPs and will be available for inspection by FAA personnel. It is strongly recommended that there be an effective program to collect, plot, analyze, and act on KC and KPP data. It is expected that action will be taken when the criteria for nonrandom data trends are met. Review should be initiated when the data is still approaching upper and lower control limits established during the initial database generation and subsequent production batches. Action should be taken when the data falls outside the upper lower control limits.

If a KC is out of control, the cause of variation should be identified and eliminated, re-establishing statistical control. The part producer must document all corrective actions affecting the process and monitor if the corrective action has been effective.

Reduced testing may be established based on the capability of the KCs and KPPs. Reduced testing will require approval by the FAA prior to being implemented. The reduced testing plan will be documented in the process specification. If KCs are found to be out of control, testing must return to the original level for a period of time until confidence in the control of the material is re-established. The reduced testing may take the form of a reduction of part level testing by the part producer. A prerequisite for reduced testing is adherence to monitoring and action based on control charts.

7.4.4 The Test Methods Section.

Recommended test methods for each property are given in Chapters 3 through 7 of Volume 1 of MIL-HDBK-17, Rev. F. In general, ASTM Standard Test Methods are recommended. However, in most cases, additional test specimen configuration requirements and test procedures will have to be defined to provide sufficient detail to avoid undesired variations. Deviations from industry standard methods must be clearly detailed in the specification.

It is recommended that all testing be conducted by a laboratory certified to conduct the tests to the specified methods; this certification applies to the part producer and independent test laboratories. A certified laboratory follows established policies and procedures such as training of test technicians, written procedures for performing tests, documenting the dimensional accuracy of test fixtures, and tracing calibration to national standards organization such as NIST standards. The specification should define the requirements and procedures for certifying a test laboratory.

7.4.5 Section 4.5—Records.

The supplier and procuring organization should retain records of the batch raw ingredients for a minimum of 10 years from date of manufacture. Records should contain date of manufacture, process control tests, certification tests, acceptance tests, and storage conditions.

7.5 THE NOTES SECTION OF A CURED MATERIAL ACCEPTANCE SPECIFICATION FOR COMPOSITE PARTS.

7.5.1 The Definitions Section.

This section should include definitions (which provide clarity) for terms or abbreviations that are used. Material properties, quality, and defects must be defined such that batches made after the original qualification have the same level of quality and properties. For example, fabric defects such as fuzz balls, creases, foreign material, dry spots, fiber alignment, splices, and edge deviation from a straight line should have a specific definition (see appendix A for recommended fabric defect definitions). The degree of advancement of the resin, storage life, out life, and handling life must be clearly defined, since they affect the fabrication process. Where possible, definitions from industry standards such as MIL-HDBK-17, SAE, and ASTM should be used.

The following batch definitions are recommended:

- Batch (or Lot) (general)—n, A quantity of material produced essentially at the same time and under the same conditions from a well-defined collection of raw materials. The quantity of material must have minimal variation in properties throughout to be considered a unique batch.

- Batch (or Lot) (fibers)—n, For fibers, a quantity of material formed during one essentially continuous uninterrupted production run under the same process conditions using one to three precursor lots. An interruption in the process of up to 72 hours is permitted, provided that the production equipment settings are not modified or another material is not produced on the equipment during the interruption.

- Batch (or Lot) (fabric)—n, For fabrics, a quantity of material woven from one to three batches (lots) of fiber. The weaving process can be interrupted for up to 72 hours if the loom settings are not changed and another material is not produced in the interim.

- Batch (or Lot) (resin)—n, For a batch of resin, the definition varies, depending on the specific mixing process:

    - In a batch mixing process, a large vessel is charged with the desired types and quantities of raw ingredients. After mixing is complete, the vessel is discharged. The material made from this single-mix process is defined as a single batch of resin.

    - A continuous mixing process for producing resin typically involves incrementally feeding raw ingredients into a mixing device that blends them into a stream of resin. A batch of resin made by this process is defined as a quantity of material formed during one essentially continuous uninterrupted production run under the same process conditions using the same raw ingredients. Since start-up and shutdown usually require purging the equipment, a shutdown will signal the end of a specific batch. Material made after start-up is defined as a new batch. If a process shutdown does not require purging, an interruption in the process of up to

72 hours is permitted, provided that the production equipment settings are not modified or another material was not produced on the equipment during the interruption.

- In one version of a semicontinuous mixing process, a large vessel is charged with a portion of the raw ingredients (premix). After mixing, the vessel is discharged into several smaller containers, each of which acts as the vessel for subsequent mixing steps. The remaining raw ingredients are added to these smaller vessels and further mixing results in the final resin composition. The premix produced in the large vessel can be considered as a single batch of raw ingredient. The material produced during the final mixing in the small containers can be considered one batch if it is produced from the same raw ingredients batches without an interruption of more than 72 hours without the production of another material in the interval, and until the premix is consumed.

- In another version of a semicontinuous mixing process, small complete mixes of raw ingredients are made without the premix step. A batch of resin then consists of any number of these small mixes if they are made from the same lots of raw ingredients, the production run is not interrupted for more than 72 hours, and there is no other material made in the interval.

- For all mixing processes, blending of raw ingredient lots is permissible if the same blend ratio is found throughout all portions of the resin batch. Traceability must be retained on the ingredient lots that were used. For all mixing processes, a single resin batch may contain a maximum of three blended lots of each raw chemical ingredient.

- Solvated resins typically can be handled and blended easily without the heat history associated with reactive processes. In this case, up to five resin lots may be blended, but only if the individual resin lots themselves do not consist of blends of resin lots. Traceability must be maintained as to lot designations and amounts blended.

- Batch (or Lot) (specific to lamina, laminates, plates and parts)—n, For laminae, laminates, plates and parts, material made from:
  - One batch (lot) of fiber and one batch of resin(s)
  - One batch of fabric and one batch of resin(s)

The above definitions are generally applicable for use with material acceptance processes, including sampling plans for acceptance testing. For material qualification and allowables test programs, stricter definitions of a batch are often specified to control the amount of material variability to be evaluated in the test program. For instance, a particular batch of LRM composite may be restricted to a single batch of fabric (containing a single lot of fiber) and a single mix of resin.

7.5.2 The Approved Products Section.

A listing of products that have qualified as defined within the specification is provided in this section.

8. DEVELOPMENT OF MATERIAL CONTROLS.

Before the initiation of a qualification program, the sensitivities of the material to variations in the tolerances set on the material—chemical and physical—properties and processing should be investigated. This investigation should explore the characteristics of the material as the various limits are reached. These will determine the suitability of control limits in establishing the required reliability for the normal production phase of a qualified composite material.

This investigation can be performed in a structured design of experiments that will give the relative sensitivities to the process variables with minimum tests. These parametric studies should be performed well before the qualification batches are run to allow time for any required adjustments.

The rest of this section outlines the differences between qualification of constituent materials and cured panels to industry standard versus part producer material specifications, the responsibilities of an part producer related to establishing the suitability of a particular material and part fabrication process, and the steps required to establish the material specifications and qualify the materials and cured panels. The following two sections discuss different types of material procurement specifications: (1) industry standard specifications established by an industry committee and (2) specifications established by an individual part producer.

The authors of this document believe that the full benefits of shared material databases can only be achieved through the use of industry standard material specifications. However, it is recognized that there will continue to be cases where part producer material specifications are appropriate or required. This is particularly true for the current maturity of LRM processes where standardization has not yet been achieved in materials or techniques. This section discusses the qualification steps for both approaches. It is intended that this document apply to both approaches.

8.1 INDUSTRY MATERIAL SPECIFICATION.

The recommendations in this document are particularly applicable to LRM specifications that will be released as industry standards. For LRM materials, industry standard specifications could be developed for the various constituent materials as well as for the cured part material.

8.1.1 Constituent Materials.

The process envisioned for industry standard constituent material specifications would involve the development of an initial material database by the material supplier(s). The material supplier controls the incoming raw materials and processes to produce a consistent product.

8.1.2 Cured Part Material.

The process envisioned for an industry standard cured part material specification would involve the development of an initial material database by either a material supplier or an industry consortia. Typically, it would be the resin material supplier who would have the interest in and capability for developing the material characterization data. The cured part material specification (referred to as the cured material acceptance specification in section 7) would control the cured part properties and would contain material property acceptance limits, which the part producer would be required to meet.

8.1.3 Qualification.

Material qualification is defined as the process of evaluating a material (constituents and cured parts), using a prescribed series of tests, to establish its characteristics as produced by the baseline manufacturing process and using the evaluation results to define material specification requirements. A material qualification is performed initially for a new material; it is repeated in part or in whole when changes to materials or manufacturing processes need to be evaluated, or when a new combination of material constituents is desired. The scope of a previous qualification may also need to be expanded when requirements for additional characteristics are either added to an existing application or result from using the material in a new application. For material characteristics that have never been qualified, a material specification may contain target values in place of requirements; in this case, following qualification, the target values are updated to requirements based on the evaluation results.

The initial database will result from testing conducted to an FAA-approved and FAA-witnessed test plan and will provide sufficient data to establish the specification requirements and acceptance limits for both the constituent material specifications and the cured material acceptance specification. In this scenario, the material supplier or industry consortia would calculate proposed specification requirements and brings the material test results along with the proposed specification requirements to an industry committee (such as SAE AMS Committee P, SAE Commercial Airplane Composite Repair Committee (CACRC), MIL-HDBK-17, and American Society for Testing and Materials (ASTM) Committee D-30) for development of an industry specification. The committee would review the data and, after finding a need, would approve development of specifications. These specifications would uniquely define the material and would include specific property requirements and batch acceptance limits.

With this industry specification approach, the traditional process of qualifying a material to an existing material specification (containing either target requirements or requirements from a previously qualified material) is no longer applicable. The specification requirements will be determined based on the properties of the specific material system. It is envisioned that specifications will be issued for any material that the minimum dataset, process control, and documentation requirements have been met. Part producers desiring multiple material sources for an application can either callout the acceptable materials on the part drawings, on a substitution document, or on an internal specification once they have validated that all materials are acceptable for the intended designs. However, the materials would be purchased and accepted to the requirements of the industry specifications.

It will be the responsibility of the material suppliers (for constituent materials) and the part producer (for the cured part material) to continually test and evaluate the materials to revalidate the database in an ongoing process to ensure that the materials have not changed. This is expected to be accomplished by batch certification and equivalency baseline enhancement (EBE) tests outlined in this section.

8.2 PART PRODUCER MATERIAL SPECIFICATION.

The traditional approach in the aerospace industry is for each part producer to prepare material and process specifications. After qualification of a material to these specifications, the part producer then purchases the material and manufactures a part. This approach has involved the qualification of a material to an existing material specification (either in draft or released form).

In many cases, different materials have been qualified to the same set of specification requirements, even though the properties of the materials may be significantly different. This approach can result in undesirable levels of control of the individual materials qualified to the specification. This may then translate into less than optimum control over structure made with these materials. Therefore, control limits should be specific to a particular material based on the database statistics.

Since it may be many years before the industry standard specifications are in place, this document includes recommendations for the preparation of part producer material specifications, and the qualification of materials to these specifications, to meet the goals stated in section 1.2.

8.3 PART PRODUCER RESPONSIBILITIES FOR MATERIAL USE IN STRUCTURAL DESIGN.

Unlike conventional prepreg processes, for LRM, it is the responsibility of the part producer to qualify the combination of constituent materials and the resulting cured material for use in a particular aircraft or rotorcraft application. This process may involve additional tests to characterize the material and validate specific design details. These tests will fully validate the certification database and then, on a reduced frequency, to ensure that the design allowables remain valid. The part producer is also responsible for validating that alternate materials are acceptable for the application, if this is so desired.

If the part producer decides to use the material property information from previously developed databases in the certification project, they will need to perform equivalency tests on cured plates or parts to demonstrate capability to produce equivalent material to the associated material and process specifications. This involves demonstrating that the part producer can produce test panels and specimens that give results that are statistically equivalent to the values in the existing database.

To reduce the risk of failing the equivalency demonstration, it is recommended that the equivalency tests first be done using the resin material supplier's baseline infusion and cure process prior to attempting to demonstrate equivalency to an alternate process. The part producer has the option of skipping the first step and directly demonstrating the equivalency of their infusion and cure cycle to the baseline database and process. However, the two-step

process is suggested, since it is recommended that the part producer perform the purchaser batch acceptance tests on panels cured using the material supplier's baseline process.

Further, it is the responsibility of the part producer to validate any deviations from the baseline cure cycle in the material and process specifications. The part producer's production process must not result in statistically significant changes to design allowables established by using the baseline process. Successful demonstration of equivalency to an existing shared database will allow the part producer to avoid additional material qualification tests and to use the material allowables derived from the shared database. Once an equivalency evaluation is performed by a part producer for one application, it does not have to be repeated by that part producer for follow-on applications that use the same preform architecture, infusion process, and cure process.

8.4 MATERIAL QUALIFICATION PROCESS WHEN USING INDUSTRY MATERIAL SPECIFICATIONS.

This section outlines the process of material qualification, part producer demonstration of equivalency for their part fabrication process, and the ongoing material acceptance tests. Details of the industry committee procedures, acceptance limit and allowables calculation procedures, and FAA involvement and procedures for this material qualification process will be defined at a later date.

In this process, it is anticipated that the resin material supplier will

- develop a new resin material for potential market requirements or want to qualify an old material to an industry specification.
- stabilize the resin material production process through production trials.
- select a baseline fiber preform architecture to develop the material characterization database.
- establish and document the baseline infusion and cure process parameters for the material. This process will be used to generate the qualification database.
- perform the minimum qualification tests as defined in the constituent and cured part material specifications. A minimum of three batches of material will be produced for the manufacture of test panels.
- develop statistical material batch control limits for the constituent and cured materials and B-basis allowable values upon completion of the tests.
- provide the test data and specification limits to the industry committees responsible for the industry constituent material procurement specifications, cured material acceptance specification, material processing specification, and database approval.

- make the constituent PCDs available for on-site review by the industry committee and customer personnel who have executed proprietary agreements with the supplier(s).

- submit the material and accompanying data, material specifications, and allowables to a potential part producer.

The industry committee will

- review the data and specification values and if acceptable, will issue appropriate notifications (documents, web announcements, etc.).

- develop a test plan for additional material characterization based on marketing requirements. They will also obtain additional tests, calculate material equivalence limits and allowables, and review the data and calculated values.

At this point, the part producer will

- perform equivalency tests to the cured material acceptance specification, material processing specification, and property database. These tests verify that the end-user's processes for fabricating test panels and production parts can produce equivalent properties compared to the industry-approved database.

- compare the results of the equivalency tests to the published material database. If all test data meets the requirements, then the part producer can use the material allowables developed from the supplier's database in the design and certification of the part producer's structure.

- do one of the following if equivalency is not demonstrated: (1) modify their fabrication process and rerun the equivalency test program or (2) perform additional tests to develop design allowables specific to their situation.

- perform additional design verification and certification tests to validate specific configurations and design details of their structure. Upon completion of all certification tests and analyses, the FAA will approve the design, which specifies the materials, for a Type Certificate.

8.5 MATERIAL QUALIFICATION PROCESS WHEN USING PART PRODUCER MATERIAL SPECIFICATIONS.

This section outlines the process of material qualification, part producer demonstration of equivalency for their part fabrication process, and the ongoing material acceptance tests. It assumes that the new material will qualify to a material specification written and maintained by an part producer. It also assumes that all qualification and design-related tests will be performed or controlled by the part producer. This material qualification process is consistent with the current FAA procedures for an aircraft certification program.

In this process, it is anticipated that the material supplier(s) will

- develop new constituent materials for potential market requirements.
- stabilize the constituent material production process through production trials.
- establish and document the baseline infusion and cure process parameters for the materials. This cure process will be recommended to potential part producers.
- submit the material and accompanying data to potential part producers.

At this point, the part producer will

- submit a qualification and design-allowables test plan and constituent and cured material specifications to the FAA.
- perform the qualification and allowables tests, using the part producer's planned production infusion and cure process. A minimum of three batches of material will be used for the manufacture of test panels. Panel fabrication and testing will be witnessed as required.
- calculate proposed material batch acceptance limits for the constituent and cured materials and B-basis allowables values upon completion of the tests. Specification limits and allowables will be calculated using procedures documented in DOT/FAA/AR-03/19 and MIL-HDBK-17.
- submit the test data, material specifications, and infusion and cure process documentation to the FAA. The FAA will review the data and specification values, and if acceptable, will approve the use of the material specification and allowables data for the part producer's aircraft certification project.
- perform additional design verification and certification tests to validate specific configurations and design details of their structure. Upon completion of all certification tests and analyses, the FAA will approve the materials and design for a Type Certificate.

9. QUALIFICATION PLAN.

The qualification test plan may be either defined within the material acceptance document(s) or as a separate document (there is no cured composite-level material procurement document when using an LRM process). Common practice is to use a separate document. The type and number of tests to be performed, acceptance requirements, and additional qualification requirements are defined in the qualification plan document. Additional qualification guidelines are listed below.

It is highly recommended that qualification tests be performed at the system level, i.e., a specific resin, tackifier, and fiber preform are tested together as a cured composite or part. It is not appropriate to perform qualification tests on a resin material and then approve its use with a variety of fiber reinforcement forms without having tested the resin in conjunction with each

fiber reinforcement form. Prediction of composite-level strength properties from constituent properties is not sufficiently accurate at the present time.

9.1 INITIAL MATERIAL QUALIFICATION.

This section should include procedures and requirements for initially characterizing the material to establish the material procurement specification and material acceptance document requirements.

9.1.1 Industry Material Specification.

To develop the information needed to qualify a material to an industry specification, tests will be conducted to establish an initial database. The tests can be performed by a material supplier, a part producer, or an industry consortium (suppliers and multiple part producers, e.g., AGATE). The results from the tests are used to establish the initial material specification and batch acceptance limits. The decision on whether the specification becomes industry standard or a part producer proprietary specification is for the developers of the database to determine.

A request for the initial qualification will be reviewed by the FAA. The organization that will conduct the tests should submit a test plan, material specifications, and process specifications prior to the actual qualification. Appropriate reviews and inspections should be agreed upon to ensure FAA acceptance of the qualification.

9.1.2 Part Producer Material Specification.

For qualification to part producer specifications, the material suppliers and part producer typically will negotiate as to which party will fund and conduct the qualification tests. The part producer will be responsible for submitting a test plan, material specifications, and process specifications to the FAA prior to the actual qualification. The results from the qualification tests are used to establish the initial material specification and batch acceptance limits.

9.2 MINIMUM LEVEL OF TESTING.

It is recommended that the initial material database include the minimum required properties listed in sections 4.3.2, 4.3.3, 5.3.2, and 7.3.4 for the resin, fabric, and cured composite systems. At the discretion of the organization(s) developing the database, the test program may include the additional recommended tests listed in section 7.3.4, and any additional tests desired by the prospective part producers of the material. It is strongly recommended that fatigue be among the tested properties.

It is also recommended that a minimum of three different material batches consisting of a minimum of two different fiber or preform batches, three different resin batches, and three different tackifier batches be used for the initial database.

Per the AGATE approach, it is also recommended that composite mechanical property data for each batch be processed using two independent cure cycles. The data from the two processing cycles can be considered separate batches when calculating design allowables from the data.

The statistical procedures given in DOT/FAA/AR-03/19 and MIL-HDBK-17 can be used to calculate the material property equivalency requirements and material batch acceptance limits. When using these procedures, the equivalency requirements should be calculated using an α (alpha) = 0.05, while the batch acceptance limits should be calculated using an $\alpha = 0.01$. The α level is related to the risk associated with the rejection of conforming material. It is set higher for equivalency to ensure higher probability of rejecting material that is not equivalent. The equivalency requirements for all tested properties, and the acceptance limits for specified properties, should be listed in the specification. These requirements and acceptance limits are recommended to be established as

- maximum average, minimum average, and minimum individual values for all strength properties.
- maximum and minimum average values for all stiffness properties.
- maximum and minimum average values for cured ply thickness, resin content, areal weight, T_g, etc.
- maximum average values for volatile content, void content, etc.

9.3 EQUIVALENCY BASELINE ENHANCEMENT.

Since the initial material qualification testing is typically performed on only three batches of material (containing only three batches of resin and tackifier, and two batches of fiber), and since the qualification batch material is often produced using processes that are not completely representative of full-scale resin and preform production, it is strongly recommended that the material acceptance document contain requirements to test additional structural and other properties on each batch with the test frequency for these tests reduced once the properties are verified to be stable.

The reasons for recommending these additional tests are as follows:

- The additional data will provide a more robust database (closer estimate of the population means and variabilities) for calculating the material batch acceptance and material equivalency requirements. This is expected to result in fewer material batch rejections and fewer failures of follow-on material equivalency programs.
- The data provides an ongoing validation of structural properties, thereby minimizing the chance of surprise changes in material properties.
- A larger database will result, thereby providing the potential for higher allowables.

It is recognized that updating statistical basis values may require significant engineering expense to revisit strength calculations. It should be understood that basis values are not a constant value for samples drawn from a population, but that they have a distribution of values. For instance, two samples drawn from the same population will produce two different basis values; both values are valid because they represent an estimate of the statistical population distribution. For

this reason, it is not practical to continually recalculate basis values as new data points are obtained.

The following test protocol is recommended:

1. After qualification, the EBE tests listed in this section should be performed for each prepreg production batch. After the 12th batch of production material is tested, the material equivalency and batch acceptance requirements should be recalculated, and the specification revised with the updated values. This gives a total of 15 batches of data that, assuming the material properties are in statistical control, will produce a fairly stable and representative set of specification requirements.

2. If there are no significant changes in the specification requirements from the calculations in step 1, and an SPC analysis of all the batch data shows that the material is in control, then the EBE testing frequency can be reduced to once every 30 batches or once a year, whichever is more frequent. Normally, the material supplier should not have to obtain formal end-user or FAA approval for the reduction in EBE testing frequency; the batch data will be reviewed as part of the specification update described in step 1. A recommended testing frequency of every 30th batch or once a year is a reasonable compromise between minimized cost and the desire to obtain periodic data to detect material drift or changes.

3. Upon accumulation of each additional ten sets of test results (either from the EBE tests or from intervening material equivalency tests), the material equivalency and batch acceptance requirements should be recalculated, and the specification revised with the updated values. For those properties tested for each batch of material, the data from all batches is included in the recalculation. Periodic recalculation is recommended since it does not make sense to update the specification values after every new dataset (collected on every 30th batch or once a year).

4. Base values should only be recalculated if there is a significant change in the specification values, i.e., there is a statistically significant change in the population mean or variability.

This protocol is outlined in table 16.

Table 16. Batch Acceptance and Equivalency Baseline Enhancement Testing Protocol

Batch No.	Qualification	Batch Acceptance	Equivalency Baseline Enhancement
1-3	All tests in tables 1 to 5b, plus tests in tables 5c to 7 as appropriate for material and application	Part of qualification	Part of qualification
4-15		Tracer spacing Fiber alignment Yarn count/inch Fabric areal weight Uncured fiber content Uncured resin content Uncured volatile content Flow HPLC	Cured fiber volume Cured resin content Cured void content Warp tension RTA Warp compression RTA Fill tension HTA, HTW Fill compression HTA, HTW OHT RTA, HTW OHC RTA, HTW
16-44		Cured ply thickness Fill tension RTA Fill compression HTA Shear RTA	none
45			Same as for batches 4-15
46-74			none
75			Same as for batches 4-15
continuing			Repeat above pattern every 30 batches

RTA = Room temperature ambient
HTA = High temperature ambient
HTW = High temperature wet
OHC = Open-hole compression
OHT = Open-hole tension

9.4 ADDITIONAL CHARACTERIZATION TESTING FOR SPECIFIC DESIGN APPLICATIONS.

Depending on the intended application for the material, additional tests at the plate, element, and subcomponent levels may be required to fully characterize the material. This testing would include evaluations of process and configuration variations, such as for cocured sandwich structures. These tests could also include evaluations of solvent resistance, impact damage resistance and residual strength, fracture toughness, and bolted and bonded joint strength.

These tests can be performed at the discretion of a material supplier if a common database of properties is desired; otherwise, the tests can be left to the individual part producers of the material.

9.5 SUPPLIER SITE QUALIFICATION.

The material manufacturing site should demonstrate to part producers and certification agencies the capability to conduct raw material testing, final product testing, record maintenance, calibrations, and statistical process control. Training programs and records should be in place to assure that personnel are capable of conducting testing, running equipment, and assembling and interpreting test results. Adequate and consistent document control should be demonstrated. Major equipment maintenance and modification records should be available. An appropriate organizational structure should exist to ensure that each major function (i.e., operations and quality assurance) can perform their functions.

9.6 CHANGES TO QUALIFIED MATERIALS.

This section should include the procedures and requirements for establishing the equivalency of future material data to the baseline database.

Material equivalency is the process of determining whether two materials or processes are similar enough in their characteristics and properties that they can be used without distinction and without additional evaluation. In this discussion, equivalent material is defined as the cured part material. Statistical tests are used to determine whether data from the same material processed in two different manners are significantly different. Equivalency is limited to the evaluation of changes in a material's constituents, manufacturing process, or to changes in the fabrication (e.g., resin mixing, infusion, and curing) process used with a material. Two materials that meet the same minimum material specification requirements but have statistically different property distributions are not considered equivalent.

Final report DOT/FAA/AR-03/19 provides procedures for evaluating material equivalency. The procedures for material equivalency described in that document are only applicable to specific types of changes and subject to limitations. For details of the changes and conditions, see the report.

The following sections are intended to expand upon the material equivalency guidelines given in DOT/FAA/AR-03/19 by encompassing a greater range of material changes. MIL-HDBK-17, Rev. F, Volume 1, section 8.4.1, "Tests for Determining Equivalency Between an Existing Database and a New Dataset for the Same Material," gives statistical procedures that can be used to determine whether there is a statistical difference between the data from the two materials or fabrication processes. For two materials to be truly equivalent, their population means and distributions for every property of interest must be essentially identical. However, in practice, this will almost never be achieved, so engineering judgment will be required when equivalency determinations are necessary.

Since processes and materials undergo continual evolution and change, it is necessary to establish that the material remain true and consistent to the original database and allowables. It is the responsibility of the material supplier to conduct tests to demonstrate that the current material, when processed to the baseline process specification, will generate composite properties statistically equivalent to the properties of the original materials.

Any material changes that result (or can be expected to result) in a change to the material allowables, or to the acceptance limits, should be considered to be a major change under Title 14 Code of Federal Regulations (CFR) Part 21.93. The approval of minor and major changes are covered in 14 CFR Parts 21.95 and 21.97, respectively. The following sections describe five levels of material changes and the testing and notification requirements associated with these levels.

9.6.1 Level 0 Changes.

These are changes that do not affect the material. Some examples of these changes are typographical error corrections to the specification or PCD, changes to the names of incoming materials due to company name changes, and use of alternate storage facility locations using identical storage conditions. No notification to the part producers is necessary for these changes. Related document updates are not required.

9.6.2 Level 1 Changes.

These changes are minor changes that have been tested internally at the supplier beyond normal batch acceptance testing on the same or similar material, and have been found not to affect the material.

Typical examples of level 1 changes are:

- Change in a release (backing) paper or other process aid
- Alternate vendor for chemically and physically identical raw materials (there should be compelling data verifying that the alternate material is identical to the original material)
- Changes to packaging methods and materials

Physical aspects of constituent resin chemicals, such as particulate size and shape, can have a significant effect on the properties of the mixed resin even if the constituents are chemically identical.

Current part producers will be notified of these changes. A new revision of the applicable material specification is recommended. Any related documents must be updated to reflect the change.

9.6.3 Level 2 Changes.

Due to the type of change involved, this level is considered major by the FAA. These changes are not subjected to the full equivalency test plan required for a level 3 change. These changes will require that the material supplier or part producer conduct tests to an extent that establishes the requirements listed in the material and process specifications will not change.

Typical examples of level 2 changes to constituent materials are:

- Change in feedstock or precursor to resin ingredients
- Change in feedstock or precursor to fiber ingredients
- Second source of chemically and physically similar raw materials that have not been shown to be chemical equivalents
- Changes to test methods that reduce variability
- Modifications to process equipment or processes that do not change KC or KPP
- Addition of new similar equipment
- Expansion of existing facilities, including start up of additional production facility machines

Typical examples of level 2 changes to cured part materials are:

- Changes to test methods that reduce variability
- Modifications to tackifier application, infusion or cure process equipment, or processes that do not change KCs or KPPs
- Addition of new similar tackifier application, infusion, or cure process equipment
- Expansion of existing facilities, including start up of additional production facility machines

The type of change and tests that demonstrate no significant effect must be documented in the appropriate part of the supplier or part producer PCD. It is recommended that side-by-side testing of the original material or method and the new material or method be conducted.

Using the requirements contained in the specification or PCD, the statistical procedures given in DOT/FAA/AR-03/19 can be used to verify that the data from the altered material is equivalent to the baseline database for the material.

A new revision letter for the applicable material specification or PCD should be used when this level or higher change is incorporated. Current part producers will be notified of these changes and approval of the part producers obtained prior to incorporation. Part producer approval is only required for those users receiving material to the new revision of the material specification.

9.6.4 Level 3 Changes.

These are major changes that are subjected to a full equivalency test program, such as defined in DOT/FAA/AR-03/19. Level 3 major changes are those that have the possibility of changing

either the part processing characteristics or the cured lamina properties such that there is a shift away from the average values established for the material. The supplier or part producer should develop a test plan to prove the acceptability of the change. Some part producers may require additional tests beyond those given in DOT/FAA/AR-03/19 to address specific critical design issues.

Typical examples of level 3 changes to constituent materials are:

- Change in fiber manufacturing process
- Change in fiber size type, size level, finish, or coupling agents
- Change in resin chemical characteristics (e.g., alternate resin ingredient)
- Change in viscosity of major resin components
- Change in manufacturing site for fiber resin or preform
- Change in resin mixing, mixing equipment, process, and KPPs that change KCs or KPPs
- Change in viscosity due to change in raw materials or processing conditions
- Change in nominal number of fibers per tow (small difference of less than 200 fibers per tow)

Some examples of level 3 changes to cured part materials are:

- Change in resin mixing, mixing equipment, process, and KPPs that change KCs or KPPs
- Change in cure cycle (e.g., temperature, dwell time, and pressure)
- Change to or from closed mold from or to open mold process
- Change in preform (small)
- Change in amount of tackifier material (large)

Test that validate level 3 changes should involve a minimum of one batch of prepreg. The material batch acceptance tests and the EBE tests are the minimum recommended tests for demonstration of equivalency. In addition, any other critical properties that are expected to be affected by the change should be included in the test plan.

Using the values contained in the specification, the statistical procedures given in DOT/FAA/AR-03/19 can be used to verify that the data from the altered material is equivalent to the baseline database for the material. If equivalency to the original data cannot be confirmed, then the change will not be allowed, or a new material specification designation will be required for the altered material (see section 9.6.5).

A new revision letter for the applicable material specification or material acceptance document should be used when the change is incorporated. Current part producers will be notified of these changes and approval by the part producers obtained prior to incorporation. Part producer

approval is only required for those users receiving material to the new revision of the process specification.

9.6.5 Level 4 Changes.

Level 4 is a major change, where equivalency tests will not suffice for links to a previous material characterization. Level 4 changes require a new product identification (new specification designations) and a new qualification test program. Level 3 or lower material changes that fail to demonstrate equivalency will typically be considered level 4 changes. Some changes will be considered level 4 changes regardless of the results of the equivalency results, due to their significant potential effect on material properties or on part fabrication processing.

Typical examples of level 4 changes are:

- Change in resin or tackifier composition
- Change in nominal number of fibers per tow (e.g., 3K fibers per tow to 6K)
- Change in fiber areal weight (e.g., 145 to 190 gm/m^2) that changes cured ply thickness
- Change in fiber type (e.g., T300 to AS4)
- Change in fiber manufacturer (e.g., Toray to Amoco)
- Change in type of fabric weave (e.g., plain weave to eight harness satin)
- Change in preform (large), including fiber architecture, stitching, etc.

Because level 4 changes are considered a new material, existing part producers will not be affected unless they elect to purchase the new material. An part producer who wishes to use the new material must perform sufficient tests to qualify and certify the use of the material in the intended application.

10. PRODUCIBILITY VALIDATION GUIDELINES.

Certification and qualification test programs typically concentrate on the validation of mechanical properties and allowables. Of equal importance is the validation of processing parameters and part producibility. This section presents recommended producibility validation guidelines, which address verification of material attributes that affect producibility and qualification and verification of fabricator processes to ensure the part meets the expected properties.

10.1 PRODUCIBILITY QUALIFICATION TESTS.

An important element of the material qualification effort is the verification of the material's producibility. During the material qualification test program, thin, flat, constant-thickness test panels are used to develop material performance properties, i.e., strength and stiffness. It is the inherent characteristics, or attributes, of the fabrication materials (resin, fibers, tackifiers, etc.) that govern the material's producibility (e.g., viscosity, fiber sizing, and preform format).

In addition to validating the influence of material attributes, scale-up effects on producibility must also be addressed during the qualification process. The fabrication of constant thickness

flat panels does not fully demonstrate the material's ability (or inability) to be fabricated into large-scale production parts. These scale-up effects could include thickness changes, part area, internal ply drop-off features, and in the case of sandwich structure, core density, ramp angle, and surface characteristics. Due to their nature, the performance of mechanical property tests obtained from flat test panels does not assess the impact of processing scale-up effects. These effects can have a major impact on producibility of large-scale components and, thus, the structural performance of the component.

Panel designs need to discriminate these material attributes and their ability to minimize scale-up effects (robustness). This panel can then be fabricated as part of the qualification test program. The objective of the discriminator panel is to distinguish one material from another material by exposing their different producibilities. For instance, the extent to which reinforcement materials may be moved or washed by the resin is dependant on the resin properties, process conditions, and the forces holding each individual fiber/tow in place inside the tool (e.g., friction, binder, and stitching). A discriminator panel can assess if this is a problem and differentiate between conditions within the part.

Instead of fabricating a discriminator panel, an actual part can be fabricated to address processing attributes. A preform may be disassembled, sometimes referred to as a preform teardown, to verify the ply drop-offs, orientations, etc. This allows a direct evaluation of scale-up effects. The downside to using an actual part is that the performance of any evaluation is tied to tool availability. It is rare that a part is designed, and applicable tooling is available, when the material qualification program is being performed. Material selection decisions are typically made prior to the start of the design process.

Tests typically performed on the discriminator panel could include NDI and thickness, glass transition temperature, degree of cure, and mechanical property tests.

The discriminator panel can also be used in conjunction with test panels to assess the impact of processing or material changes. In cases where there is the need to assess a change in processing parameters, the discriminator panel often will be more discerning to the changes than mechanical properties from test panels. In this case, the discriminator panel should be of a similar level of complexity to the expected final parts (e.g., geometry changes and combinations of different preform materials).

10.2 FABRICATOR QUALIFICATION.

During many building block certification efforts, the initial fabrication of coupon test panels, elements, and components is performed at a different location or fabricator than the production components. This could result in material property values that are not representative of those produced by the full-scale production facility. It is recommended that the part fabricators, even if part of the same organization, also be qualified as part of the certification process. The fabricator qualification consists of three elements: (1) verification of coupon performance property equivalency, (2) verification of component structural equivalency, and (3) verification of engineering compliance. Each of these elements is discussed below.

10.2.1 Performance Property Equivalency.

Performance property equivalency is verified by the fabrication and testing of test panels. The purpose of this is to validate that their processes yield properties, which are from the same statistical population as the qualification and allowables data. The process of validating the material properties for an alternate process or facility is termed equivalency testing [4]. An audit to verify the compliance with the process specification requirements is also recommended as part of the fabricator qualification process.

10.2.2 Component Structural Equivalency.

Verification of component structural equivalency can only be accomplished by the destructive testing of a full-scale component. This is not the same as testing an element specimen or subcomponent. As a rule, the design of element and subcomponent specimens includes provisions for load introduction that would not be a part of the production design. In addition, the tooling concepts are not always identical between test parts and production parts. Therefore, it is necessary to destructively inspect a part fabricated with production tooling and processes.

The objectives for performing a destructive inspection on a part are to

- verify the performance properties established during coupon- and element-level testing (qualification and allowables) are the same in the component.
- quantify internal (hidden) defects or indications detected by NDI, i.e., validate NDI methods.
- validate panel physical properties (resin content and thickness).
- verify fiber path continuity within joints and complicated geometries (typically features that cannot be verified through a discriminator panel or by NDI).
- verify preform component assembly.

A typical geometric feature that can only be evaluated by a destructive inspection is a cored section. Inclusion of core materials frequently makes NDI difficult to interpret, and areas of poor adhesion between the core and the composite cannot be reliably identified. It is only through the fabrication of full-scale hardware with the actual production tooling that the strength of a cored section can be evaluated.

The fabrication of a destruct article provides a great opportunity to assess the impact of anticipated manufacturing defects on structural performance. Known defects can be placed within the destruct article during fabrication. NDI procedures can then be validated through the detection and identification of these known defects. Element test specimens can then be machined from the article such that the test section contains the known defects. The impact of the defect on structural performance can then be determined. Data of this nature is very valuable to the material review board disposition process. In some cases, the defect can be repaired prior to testing. Typical defects to include within the destruct article are:

- Microcracking
- Porosity or voids
- Resin fillets
- Wrinkles or ply waviness
- Tow angle variations (e.g., in wound/braided preforms)
- Thickness variation
- Tool mark off (resin ridge or surface wrinkle)
- Foreign inclusions

The destructive inspection process typically includes:

- Full dimensional inspection

- NDI

- Section cuts through defect areas indicted by the NDI, complex geometry and lay-up areas, and bonded or cocured joint regions.

- Photomicrographs of complex sections

- Fiber volume testing

- Removing coupons for mechanical property testing

Coupons typically include T_g, degree of cure as determined by DSC, resin content, short-beam strength, compression strength, open-hole tension or compression strength, and flexural strength. If possible, element or joint specimens should also be tested.

Prior to the performance of any mechanical property coupon or element tests, it is critical that the pass/fail criteria be established. These criteria must be tied to the analysis approach and allowables used to design the part and also must account for part configuration effects. Thought must be given to what action will be taken if the criteria are not met. Do not go into these tests without thinking through the benefits and consequences of these tests. Selection of which tests to perform is also a critical element of this process.

If other fabrication techniques, such as bonding or mechanical fastening, are used, they should also be verified. The development of requirements for those additional fabrication techniques is beyond the scope of this document but should be included in the destructive inspection process.

Destructive inspections should be performed on part families. A part family is a series of structures of a similar complexity shape and size, using the same tooling methodology, preforming, and infusion process. (For example, a left- and right-hand version of a control surface will belong to the same part family.) A destructive inspection is typically performed on one part that is representative of a given process, design, and tooling approach. The destructive inspection is repeated for each major change in tooling, design, alternate materials, fabricator location (or company), or process. A discriminator panel can be used to assess minor material

and process changes. The destructive inspection does not have to be performed on the first assembly (component) produced, but it should be performed such that the results are evaluated prior to the assembly of the component on the first aircraft.

10.2.3 Engineering Compliance.

The final step in the producibility validation process is to verify that the as-produced parts comply with engineering drawings and specifications. This can be accomplished through a first article inspection (FAI). The objective of the FAI is to verify that everything has come together (specifications, tooling, process instructions, process parameters, and design details) to produce a conforming part. The FAI is a physical examination of the part to verify engineering design (fit, form, and function, e.g., as-fabricated weight, finish, physical interfaces, and workmanship). This is normally accomplished by NDI in conjunction with an expanded dimensional inspection and a thorough audit of the fabrication records. The FAI should expand the types, number, and locations of physical measurements beyond those identified as KC. Each part type should go through the FAI process.

11. SUMMARY.

This document provides preliminary guidelines for a standard practice to control LRM composite systems in civil aviation applications. The preliminary guidelines are the result of lessons learned from current applications of LRM composite processes for large structural parts. The intent of this document is to promote a control protocol for this process, thus reducing variation in validation requirements and eventually leading to standard industrywide practices.

These preliminary guidelines review necessary requirements for all control aspects from procurement to processing of LRM composite structures. The guidelines describe the overall process of creating a part with an LRM system. The document then discusses the elements of the LRM system that different organizations may produce, therefore requiring multiple specifications and standards to ensure that the process is completely controlled. The major areas identified are:

- The procurement of individual components of an LRM composite system, resin components, and fabric
- Control of the mixing and molding process
- The fabricated part conformance to design requirements

These preliminary guidelines recommend development of KCs and KPPs to ensure control of undesired changes. It recommends overall control through a rigorous statistical process control scheme.

These guidelines provide information on LRM composite material control to those who may not have experience in composite processes. In the metallic materials community, these controls are provided by industry standards and not apparent to the individuals designing and fabricating with those materials. LRM fabrication is a new technology and even individuals familiar with

traditional composite materials must change their thinking to adequately control the LRM processes. The process is maturing, and more experience with the processes will give better insight on control. This document will be revised or superseded when warranted to provide more detail on control requirements for civilian applications. When designers and fabricators enter into LRM composites design, a source for material control techniques must be available; this document is a preliminary step toward that source of information.

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APPENDIX A—DEFINITION OF TERMS

This glossary is a compilation of terms with their definitions used within this report or of general interest. Definitions for this glossary were obtained from a variety of sources, which are noted at the end of the definition. Refer to MIL-HDBK-17 for a more complete listing of terms and their definitions.

A.1 GENERAL.

Autoclave, n—a closed vessel for conducting a chemical reaction or other operation under pressure and heat (Handbook of Composites).

B Stage, n—an intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells when in contact with certain liquids but does not entirely fuse or dissolve. Materials are usually procured to this stage to facilitate handling and processing prior to final cure. See also C Stage (MIL-HDBK-17).

Bag, v—the process of enclosing the ply layers within a flexible container. See also vacuum bag (ASTM D 5687).

Baseplate, n—a flat plate on which a laminate is laid up. See also mold (ASTM D 5687).

Bleeder, n—cloth that allows matrix to flow into it for the purpose of removing excess matrix from the laminate. Net resin prepreg systems do not require the use of bleeder materials (ASTM D 5687).

Braided fabric, n—a cloth constructed by a braiding process (ASTM D 3878).

Breather, n—cloth that allows even gas flow over the layup surface. The breather also helps minimize bag punctures by protecting the bag from sharp points (ASTM D 5687).

> Discussion: Typically within the bagging layup sequence, the breather material is a mixture of materials. The layer closest to the laminate is a lightweight glass fabric, such as Style 120, in order to minimize mark off on the laminate. The remaining layers are materials selected for their ability to transport gasses under pressure and elevated temperature. Typical materials are heavy-weight glasses such as Style 1000 or synthetic nonwoven materials.

Breather string, n—a glass string connected from the laminate to a breather in the bagging lay-up. It provides a path for gasses to be transferred from the laminate while minimizing matrix flow (ASTM D 5687).

Broadgoods, n—prepreg material (fabric or unidirectional) where the width is greater than 24 inches. See also tape.

C Stage, n—the final stage of the curing reaction of a thermosetting resin in which the material has become practically infusible and insoluble. See also B Stage (MIL-HDBK-17).

Caul plate, n—a flat plate used to provide a flat surface to the top of the laminate during laminate consolidation or cure (ASTM D 3878).

CFR—Code of Federal Regulations.

Cloth, n—a piece of textile fabric containing woven reinforcement without a load transferring matrix (ASTM D 5687).

Composite material, n—a substance consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents. Composites are subdivided into classes on the basis of the form of the structural constituents; Laminar: Composed of layer or laminar constituents; Particular: The dispersed phase consists of fibers; Flake: The dispersed phase consists of flat flakes; Skeletal: Composed of a continuous skeletal matrix filled by a second material (ASTM D 3878 and Handbook of Composites).

Consolidation, v—the process of forming individual plies into one solid composite laminate. For polymeric-based composite materials, consolidation is the compaction of the plies under pressure at elevated temperature until the polymer matrix material is cured.

Cure, v—to change the physical properties of a polymer by chemical reaction, which may be by condensation, polymerization, or vulcanization. This is usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure (ASTM D 907).

CPT—Cured ply thickness, n—the theoretical thickness of an individual ply, which is a function of the fiber areal weight, resin content, fiber density, and resin density.

Discussion: Cured per ply thickness is determined from the fiber areal weight, fiber volume, and fiber density:

$$CPT = \frac{FAW}{25400 \rho_f FV}$$

where

CPT	is theoretical cured ply thickness (inches)
FAW	is fiber areal weight (g/m^2)
25400	is a units conversion factor
ρ_f	is the fiber density (g/cc)
FV	is fiber volume (fraction, e.g., 0.61)

Cured per ply thickness can also be determined from the fiber areal weight, resin content, fiber density, and resin density:

$$CPT = \frac{FAW}{25400}\left[\frac{1}{\rho_f} + \frac{RC}{\rho_r(1-RC)}\right]$$

where

CPT	is theoretical cured ply thickness (inches)
FAW	is fiber areal weight (g/m^2)
25400	is a units conversion factor
ρ_f	is the fiber density (g/cc)
ρ_r	is the resin density (g/cc)
RC	is resin weight content (fraction, e.g., 0.33)

The actual cured ply thickness is determined by measuring the laminate thickness and dividing it by the number of plies (see SACMA SRM 10).

Fiber volume and resin content are related by the fiber and resin densities:

$$FV = \frac{1 - RC}{\rho_f}\left[\frac{1}{1 - RC/\rho_f + RC/\rho_r}\right]$$

where

FV	is fiber volume (fraction, e.g., 0.61)
ρ_f	is the fiber density (g/cc)
ρ_r	is the resin density (g/cc)
RC	is resin weight content (fraction, e.g., 0.33)

Dam, n—a solid material (such as silicone rubber, steel, or aluminum) used in the lay-up to contain the matrix material within defined boundaries during laminate consolidation (ASTM D 5687).

DAR—Designated Airworthiness Representative. FAA designees authorized to conduct conformity inspections on behalf of the FAA.

Darcy's Law—The most commonly used relationship to allow modeling of flow phenomena in LRM processes.

Discussion: LRM flow phenomenon are generally described in terms of Darcy Flow, i.e.,

$$\langle v \rangle = -\frac{K}{\mu}.\langle \nabla P \rangle$$

v	is the velocity vector
K	it's the permeability tensor and
μ	is the viscosity
$\langle \nabla P \rangle$	is the pressure gradient

The angular brackets indicate that this is the averaged measurement over the various flow scales present in the material.

Debulk, v—process of decreasing voids between lamina before laminate consolidation through the use of vacuum or by mechanical means. Lamina can be debulked at ambient or elevated temperature (ASTM D 5687).

Degree of cure (α), n—in thermoset polymers, the quantity of heat of reaction of the unreacted resin remaining after a reaction (cure cycle) compared to the total available quantity of heat of reaction expended by the complete reaction (cure) of a reacted resin.

Discussion: The degree of cure of a laminate can be obtained from differential scanning calorimetry (DSC) data. In order to obtain the degree of cure of a laminate, the baseline or total heat of reaction released by the complete curing of the resin (or prepreg) must first be obtained. This total heat of reaction is determined from the DSC curve. It is important to obtain the total heat of reaction from a sample that is of the same resin content as the laminate in question. This is typically accomplished by testing a sample of the prepreg used to fabricate the laminate. The laminate in question is then tested to determine the partial heat of reaction. The DSC heating rate used to determine the baseline heat of reaction and partial heat of reaction must be the same. Typically, a heating rate of 10°C per minute is used. The degree of cure is calculated as follows:

$$\alpha = 100 - \left(\frac{\Delta H_P}{\Delta H_T} \times 100 \right)$$

where

α is the percent degree of cure (ranges from 0% to 100% with 100% being fully cured)

ΔH_P is the heat of reaction released by the partially cured sample (laminate in question) expressed in Joules

ΔH_T is the total heat of reaction released by the uncured resin expressed in Joules (baseline)

Resin formulations commonly used in the aerospace industry rarely reach a degree of cure of 100%. Values of 95% to 98% are common. It should be noted that determining degree of cure by DSC is not considered the most repeatable test and is best limited to research investigations and not used as a production test. Depending on the circumstances, measurement of the glass transition temperature may be the best method to determine if a laminate is fully cured.

DER—Designated Engineering Representative. FAA designees authorized to approve engineering data.

DSC—differential scanning calorimetry, n—a technique in which the temperature difference between the substance and a reference material is measured as a function of temperature while the substance and reference material are subjected to a controlled temperature program (ASTM E 473).

DMIR—Designated Manufacturing Inspection Representative. FAA designees authorized to conduct conformity inspections on behalf of the FAA.

End, n—in fabric, an individual warp yarn (single or ply) or cord (ASTM D 123).

ETD—Elevated Temperature Dry.

ETW—Elevated Temperature Wet.

FAA—Federal Aviation Administration.

fabric, n—in textiles, a planar structure consisting of yarns or fibers (ASTM D 123).

FEP, n—fluorinated ethylenepropylene.

> Discussion: fluorinated ethylenepropylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® FEP.

Fiber, n—in textiles, a generic term for any one of the various types of matter that form the basic elements of a textile and that is characterized by having a length at least 100 times its diameter (ASTM D 123).

FAW—Fiber areal weight, n—the weight per area of the fiber reinforcement within a composite, expressed as grams per square meter or ounces per square yard. See also prepreg areal weight.

Fiber content, n—the amount of fiber present in a composite expressed either as a percent by weight or percent by volume. This is sometimes stated as a fraction, that is, fiber volume fraction (ASTM D 3878).

Fiber volume fraction (FV or V_f), n—see fiber content (ASTM D 3878).

Filament, n—a fibrous form of matter with an aspect ratio >10 and an effective diameter <1 mm (ASTM D 3878).

Fill, n—in a woven fabric, (1) the yarn running from selvage to selvage at right angles to the warp and (2) fiber inserted by the shuttle during weaving also designated as filling (ASTM D 3878, MIL-HDBK-17, and ASTM D 5687).

Fill surface, n—in a woven fabric where each fill yarn crosses over more than one warp yarn, the ply surface that shows the larger area of fill tows with respect to warp tows.

Flip/flop, v—the process of alternating plies through an angle orientation of 180° during laminate lay-up. This practice is commonly used if the material of the same width as the laminate has a recurring flaw. The process changes the location of the flaw so that it does not unduly affect the laminate structure (ASTM D 5687).

Gate, n—point on the tool where resin is introduced.

Gallery, n—a cavity within the tool or bag intended to distribute resin.

Glass transition, n—the reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one (MIL-HDBK-17).

> Discussion: The glass transition generally occurs over a relatively narrow temperature region and is similar to the solidification of a liquid to a glassy state; it is not a phase transition. Not only do hardness and brittleness undergo rapid changes in this temperature region but other properties, such as thermal expansibility and specific heat, also change rapidly. This phenomenon has been called second order transition, rubber transition, and rubbery transition. The word transformation has also been used instead of transition. Where more than one amorphous transition occurs in a polymer, the one associated with segmental motions of the polymer backbone chain or accompanied by the largest change in properties is usually considered to be the glass transition (ASTM D 883).

Glass transition temperature (T_g), n—the approximate onset or midpoint of the temperature range over which the glass transition takes place (MIL-HDBK-17).

> Discussion: The glass transition temperature can be determined readily only by observing the temperature at which a significant change takes place in a specific electrical, mechanical, or other physical property. Moreover, the observed temperature can vary significantly, depending on the specific property chosen for observation and on details of the experimental technique (for example, rate of heating and frequency). Three common methods for determining T_g are Thermal Mechanical Analysis, Differential Scanning Calorimetry, or Dynamic Mechanical Analysis.

Injection, n—introduction of resin into the mold cavity under applied pressure.

Knit, v—a textile process that interlocks, in a specific pattern loop, by means of needles or wires (ASTM D 3878).

Knitted fabric, n—a cloth constructed by a knitting process (ASTM D 3878).

Lamina, n—a subunit of a laminate consisting of one or more adjacent plies of the same material with identical orientation (ASTM D 3878).

Laminate, n—any fiber or fabric-reinforced composite consisting of lamina (plies) with one or more orientations with respect to some reference direction (ASTM D 3878).

Lamination, v—see consolidation.

Laminate coordinate axes, n—a set of coordinate axes, usually right-handed Cartesian, used as a reference in describing the directional properties and geometrical structure of the laminate. Usually the x-axis and the y-axis lie in the plane of the laminate, and the x-axis is the reference axis from which ply angle is measured (ASTM D 3878).

Laminate principal axis, n—the laminate coordinate axis that coincides with the direction of maximum in plane Young's modulus (ASTM D 3878).

Lay-up, n—(1) the stack of plies in specified sequence and orientation before infusion, cure or consolidation; (2) the complete stack of plies, bagging material, and so on before cure or consolidation; and (3) a description of the component materials, geometry, etc., of a laminate (ASTM D 3878).

Lay up, v—to stack plies of material in specified sequence and orientation (ASTM D 3878).

Lay-up code, n—a designation system for abbreviating the stacking sequence of laminated composites (ASTM D 3878).

LRM—Liquid Resin Molding. Any process in which liquid resin is mechanically introduced to a preshaped reinforcement.

Mandrel, n—a form, fixture, or male mold used as the base for production of a part in processes such as lay-up or filament winding (ASTM D 3878).

Material form, n—the contour, arrangement, and structure of an unconsolidated composite material, especially with regard to the geometry and nature of the reinforcement. Factors considered part of the material form include, but are not limited to, reinforcement length (for discontinuous reinforcements), tow size or count, fabric areal weight, fabric style, reinforcement content, and ply thickness (ASTM D 3878).

Matrix, n—the continuous constituent of a composite material, which surrounds or engulfs embedded filler or reinforcement (ASTM D 3878).

Matrix content, n—the amount of matrix present in a composite expressed either as a percent by weight or percent by volume. Standard practice is to specify matrix content as weight percent (ASTM D 3878).

MIDO—Manufacturing Inspection District Office for the FAA.

MOL—Material Operational Limit.

Mold, n—the support structure that holds the laminate or lay-up during laminate consolidation process (ASTM D 5687).

MRB—Material Review Board.

NIST—National Institute of Standards and Technology.

NDI—nondestructive inspection, v—to identify and measure abnormal conditions within a laminate without degrading or impairing the utility of the material.

Nonperforated FEP, n—a nonporous fluorinated ethylenepropylene film used as a release film in the bagging lay-up.

Discussion: Fluorinated ethylenepropylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® FEP.

Nonperforated TFE, n—a nonporous tetrafluoroethylene film used as a release film in the bagging lay-up (ASTM D 5687).

Discussion: Tetrafluoroethylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® TFE.

Nonporous TFE-coated cloth, n—a cloth coated with tetrafluoroethylene used as a release material in the bagging process (ASTM D 5687).

Nonwoven fabric, n—a cloth constructed by bonding or interlocking, or both (but not interlacing), fiber by any combination of mechanical, chemical, thermal, or solvent means (ASTM D 3878).

O-ring, n—a continuous circular seal used to contain the resin within the injection system/tool.

Packing pressure, n—the pressure applied in resin transfer molding (RTM) after the end of injection during the cure process. (also consolidation pressure)

Panel, n—a uniformly contoured composite laminate, typically flat (ASTM D 5687).

Peel ply—a cloth material that does not contain transferable chemical release agents and is designed for cocure with the surface ply of a laminate. It is generally used for the purpose of protecting a bonding surface. It is intended to be completely removed from the laminate by peeling immediately prior to a subsequent bonding operation. Removal can be difficult, but the result is a clean and highly textured resin fracture surface. It may undergo treatment (e.g., mechanical calendaring), but not with release chemicals. This surface is typically suitable for structural adhesive bonding.

Perforated FEP, n—a porous fluorinated ethylenepropylene film used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation while protecting the laminate from physical bonding to other items such as caul plates.

Perforated TFE, n—a porous tetrafluoroethylene film used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation while protecting the laminate from physical bonding to other items such as caul plates (ASTM D 5687).

Permeability, n—a measure of the ratio of apparent flow velocity to pressure gradient for a reinforcement material. In effect, a measure of how easily a resin can flow through a porous reinforcement.

Plied yarn, n—a yarn formed by twisting together two or more single yarns in one operation (ASTM D 3878).

Ply, n—in laminar composites, the constituent single layer used in fabricating or occurring within a composite structure (ASTM D 3878).

Ply coordinate axes, n—a set of Cartesian coordinates, two of which lie within the plane of the ply, one axis of which is parallel to the principal fiber direction, and the other axis perpendicular to the principal fiber direction (the third axis is through the ply's thickness) (ASTM D 3878).

Ply count, n—in laminated composite materials, the number of plies or lamina used to construct the composite (ASTM D 3878).

Ply orientation, n—the acute angle (theta) including 90° between a reference direction and the ply principal axis. The ply orientation is positive if measured counterclockwise from the reference direction and negative if measured clockwise (ASTM D 3878).

Ply principal axis, n—the ply coordinate axis that coincides with the direction of maximum in plane Young's modulus. For balance weave fabric, either warp or fill direction may be chosen (ASTM D 3878).

Polymer, n—an organic material composed of molecules characterized by the repetition of one or more types of monomeric units (MIL-HDBK-17).

Polymerization, n—a chemical reaction in which the molecules of a monomer(s) are linked together in repeating units to form larger molecules (ASTM D 907).

Porosity, n—a condition of trapped pockets of air, gas, or vacuum within a solid material, usually expressed as a percentage of the total nonsolid volume to the total volume (solid plus nonsolid) of a unit quantity of material (MIL-HDBK-17).

Porous TFE-coated cloth, n—a porous cloth coated with tetrafluoroethylene used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation. It differs from perforated TFE in that it gives a textured surface to the laminate (ASTM D 5687).

Prepreg, n—a ready to mold or cure fibrous reinforcement impregnated with a polymeric matrix. Its form may be sheet, tape, or tow. For thermosetting matrices, it has been partially cured to a controlled viscosity called B stage (ASTM D 3878 and MIL-HDBK-17).

PAW—prepreg areal weight, n—the weight per area of the prepreg composite material, expressed as pounds per square foot or the inverse square feet per pound. Used as a conversion factor to convert prepreg area to prepreg weight. See also fiber areal weight.

Discussion: Prepreg areal weight is a function of resin content and fiber areal weight:

$$PAW = \frac{FAW}{1 - RC}$$

Where:

PAW is prepreg areal weight (g/m^2)
FAW is fiber areal weight (g/m^2)
RC is resin weight content (fraction, e.g., 0.33)

To convert g/m^2 to lb/ft^2 multiply by 204.81×10^{-6}.

Pressure pot, n—a form of a resin infection machine in which the resin reservoir is pressurized, forcing the resin into the mold.

Prolong, n—a deliberate extension of the part designed to yield material for quality assurance/control.

Pump, n—a form of a resin injection machine in which the resin is transferred mechanically into the mold, e.g., reciprocation pump, piston pump, gear pump, etc.

Reinforcement, n—in a composite material, the discrete constituent of a composite material, either fiber or particle, which is contained within the continuous matrix (ASTM D 3878).

Resin, n—a solid or pseudo solid organic material, often of high molecular weight, which exhibits a tendency to flow when subjected to stress, usually has a high softening or melting range, and usually fractures conchoidally (ASTM D 3878).

RC resin content, n—see matrix content (ASTM D 3878).

Reservoir, n—the vessel in which the resin supply is contained during processing.

Reservoir temperature, n—the measured temperature of the resin in the reservoir.

RTM—Resin Transfer Molding. a closed mold process in which resin is forced under pressure into a closed mold containing reinforcement materials.

Release fabric—A cloth material that contains transferable chemical release agents and is designed for cocure with the surface ply of a laminate. It is generally used for the purpose of allowing the laminate to be more easily removed from the tooling. It is intended to be completely and easily removed from the laminate by peeling. It leaves an unfractured, relatively smooth surface impression and a chemical residue on the laminate. This surface is typically unsuitable for structural adhesive bonding.

Release film—a sheet of film designed for cocure with the surface ply of a laminate. It is generally used for the purpose of allowing the laminate to be more easily removed from the tooling. The film material is generally a derivative of polytetrafluoroethylene, PTFE (Teflon). It is intended to be completely and easily removed from the laminate by peeling. It leaves a smooth surface finish with minimal impression and a chemical residue on the laminate. This surface is typically unsuitable for structural adhesive bonding.

Sealant, n—a high-temperature material used to seal the edges of a vacuum bag to a base plate during consolidation (ASTM D 5687).

Selvage, n—the woven edge portion of a fabric parallel to the warp (ASTM D 3878).

Single yarn, n—an end in which each filament follows the same twist (ASTM D 3878).

Stacking sequence, n—the arrangement of ply orientations and material components in a laminate specified with respect to some reference direction (ASTM D 3878).

Staggered, adj—the description of ply placement where the joints are not positioned in the same in-plane location through some specified thickness of the laminate (ASTM D 5687).

Stitching, verb—the act of combining fabrics/textiles by joining together with a separate stitching thread using one or more needles.

Tape, n—prepreg material (typically unidirectional material) equal to or less than 24 inches in width. Also see broadgoods.

Textile, n—a general term applied to fibers and organized assemblies of fibers with sufficient integrity to retain the organization (ASTM D 3878).

Thermoplastic, n—a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and in the softened state, can be shaped by flow into articles by molding or extrusion for example (ASTM D 883).

Thermoset, n—a class of polymers that, when cured using heat, chemical, or other means, changes into a substantially infusible and insoluble material (ASTM D 3878).

Tow, n—in fibrous composites, a continuous, ordered assembly of essentially parallel, collimated filaments, normally without twist and of continuous filaments (ASTM D 3878).

Tracer yarn, n—in a woven fabric, a yarn woven into the fabric for the purpose of tracing the direction of the warp and fill fibers or tows.

Traveler, n—a coupon with the same nominal thickness, and preferably width, as the test specimen made of the same material, and processed similarly to the specimen except usually without tabs or gages. The traveler is used to measure mass changes during environmental conditioning when it is impractical to measure these changes on the actual specimen (ASTM D 5687).

Traveler panel, n—(a.k.a. witness panel) a panel that is subjected to the same conditions as a part or group of parts to allow destructive tests to verify processing.

Unidirectional, n—any fiber-reinforced composite with all the fibers aligned in a single direction. Both prepreg material and consolidated laminates can be described as being unidirectional.

Vacuum bag, n—a low gas permeable material used to enclose and seal the lay-up during a consolidation or debulking cycle (ASTM D 5687).

Vacuum couple, n—the mechanical connection that seals the vacuum source to the lay-up during a consolidation or debulking cycle (ASTM D 5687).

VARTM—vacuum assisted resin transfer molding. An RTM process in which vacuum is used to draw resin into a tool cavity or vacuum bag.

Viscosity, n—is a measure of the resistance of a liquid to shear forces (see also permeability).

Vitrification, n—the point during polymerization where the T_g of the polymer rises above the temperature of cure.

Void, n—any pocket of enclosed gas or air within a composite (ASTM D 3878).

Void content, n—the volume percentage of voids in a composite (ASTM D 3878).

Warp, n—(1) the yarn running lengthwise in a woven fabric; (2) a group of yarns in long lengths and approximately parallel, put on beams or warp reels for further textile processing including weaving, knitting, twisting, dyeing, and so forth (ASTM D 3878).

Warp surface, n—in a woven fabric, where each warp yarn crosses over more than one fill yarn, the ply surface that shows the larger area of warp tows with respect to fill tows (ASTM D 3878).

Warp surface nesting, v—process of laying up fabric plies in an alternating pattern where the warp surface is placed up, and then for the next ply, the warp surface is placed down, thus nesting the plies.

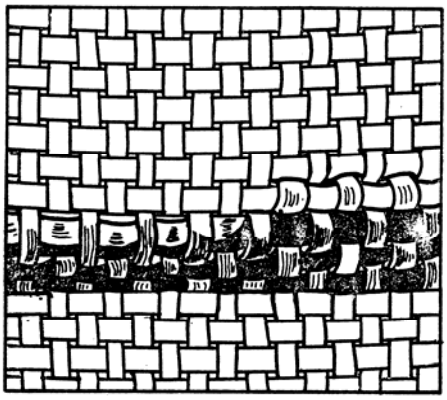
Weave, v—interlaces, in a specific pattern, strands or yarns orientated in two or more directions in a planar textile process (ASTM D 3878).

Woven fabric, n—a cloth constructed by a weaving process (ASTM D 3878).

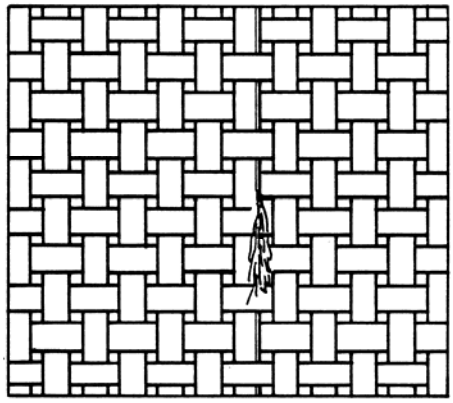
Yarn, n—in fibrous composites, a continuous, ordered assembly of essentially parallel, collimated filaments, normally with twist, and either discontinuous or continuous filaments (ASTM D 3878).

A.2 FABRIC DEFECT DEFINITIONS.

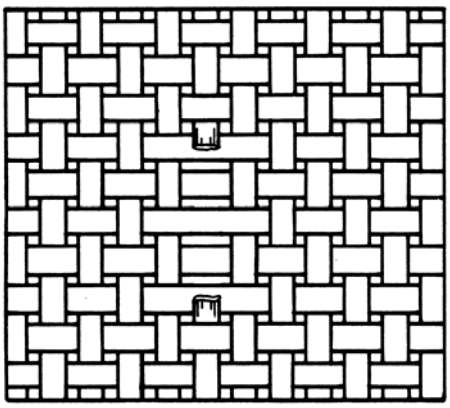
Baggy cloth, n—in a woven fabric, a cloth that will not lie flat on a cutting table (also, crooked cloth, ridgy cloth, wavy cloth).



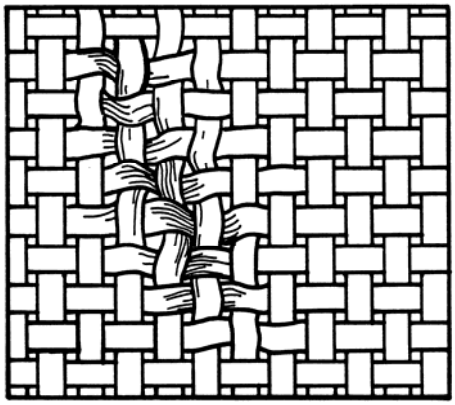
Broken tracer yarn, n—in a woven fabric, a damaged tracer yarn.



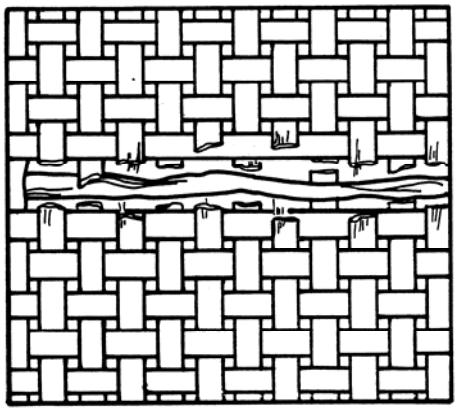
Broken warp or fill, n—in a woven fabric, a single warp fill tow, or yarn that has been severed or broken (also, broken pick, cut pick).



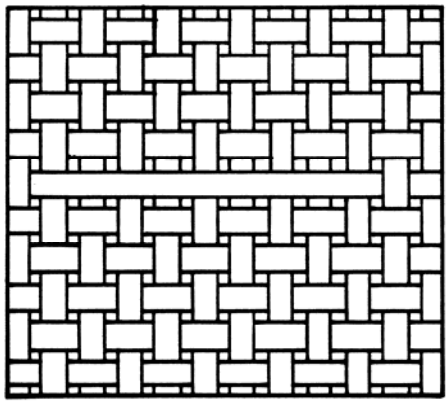
Crease or wrinkle, n—in a woven fabric, a break or line in a fabric usually caused by a sharp fold (also, mill wrinkle, wrinkle mark).



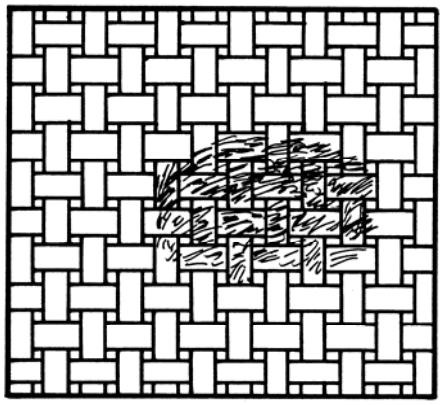
Cut or tear, n—in a woven fabric, adjacent yarns or tows that have been cut or broken.



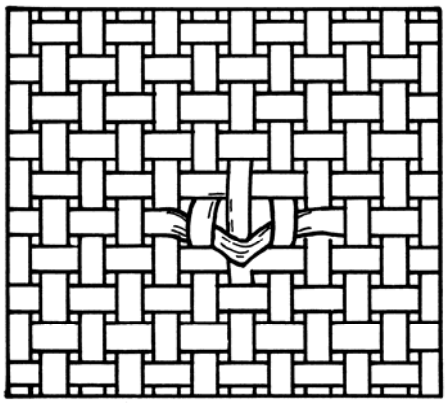
Float, n—in a woven fabric, a place in the fabric where a warp or filling yarn or tow extends unbound over the yarns or tows that should be interlaced (also, harness skip, overshot, skip).



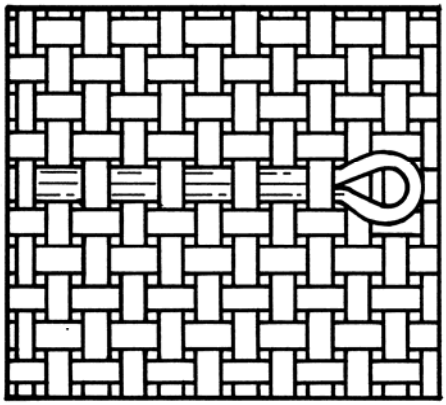
Fuzzball (also fuzz ball), n—in a woven fabric, loose or frayed fibers that have formed into a ball and are entwined either within the fabric or on the surface (also balling up, lint ball, snowball).



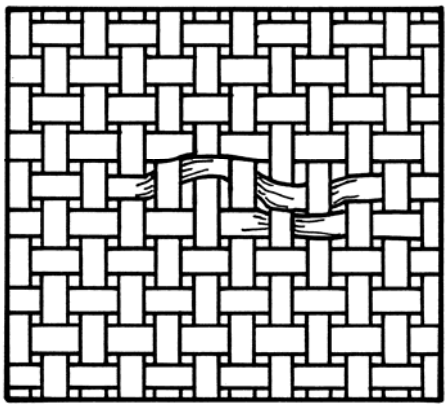
Hang pick, n—in a woven fabric, a pick (fill yarn) caught on a warp yarn producing a triangular-shaped hole in the fabric (also, hung filling yarn, hang shot).



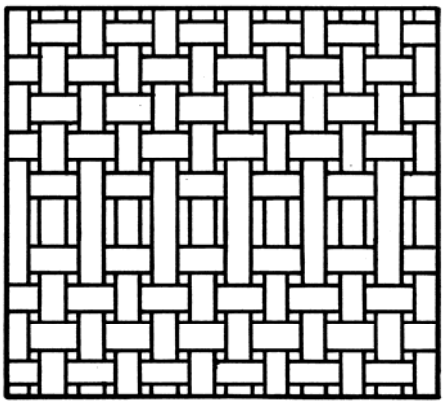
Kink, n—in a woven fabric, a yarn that has doubled back on itself to form a loop in the yarn (also, center loop, curl, snarl, kinky thread, looped yarn).



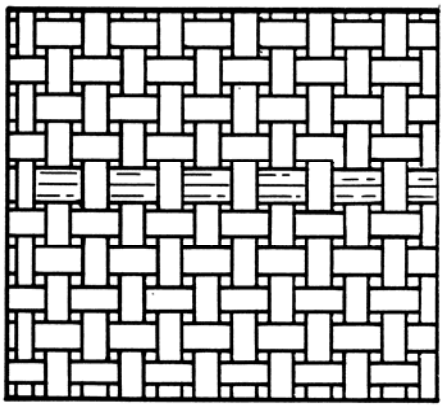
Loose pick, n—in a woven fabric, a filling yarn that is not flush with the surrounding fabric usually caused by insufficient tension (also, loose filling yarn, slack pick, slack filling).



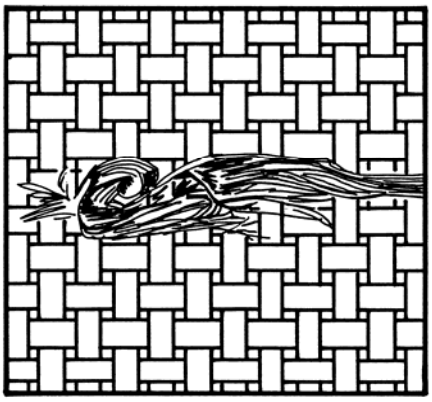
Missing pick, n—in a woven fabric, a filling yarn or tow missing from all or a portion of the width of the fabric (also, missing filling yarn, filling run out).



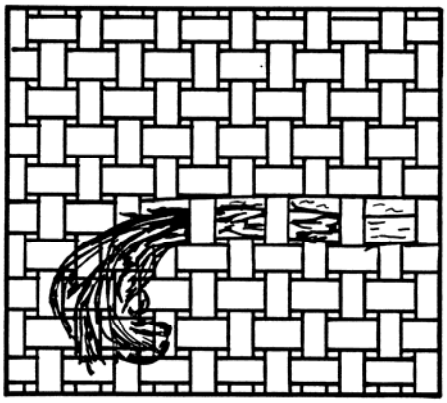
Mispick, n—in a woven fabric, a pick that is not properly interlaced, which causes a break in the weave pattern (also, wrong pick).



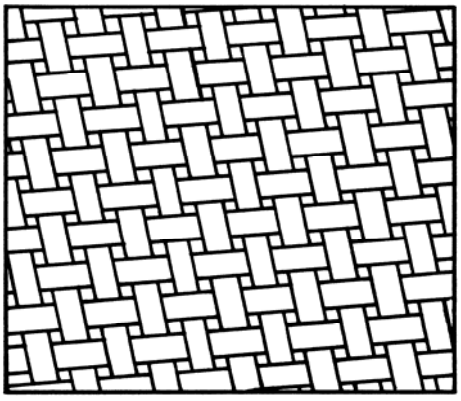
NEP, n—in a woven fabric, one or more fibers occurring in a tangled and unorganized mass (also, bird's nest, fly waste).



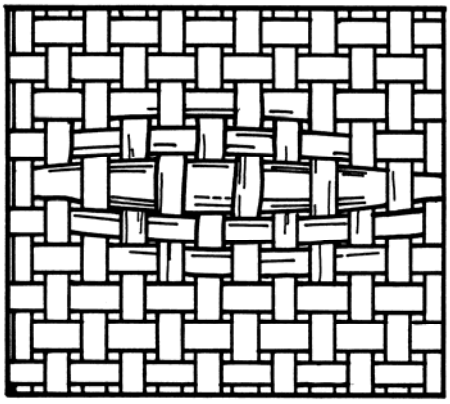
Pulled-in filling, n—in a woven fabric, an extra filling yarn or tow dragged into the fabric along with a regular filling yarn or tow (also, double pick, dragged-in, jerked-in, lashed-in, whipped-in).



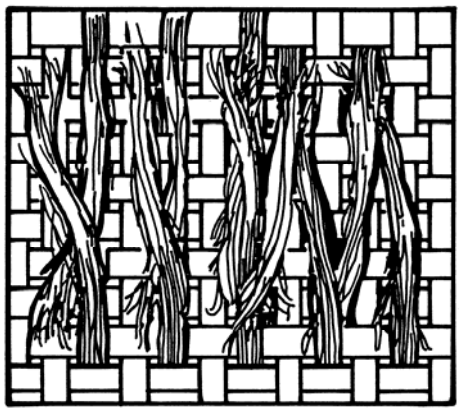
Skewing, n—in a woven fabric, a condition where the warp and fill yarns or tows are not at right angles to each other (also, bias filling).



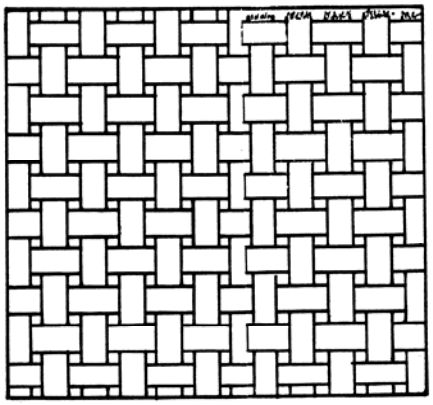
Slub, n—in a woven fabric, an abruptly thickened place in the yarn or tow (also, slug, bunch, lump, piece, slough off).



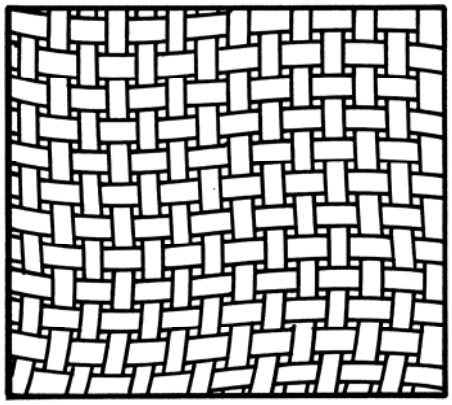
Smash, n—in a woven fabric, a place in the fabric where a number of warp or fill yarns or tows have been broken (also, breakout, slam-off).



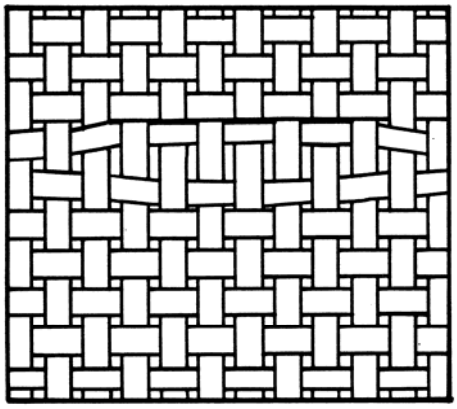
Splice, n—in a woven fabric, a portion of the fabric that has been cut and rejoined.



Waviness, n—in a woven fabric, a condition where the warp, fill yarns, or tows are in a sinusoidal or wave pattern (weave distortion).



Weave separation, n—in a woven fabric, an opening between yarns or tows due to improper yarn or tow alignment (also, crack, broken weave, open place, thin spot, shier).



Yarn splice, n—in a woven fabric, a yarn or tow that has been cut or broken and subsequently overlap spliced (also, tow splice).