DOT/FAA/TC-25/44

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Guidelines for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Oxide/Oxide Ceramic Matrix Composites

September 2026

Final report



U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-25/44		

4. Title and Subtitle	5. Report Date
Guidelines for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Oxide/Oxide Ceramic Matrix Composites	September 2026
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Allison L. Horner, Rachael M. Andrulonis, Matthew S. Opliger, and John S. 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 Office of Aviation Research Washington, DC 20591	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report establishes recommendations to guide the development of process specifications for continuous fiber-reinforced woven fabric oxide/oxide (ox/ox) ceramic matrix composite (CMC) prepreg and an approach for the validation of ox/ox CMC fabrication processes used during the certification of composite aircraft structure. This report is intended to advance the work that has been done through previous Federal Aviation Administration (FAA) programs that have established a methodology for developing and standardizing statistically-based databases for polymer matrix composite (PMC) materials. This and other reports extend the qualification framework to ox/ox CMC materials. This report is categorically similar to guidelines provided for the development of process specifications for PMC materials in DOT/FAA/AR-02/110 but has been revised to reflect unique requirements necessary for ox/ox CMCs.

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 ox/ox CMC process specifications. The framework for development of ox/ox CMCs process specifications is still being studied, and it is anticipated that revisions to strengthen or adjust the recommendations provided herein will be available in the future. This research report provides the current recommendations for ox/ox CMCs process specifications until and unless additional research or experience that points towards alternative guidelines is developed. This report can also be used to develop common industry specifications. This report is limited to recommendations for the development of process specifications. Additional guidelines on the development of material specifications can be found in the companion report *Guidelines and Recommended Criteria for the Development of a Material Specification for Oxide/Oxide Ceramic Matrix Composite Prepregs*, DOT/FAA/AR-25/45. Additional guidelines on performing an ox/ox CMC material qualification or equivalency can be found in DOT/FAA/TC-25/27, *Material Qualification and Equivalency for Oxide/Oxide Ceramic Matrix Composite Material Systems*.

17. Key Words	18. Distribution Statement
Material specification Certification Qualification	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	37	

Contents

1 Introduction 1

1.1 Objective 1

1.2 Background 2

1.3 Scope 3

1.4 Recommended specification format 4

2 Sections of process specifications 5

2.1 Scope section 6

2.1.1 Purpose 6

2.1.2 Health and safety 6

2.2 Applicable documents section 6

2.2.1 References 6

2.2.2 Guidelines and guidance documents 7

2.3 Personnel section 7

2.4 Materials section 8

2.5 Equipment description section 10

2.6 Facility description section 11

2.7 Tooling section 13

2.8 Laminate fabrication section 15

2.8.1 Prepreg cutting 15

2.8.2 Layup and bagging 15

2.8.3 Baseline consolidation cycle 16

2.8.4 Baseline sinter cycle 17

2.8.5 Alternative consolidation or sinter cycle 17

2.8.6 Identification 18

2.8.7 Machining 18

2.8.8 Heat cleaning 19

2.9 Quality assurance section 19
2.9.1 Intermediate inspection 19
2.9.2 Final inspections 20
2.9.3 Process monitoring 21
2.9.4 Documentation 22
2.10 Shipping section 22
2.11 Notes section 22
2.12 Revisions section 22
3 Producibility validation guidelines 23
3.1 Producibility qualification tests 23
3.2 Fabricator qualification 24
3.2.1 Performance property equivalency 25
3.2.2 Component structural equivalency 25
3.2.3 Engineering compliance 27
4 Conclusions 28
5 References 28

Figures

Figure 1: Definitions of Storage Life, Work Life, Staging Life, and Mechanical Life from CMH-17 VOL 3 10

Acronyms

Acronym	Definition
CMC	Ceramic Matrix Composite
CT	Computed Tomography
FAA	Federal Aviation Administration
FAI	First Article Inspection
IR	Infrared
NDI	Non-Destructive Inspection
Ox/ox	Oxide/oxide
PMC	Polymer Matrix Composite
TGA	Thermo-Gravimetric Analysis
XRD	X-Ray Diffraction

Executive summary

This research report provides a set of guidelines for developing process specifications for the fabrication of continuous fiber-reinforced woven fabric oxide/oxide (ox/ox) ceramic matrix composite (CMC) laminate parts or test panels used in the generation of mechanical properties. It also provides an approach for the validation of ox/ox CMC fabrication processes used during the certification of composite aircraft structure. Guidelines are provided based on processes and sound engineering practices currently used within industries such as aerospace. This report is intended to advance the work done through previous Federal Aviation Administration (FAA) programs that have established a methodology for developing and standardizing statistically-based databases for polymer matrix composite (PMC) materials. This and other reports extend the qualification framework to ox/ox CMC materials. The framework for development of ox/ox CMC process specifications is still being studied, and it is anticipated that revisions to strengthen or adjust the recommendations provided herein will be available in the future.

This research also provides current recommendations for ox/ox CMC process specifications until and unless additional research or experience that points towards alternative guidelines is developed. It can also be used to develop common industry specifications and complements the recommendations and guidelines for ox/ox CMC prepreg material specifications found in DOT/FAA/TC-25/45, *Guidelines and Recommended Criteria for the Development of a Material Specification for Oxide/Oxide Ceramic Matrix Composite Prepregs*, and in DOT/FAA/TC-25/27, *Material Qualification and Equivalency for Oxide/Oxide Ceramic Matrix Composite Material Systems*.

1 Introduction

1.1 Objective

This research report provides a set of guidelines for developing process specifications for the fabrication of woven fabric oxide/oxide (ox/ox) ceramic matrix composite (CMC) laminate parts or test panels used in the generation of mechanical properties. It also provides an approach for the validation of fabrication processes used during the certification of ox/ox CMC composite structure such as aircraft structure. These guidelines were prepared by a team of experts that have extensive experience in processing ox/ox CMC materials, qualification program management, generating material specifications, and material allowables development. Guidelines are given based on processes and sound engineering practices currently used within industries such as aerospace. However, the framework for ox/ox CMC process specification development is still an active area of research, and it is anticipated that revisions to strengthen or adjust the recommendations provided herein will be available in the future.

This research provides current recommendations for process specification development for ox/ox CMCs until and unless additional research or experience that points towards alternative guidelines is developed. It is intended to advance the work that has been done through previous Federal Aviation Administration (FAA) programs that have established a methodology for developing and standardizing statistically-based databases for continuous fiber-reinforced polymer matrix composite (PMC) materials. This and other reports extend the qualification framework to ox/ox CMC materials.

The guidelines found in this report should not be viewed as policy or as the single acceptable method for ox/ox CMC composite laminate fabrication process control. They are meant to be a documentation of current knowledge and application of sound engineering principles to the ox/ox CMC laminate fabrication process. The recommendations in these guidelines are in agreement with the guidance provided in AC 20-107B on Composite Aircraft Structure (FAA, 2010).

It is envisioned that these guidelines would be used to develop:

- process specifications,
- work instructions (planning),
- sections within material specifications, and

- sections within certification and qualification test plans.

An important theme found within these guidelines is the significance of clearly documenting the procedures used to fabricate laminates. The ability to consistently repeat the fabrication process at a later date is necessary to minimize the variability in ox/ox CMC material test data and production panels and parts. This can only be accomplished if the fabrication instructions are accurately documented.

This report can also be used to develop an industry approach so the following goals can be achieved:

- Greatly reduce the number of material and process specifications for identical ox/ox CMC material systems.
- Develop property databases that uniquely define a given material.
- Establish material batch testing and process monitoring sufficient to minimize variability and preclude property changes over time.
- Reduce costs through common documentation and shared databases of basic material properties.

This report complements the recommendations and guidelines for ox/ox CMC prepreg material specifications found in DOT/FAA/TC-25/44, *Guidelines and Recommended Criteria for the Development of a Material Specification for Oxide/Oxide Ceramic Matrix Composite Prepregs* (Horner, Andrulonis, Opliger, & Tomblin, 2026a), and DOT/FAA/TC-25/27, *Material Qualification and Equivalency for Oxide/Oxide Ceramic Matrix Composite Material Systems* (Horner, Andrulonis, Opliger, & Tomblin, 2026b).

1.2 Background

The use of continuous fiber-reinforced prepreg thermoset PMCs has been prevalent in multiple industries, including both commercial and general aviation, for several decades. Their use extends from small, non-structural components to significant primary and secondary structures including entire fuselages. The certification process for these materials is relatively mature, including standardized processes to enforce quality control and quality assurance, and methods to guarantee a safe and consistent material supply. In contrast, ox/ox CMC materials are a relatively new technology in civil aircraft that are currently only being used in aircraft products such as engine parts. A limited number of ox/ox CMC parts have been certified for specific

applications, but the overall certification framework for ox/ox CMCs, and CMCs in general, is not sufficiently defined.

The material properties of an ox/ox CMC are manufactured into the structure as part of the fabrication process. Therefore, it is essential that the material and process specifications used to procure material and produce ox/ox CMC parts contain sufficient information to ensure that critical parameters in the fabrication process are controlled to facilitate adherence to standards in the final engineered part. Due to the variety of ox/ox CMC aircraft parts now emerging for certification (currently including engine exhaust nozzles, mixers, cones, combustor liners, and duct components), control of the materials is a vital issue with respect to the overall assurance of safety.

In recent years, the aerospace industry and the FAA have worked together to develop a cost-effective method of qualifying composite material systems by sharing material qualification databases such as CMH-17. By using shared databases, a manufacturer can select an approved composite material system to fabricate parts and validate with a smaller subset of testing 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 material characteristics (physical properties and other material characteristics) and be processed in accordance with a process specification that controls key process characteristics (processing parameters). The material qualification framework that has been established for continuous fiber-reinforced prepreg thermoset PMCs is now being extended to other materials such as thermoplastic matrix PMCs and PMCs processed via resin infusion, as well as for CMCs such as ox/ox CMCs.

1.3 Scope

This report covers recommendations for process specifications controlling the manufacture of parts and panels produced from ox/ox sol-gel prepreg systems with woven fabric material forms. Guidelines for the production of parts or panels is limited to those manufactured via vacuum bagging, autoclave curing, and free-standing, elevated temperature sintering in an air atmosphere. However, the methodology described in this plan is likely applicable to broader usage for other CMC materials, material forms, or processing techniques if assessed as being appropriate by engineering judgement and acceptable from the governing regulatory body.

At the time of publication of this report, unidirectional tape material forms of ox/ox CMC composites are significantly less common than woven fabric forms. Further, depending on the material constituents of the ox/ox CMC, the fully unidirectional layup necessary for obtaining

lamina properties for a tape material may produce unacceptably brittle panels that fail prematurely due to matrix cracking. For these reasons, the recommendations in this report are not written with unidirectional tape material forms in mind. Although many of the guidelines may be applicable to the development of process specifications for ox/ox CMCs with unidirectional tape material forms, that has yet to be validated.

This report also documents an approach for the validation of fabrication processes used during the certification of ox/ox CMC composite structure such as aircraft structure. However, the guidelines and recommendations presented herein are purposely written broadly, since the requirements for certification of aircraft structure can vary from application to application. The information provided is intended as a starting point in support of planning for future certification activities.

1.4 Recommended specification format

The guidelines found in the following sections can be applied to process specifications, material specifications, planning, work instructions, or test plans. These guidelines are helpful in the fabrication of continuous fiber-reinforced ox/ox CMC test laminates but should not be viewed as the only means of control for a particular application. For consistency and standardization purposes, a general content format for ox/ox CMC prepreg processing specifications should be followed. The following is a recommended content outline:

1. Scope
    - 1.1 Purpose
    - 1.2 Health and safety
2. Applicable documents
    - 2.1 Qualification documents
    - 2.2 Guideline and guidance documents
3. Personnel
4. Materials
5. Equipment description
6. Facility description
7. Tooling

8. Laminate fabrication

    8.1 Prepreg cutting

    8.2 Layup and bagging

    8.3 Baseline consolidation cycle

    8.4 Baseline sinter cycle

    8.5 Alternative consolidation or sinter cycle

    8.6 Panel identification

    8.7 Machining

    8.8 Heat cleaning

9. Quality assurance

    9.1 Intermediate inspection

    9.2 Final inspection

    9.3 Process monitoring

    9.4 Documentation

10. Shipping

11. Notes

12. Revisions

Other formats with the same content are acceptable. For example, DOT/FAA/TC-02/110 suggests a slightly different format for PMC process specifications. This format is also acceptable as long as sufficient sections and information relevant to the control of ox/ox CMC processing are included.

2 Sections of process specifications

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 composite laminates. 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 laminates are consistent in quality.

The following sections provide detailed recommendations for information that should be contained in an ox/ox CMC process specification. These follow the outline provided in Section 1.4. Additional, generalized recommendations for the generation of composite process specifications can be found in CMH-17.

2.1 Scope section

2.1.1 Purpose

The purpose section should contain general and overviewing information for the purpose and application of the process specification. The exact organization of the information may vary; however, the purpose section should include all relevant information regardless of format. The associated material specification by which the materials should be procured for the intended application should be provided.

2.1.2 Health and safety

Relevant statements regarding hazards associated with handling or processing the ox/ox CMC material should be provided in the safety section. This section may reference safety data sheets, safety procedures, processes, or requirements contained in other documents, as appropriate, in which case the referenced documents should be included in the applicable documents section.

2.2 Applicable documents section

2.2.1 References

The references section should include the following documents applicable to the original qualification or relevant follow-on equivalencies:

- The material specification associated with procuring the material
- The qualification test plan used for the original material qualification
- The qualification test report and statistical analysis
- Equivalency test plans, reports, or statistical analysis, if relevant
- Applicable work instructions for fabricating parts or laminates

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 a successful approach for the fabrication of repeatable quality laminates. 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. 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.

2.2.2 Guidelines and guidance documents

The guidelines and guidance documents section should include references to any guidance, guidelines, recommendations, or regulatory requirements relevant to the certification of parts. Some guidelines and guidance documents relevant to ox/ox CMC specification development and qualification procedures include:

AC 20-107B: Composite Aircraft Structure

- DOT/FAA/TC-25/45: Guidelines and Recommended Criteria for the Development of a Material Specification for Oxide/Oxide Ceramic Matrix Composite Prepregs
- DOT/FAA/TC-25/27: Material Qualification and Equivalency for Oxide/Oxide Ceramic Matrix Composite Material Systems
- DOT/FAA/TC-25/44: Guidelines for the development of Process Specifications, Instructions, and Controls for the Fabrication of Oxide/Oxide Ceramic Matrix Composites
- DOT/FAA/TC-25/16: Processing-Property Relationship of Oxide/Oxide Composites

2.3 Personnel section

The personnel section should describe requirements for individuals participating in the manufacturing process. Highly skilled technicians are needed to produce quality laminates. Fabricators are encouraged to establish a comprehensive training program for technicians directly involved with the fabrication of ox/ox CMC test panels. 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 laminates has a direct bearing on program cost (elimination of rework due to poor quality laminates) and optimum structural performance (establishment of design allowables). Suggested factors to be addressed in the selection of fabrication personnel include:

- 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.

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

2.4 Materials section

This section should contain requirements for all materials (and their sources) required for manufacturing. These should include materials required for fabrication procedures, and requirements relevant to the materials should be listed within the process specifications. The list 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 ox/ox prepreg should be evaluated to verify that they do not contaminate the prepreg material. It should be verified that all materials that have the potential to become a foreign object within the laminate can be detected by non-destructive inspection (NDI) methods that will be used for the inspection of test panels or production parts.

Prepreg materials should be inspected upon receipt by the purchaser, per the 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 laminate process instructions. Material that does not meet the established quality requirements should not be processed into test panels or parts.

Prepreg material cold storage conditions and shelf-life limits should be defined (controlled in the material specification). Many ox/ox prepregs require cold storage, but some must explicitly be prevented from freezing (e.g., storage temperatures of 35°F-50°F). Specific storage temperature requirements are usually driven by the matrix binder constituents. Cold storage life may be from 3 to 18 months, with 6-12 months being 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. Reinspection tests must be defined with clear acceptance criteria based on experimental testing.

Ox/ox prepreg matrices are typically perishable at ambient temperatures. The matrix most commonly contains powdered ceramic fillers that are dispersed in a carrier solvent such as water or alcohol that is evaporable at room temperature. This evaporation can reduce the matrix kinetics and flow characteristics of the material, thus affecting producibility, consolidation, and resultant properties.

Prepreg handling properties are also a function of temperature and environment. The primary risks are too high a temperature or too dry an environment during layup. Rapid solvent evaporation will cause the matrix to lose tack, making it difficult to position and handle the plies. Too humid of an environment can also be an issue if absorbed water alters the matrix carrier formulation ratios and flow kinetics. Therefore, controlling the relative humidity is important for ensuring the matrix will obtain an optimal consolidation.

Prepreg material working life (sometimes called out life) limits should be defined. The time period should be associated with a defined temperature and relative humidity range. Both a maximum and minimum working temperature, and a maximum and minimum allowable relative humidity must be defined. These temperature and humidity ranges may be different from the ranges commonly established for PMC prepregs. The working lifetime-period should have been determined during or before the initial material qualification test program.

Defining the ambient environment is critical to producing quality panels or parts and avoiding scrapped material and parts. Figure 1 is an example schematic of the relationship between prepreg storage life, out life or mechanical life, handling life or work life, and staging life. In the case of ox/ox CMC prepregs, which do not ‘cure’ in the traditional definition of the word, material consolidation must be initiated by the end of the mechanical life and/or staging life. Depending on the matrix constituents and solvents, out life could range from just a few days to more than a month. Handling life, where the prepreg material is exposed to the ambient atmosphere and is at greatest risk of evaporation of the matrix solvent, could be as short as a few hours or as long as a few days. The staging life may similarly vary depending on the matrix

solvent evaporation risks while on the tool or under vacuum hold. To the greatest extent possible, the amount of time that the prepreg is exposed to open atmosphere (i.e., is not being protected by backing film or a vacuum bag) should be controlled and maintained within pre-determined requirements. Some manufacturers or end users may additionally wish to specify separate life limits depending on whether the prepreg is protected from evaporation (i.e., if backing film has been removed or not).

Complete records should be maintained that document traceability of the fiber, matrix, prepreg, and laminate. These records should also document the total shelf-time and out-time of the prepreg up to the time of consolidation. Provisions should be made within the work instructions to record material batch and roll numbers and ambient out-time at the time of layup and consolidation.

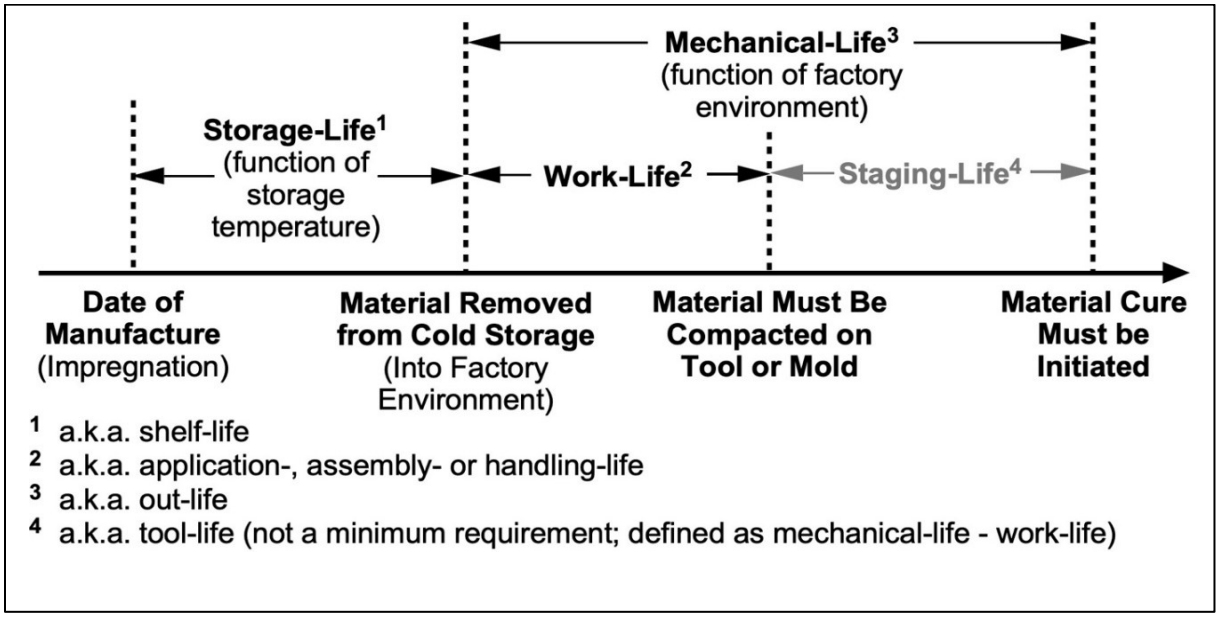

Figure 1: Definitions of Storage Life, Work Life, Staging Life, and Mechanical Life from CMH-17 VOL 3

2.5 Equipment description section

All equipment needed to perform the fabrication process with necessary requirements should be listed in this section of the process specification. Sources for the equipment should be listed, and the calibration and certification requirements should be defined. Equipment requiring calibration and certification typically includes autoclaves, furnaces, thermocouples, and vacuum gages. It is recommended that furnace calibration comply with AMS2750 (SAE, 2024). Provisions should

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

2.6 Facility description section

This section should provide requirements for facilities used to manufacture ox/ox CMC laminates or parts. Layup of plies should be performed in a clean room. The clean room is 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.

Ox/ox CMC layup should occur in clean room facilities physically separate from PMC layup clean rooms, even if the temperature and humidity control limits are identical for the two material types. The matrix constituents in PMC and CMC prepregs may cross-contaminate and create property and performance issues with laminates or parts produced from one or both materials. If it is not possible for ox/ox CMC layup to occur in a separate clean room, then it should, at a minimum, occur in a segregated area where cross-contamination risk can be kept to a minimum. Once held under a vacuum bag, CMC and PMC laminates and parts may be located in common facilities or use common processing equipment.

Ox/ox prepreg 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 layup area. The temperature and humidity requirements should align with the material's ambient out life requirements as defined by the manufacturer and verified by test. Depending on the matrix formulation, temperature and humidity requirements will vary.

The control of airborne particles is essential to maintaining a clean environment for the fabrication of composite laminates. Airborne particles are controlled through the use of filters, restricting dirty operations, and the establishment of positive pressure within the clean room. Filtration of the air is recommended to not only ensure clean air is introduced into the clean room, but also to clean particles from the air that were generated within the clean room. ISO 14644-1 Class 9 (BSI, 2001) is recommended as the minimum level of filtration for a clean room where ox/ox CMCs laminates will be laid up. 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 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.

The inclusion of a positive-pressure ventilation system in the layup room is an effective method of preventing the introduction of airborne particles from other parts of the facility, such as machine shops. A list of items to consider when specifying requirements for a clean room includes:

- Limiting room access by other equipment (gas powered forklifts)
- Limiting room access by non-layup personnel
- Level of air flow through the room
- Equipment for monitoring environmental control
- Preventing contamination by other processes (PMC layup, chemical processing, painting, and sanding)
- Treatments and cleanliness of floors
- Humidity (minimum and maximum)
- Temperature (minimum and maximum)
- Isolation from other contaminates
- Layup area status (approved, unapproved)
- Lighting (lumens)
- Particulate count
- Pressure (positive)
- Proximity to staging area, autoclave, and furnaces
- Vacuum hose status (approved, unapproved)
- Treatment and cleanliness of walls

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

2.7 Tooling section

The tooling section should describe the tools necessary for manufacturing, when they should be used, and how they should be controlled. For the fabrication of ox/ox CMC panels and parts, tooling is needed for layup, consolidation, and sinter. Layup and consolidation are generally performed on common tooling. Sintering may be performed either “free-standing” on a flat surface or rack in the furnace, or with conformal tooling to prevent the panel or part from warping under its own weight. Conformal tooling may be particularly necessary or desirable if the ox/ox CMC panel or part shape is complex or very thin.

For the layup and consolidation of flat ox/ox CMC test panels, typically, tooling consists of solely a base plate. A caul plate or other rigid tooling for the upper laminate surface may also be used with ox/ox CMCs but is not always necessary. Base plate tooling should be designed for the defined process conditions (e.g., consolidation temperature and pressure). Surface finish and flatness requirements should be defined (as applicable). Consolidation tools should be sized so that distances between the edges of the part or panel and the vacuum port positions are large enough to prevent excess, bled-off matrix material from reaching the ports and causing a vacuum seal-off condition. Locations for two vacuum sources, and a maximum of two parts or panels per tool, is recommended. All tools should be clearly identified. Tool storage conditions that ensure the tools are not damaged over time need to be defined.

A method for accurately positioning the plies during layup is required. It is imperative that the ply orientation is within the engineering requirements, as strength and modulus properties are sensitive to ply orientation. A method must be used that allows for transfer of the tool zero direction to the part or panel and then to the machining equipment. Scribe lines on the tool is one method that has been successfully used, although other methods are permissible.

For the sinter of flat ox/ox CMC test panels, typically, tooling consists of a base plate, ceramic blocks, or furnace racking on which to set the test panel in the furnace. It should be designed for the defined process conditions (e.g., heating rate, maximum temperature, duration at temperature). In the case of ceramic blocks or furnace racking that do not completely contact the panel, care should be taken to ensure the panel is sufficiently supported to prevent warping. Surface finish and flatness requirements should be defined but typically do not need to be as tightly controlled as they are for the layup and consolidation tool since the ox/ox CMC panel will not be tightly conformed to the surface of the sinter tool. A layer of s-glass or similar may also be used to loosely wrap the part and physically separate it from the sinter tooling. Similar requirements should be detailed for tooling to support the sinter of CMC parts, with additional concern paid to how and where to support the part to prevent warping. All tools should be clearly

identified, and tool storage conditions that ensure the tools are not damaged over time need to be defined. Detailed tool preparation procedures are also necessary. Areas to cover in the procedures include tool inspection, verification that all tooling details are available and in good working condition, mold release application procedures (acceptable mold releases should be listed in the materials section) for layup and consolidation tools, and tool clean-up procedures. A list of tooling control items include:

- Method of cleaning, solvents, cleaning cloths
- Mold release agents (layup and consolidation tooling)
- Scribe marking (layup and consolidation tooling)
- Tool heat-up rate
- Tool inspection intervals
- Tool surface conditions
- Tool, method of moving, transportation
- Tooling condition (mold release applied, no mold release)
- Tooling configuration (flat, vertical, part-contoured)
- Tooling status identified (approved, unapproved)
- Tooling storage conditions and locations
- Tooling, expansion and contraction rate
- Tooling material
- Location and number of vacuum ports (layup and consolidation tooling)
- Orientation rosette (layup and consolidation tooling)
- Tool repair procedures
- Tool inspection intervals

2.8 Laminate fabrication section

2.8.1 Prepreg cutting

This section should describe the processes and requirements for cutting prepreg from the parent roll. Cold prepreg in sealed containers must be warmed to room temperature prior to opening to prevent condensation from getting onto the prepreg. The length of time required to warm the prepreg to ambient temperature is a function of the roll size; the larger the roll, the longer the time required to warm to room temperature. Small rolls (5 to 10 pounds) can reach room temperature in 2 to 3 hours, while 30- to 50-pound rolls can take over 8 hours. Allowing large prepreg rolls to warm to room temperature overnight is often appropriate, as long as sufficient out life is available to do so.

Plies should be cut on surfaces specifically dedicated to cutting plies. Care should be taken during the cutting process to ensure that backing material is not snagged, pulled away, or removed. Maintaining backing material on the ox/ox prepreg is essential to avoiding unnecessary matrix solvent evaporation. Fiber orientation (e.g., warp versus fill direction) must be maintained during the cutting process. Individual plies should be identified and marked at the time of cutting. Plies should not be trimmed or cut on the tool to ensure the tool or underlying plies are not damaged. If trimming of plies on the tool is required, a clean metal shim should be placed between the prepreg and tool or lower-ply surface.

2.8.2 Layup and bagging

This section should describe the processes and requirements for laminate layup and bagging. The plies are collated onto the tool as defined in the detailed work instructions. Care should be taken to accurately align the plies with respect to the tool zero-degree reference direction. During the layup process, each ply must be laid up within a specified accuracy, such as ±5°. The specified ply orientation accuracy should align with what is usable or achievable in production parts. Refer to FAA report DOT/FAA/TC-25/27 for a description of the reference edge method used to maintain ply alignment through the part or panel fabrication and subsequent specimen machining operations (Horner, Andrulonis, Opliger, & Tomblin, 2026b).

Prior to collation, the plies are inspected for visual defects. Damaged plies are replaced. After each ply is collated and the backing paper is removed, its surface is inspected for foreign objects. Plies should be laid up as quickly as practicable after removal of the backing material and in accordance with any requirements established in material handling sections of the material or process specifications.

Plies should be debulked (compacted with vacuum pressure) as necessary during layup. The frequency and duration of debulks can have significant effects on panel quality, as both solvent and matrix particulate can be pulled out of the plies along with air during the debulk process. Too infrequent or too short of debulks can leave air trapped in the laminate. Too frequent or too long of debulks can leave plies near the surface dry and matrix starved. These effects will also vary based on part size, shape, and thickness. The selection of when and how long to debulk should be verified by manufacturing trials and evaluation of key physical properties such as density, porosity, consolidated ply thickness, and sintered ply thickness before finalization of the process specification, work instructions, or qualification testing.

The part or panel is bagged for consolidation, and vacuum is pulled as specified in the detailed work instructions. A leak check should be conducted to ensure compliance with vacuum leak requirements in the work instructions. After the leak check is passed, vacuum ports should remain closed and should not be held under active vacuum while staging for consolidation. Active vacuum can continue to pull solvent or matrix particulate up through the laminate during staging to the detriment of panel quality. The bagged part or panel should be clearly marked to ensure traceability.

Thermocouples should be placed such that temperature can be directly measured. The thermocouples should be placed against the prepreg to ensure the material is heated to the specified temperatures. At least two thermocouples should be used for each panel. For a part or large panel, 4 to 6 thermocouples are recommended. In cases where the tool contains embedded thermocouples, a heat survey should be performed to validate that the embedded thermocouples are an accurate measurement of the part or panel temperature. Thermocouples should be sealed to the tool using seal tape to prevent matrix from bleeding along the wire.

2.8.3 Baseline consolidation cycle

This section defines the consolidation cycle used in the original qualification, which is defined as the “baseline” consolidation cycle. There may also be one or more alternative consolidation cycles that have been demonstrated to produce equivalent quality parts or panels, which are discussed separately. The part or panel is consolidated, typically in an autoclave, according to the applicable baseline consolidation cycle. Shortly prior to consolidation, a leak check should be performed on the vacuum bag. All leaks should be repaired before performing the consolidation cycle. Leaks through the tool can create as serious of problems as leaks around the edges of the bag. The consolidation cycle should define heat-up rate, temperature range, time, vacuum, pressure, and cool-down rate. Although autoclave chamber temperature is sometimes used, ideally, the consolidation time and temperature should be controlled by the slowest (lagging)

thermocouple in the consolidation run. Temperature, vacuum, and pressure should be recorded as a function of time for the complete consolidation cycle. The consolidation cycle tolerances (i.e., upper and lower temperature, pressure, vacuum, time, and rate envelopes) should be thoroughly investigated before being defined in the baseline consolidation cycle.

2.8.4 Baseline sinter cycle

This section defines the sinter cycle used in the original qualification, which is defined as the "baseline" sinter cycle. There may also be one or more alternative sinter cycles that have been demonstrated to produce equivalent quality parts or panels, which are discussed separately. The part or panel is sintered, typically in an atmospheric-pressure air furnace, according to the applicable baseline sinter cycle. The part or panel should be freestanding in the furnace unless prior testing has determined that conformal tooling is necessary. The sinter cycle should define heat-up rate, temperature range, time, and cool-down rate. Although furnace temperature is sometimes used, ideally, the consolidation time and temperature should be controlled by a thermocouple located in contact with, or in close proximity to, the panel or part. If the part or panel is large, multiple thermocouples should be used and the slowest (lagging) thermocouple should be used for control; however, the leading thermocouple should not be allowed to reach a temperature higher than the maximum allowable processing temperature. Temperature should be recorded as a function of time for the complete sinter cycle. The sinter cycle tolerances (i.e., upper and lower temperature, time, and rate envelopes) should be thoroughly investigated before being defined in the baseline sinter cycle.

2.8.5 Alternative consolidation or sinter cycle

These optional sections define alternative consolidation or sinter cycles that may be specified, depending on application and panel or part size and configuration, if any are necessary. It is not currently well understood how robust ox/ox CMC lamina and laminate material properties are to minor changes in the consolidation and sintering cycles. Some prepreg formulations may be extremely sensitive, in which case alternative consolidation or sinter cycles may not be possible without developing a new qualification dataset. The acceptability of alternative consolidation or sinter cycles must therefore be investigated ahead of time via the equivalency process, which is described in DOT/FAA/TC-25/27 (Horner, Andrulonis, Opliger, & Tomblin, 2026b). More significant deviations from the baseline qualification consolidation or sintering cycle may increase the risk of equivalency failure. Since not all properties are investigated in a typical equivalency program, users should not necessarily assume that successful equivalency demonstration also means that the alternative consolidation or sinter cycle has no effect on lamina or laminate properties overall. A more extensive test matrix that includes more test

methods and test conditions may be necessary to thoroughly evaluate the sensitivity of material properties to the alternate consolidation or sintering cycle(s). The alternative consolidation or sinter cycle tolerances should also be thoroughly investigated before being defined in the alternative cycle, particularly if they vary from the tolerances in the baseline cycles.

2.8.6 Identification

The identification section provides requirements for labeling unique panels and parts. Each panel or part should be marked with a unique identification code. This identification code will provide traceability to the requesting document, prepreg batch number, consolidation cycle, sinter cycle, and test type, if applicable. Lines can also be drawn at an angle across the laminate surface to aid in identifying test specimen location within a test panel.

2.8.7 Machining

The machining section describes processes and requirements for machining processed panels or parts to final dimensions. Machining should generally take place after sintering. If processing or engineering requirements necessitate machining after consolidation but before sintering, the justification should be documented, and data used to validate the acceptability of pre-sinter machining should be generated. Pre-sinter machining can induce damage, particularly delamination, into the ox/ox CMC material and should be avoided whenever possible.

Machining diagrams should be developed for each part or panel and be included in the work instructions. The type of machining equipment used should be recorded along with cutting tool type, speeds, and feed rates. Cutting tool life should be defined for each tool used for ox/ox CMC machining. Cutting tool life should be documented at the end of machining, and cutting tools reaching their end life should be disposed of. After machining, parts or specimens should be inspected for delamination, damaged edges, or other defects. Parts or specimens should also be dimensionally inspected for conformity to relevant engineering requirements and drawings. Specimens failing to meet engineering requirements should be replaced. Parts failing to meet engineering requirements should be evaluated and dispositioned. If repair procedures have been defined and validated, a topic which is outside the scope of this research report, then panels or parts failing to meet engineering requirements may be repaired instead of replaced.

A list of items to control for machining include:

- Use of and type of coolant
- Marking of trim lines

- Type of tools for trimming, hole drilling
- Tools for control of cutting surfaces
- Tool inspection intervals
- Method for transferring the 0° direction to each panel or part

2.8.8 Heat cleaning

The heat cleaning section should describe processes and requirements for panel or part cleaning using heat. Heat cleaning should be documented in the work instructions and performed at the conclusion of machining to remove any water, surfactants, lubricants, or abrasive particulate that may have been introduced during the machining or inspection processes. The temperature and duration of heat cleaning should be determined based on an analysis of the degradation of potential contaminants. A method such as thermogravimetric analysis (TGA) to determine contaminant burn-out temperature and duration may be used to determine such temperatures and times. The selected heat cleaning temperature should be less than both the sinter temperature and maximum use temperature of the ox/ox CMC material to avoid inducing chemical or molecular changes during heat cleaning.

2.9 Quality assurance section

This section defines the recommended examinations, inspections, and tests to be performed in order to verify that the engineering requirements are followed. Each inspection or examination given in this section should be tied directly to a requirement specified by the process instructions or a known process-parameter-performance relationship identified for the ox/ox CMC material.

2.9.1 Intermediate inspection

This section provides requirements for inspection after consolidation is complete, but before sintering has taken place, if necessary. It is strongly recommended that the part or panel be inspected at this stage for defects including surface pitting, fiber bridging, edge delamination, and overall conformity to geometry. This inspection may be visual or may be conducted using equipment such as a coordinate measuring machine, infrared (IR) thermography, or x-ray computed tomography (CT). The un-sintered panel or part may be fragile, and care should be taken to avoid introducing damage during inspection.

More detailed evaluation or inspection of the un-sintered panel or part may be conducted if it is required to meet a specific material or process specification requirement. For instance, if a process specification requires post-sintered density, and a relationship between pre-sintered

density and post-sintered density has been determined as part of a process-property-performance study such as that described in FAA report DOT/FAA/TC-25/16, it may be appropriate to measure density before sintering to avoid the unnecessary time or expense of sintering a part that will fail quality inspection after sintering is complete (Horner, Andrulonis, & Opliger, 2025). If an intermediate inspection process such as a density measurement, which may require excision of a sample of material for testing, is determined necessary and appropriate, care must be taken to avoid introduction of new damage to the panel or part during the excision of the potentially fragile material. Pre-sintered, consolidated weight and ply thickness are additional properties that may be valuable to inspect in order to correlate to a sintered weight or ply thickness requirement. Consolidated ply thickness or weight likely would not require coupon excision.

2.9.2 Final inspections

This section defines requirements for inspections at the completion of fabrication. After sintering, it is strongly recommended that the part or panel be inspected to ensure all engineering requirements have been met prior to machining panels, parts, or test specimens. Inspections or tests are performed on each panel or part to verify they are acceptable for submission to the machining step. Such inspections may include thickness, surface flatness, and NDI such as IR thermography or x-ray CT for identification of internal defects and embedded foreign object materials. Test panels that fail to meet engineering requirements will result in test data that is not representative of the material. Parts that fail to meet engineering requirements may not perform sufficiently in service and should be dispositioned and/or repaired.

The tests recommended in this section are not necessarily applicable to production parts (though they are often used for developmental parts and first part qualification). To what extent final inspection and/or testing is conducted on production parts is outside the scope of this report and must be defined and validated as part of the certification process. The tests recommended in this section are, at a minimum, necessary to verify that panels are acceptable for further testing and are required to provide a complete material property database. The part or panel should be visually inspected for surface defects that could be sources for premature test failures. Each part or panel should be nondestructively inspected for internal defects, such as porosity, foreign objects, or delamination. 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 time-of-flight derivative for thermography) be tied to a known physical defect type, location, and size. Specific guidelines for the creation and use of ox/ox CMC NDI reference standards is outside the scope of this report.

Final thickness and calculated sintered ply thickness should be verified at a number of locations. The measurement locations should be equally spaced (within reason) around the part or panel. The actual thickness is converted to a sintered ply thickness by dividing the average measured thickness by the number of plies in the region of measurement. A panel or part that fails to meet the required sintered ply thickness should not be tested unless it is evaluated, dispositioned, and/or repaired, as appropriate. The thickness data can also be interrogated to determine degree of flatness. Failure to meet engineering flatness requirements should also result in evaluation, dispositioning, and/or repair before any testing takes place.

A small corner of the part or panel (e.g., 1/2 by 1/2 inch) should be removed so that panel density and porosity can be determined. Other physical properties that have been identified as having significant effects on mechanical performance should also be measured at this time. Performing X-ray diffraction (XRD) may be desirable to identify matrix structure or crystallinity, if allowed by the manufacturer and previously characterized to define a standard, as a method of showing successful consolidation and sintering. Failure to meet engineering requirements for density, porosity, crystallinity, or other key physical properties results in the part or panel not being tested until and unless the part or panel is evaluated, dispositioned, and/or repaired, as appropriate. Ply layup orientation can be verified by polishing an edge for examination under a microscope (20 to 50X).

All records should be reviewed to verify the parts or panels were fabricated in compliance with the engineering requirements. The records should include material batch/lot traceability, identification number or code, consolidation and sinter cycle parameters, and ply count.

2.9.3 Process monitoring

The process monitoring section should describe requirements for monitoring during each stage of manufacturing. Per AC 20-107B, key characteristics and processing parameters should be monitored for in-process quality control. The overall quality control plan required by the certifying agency should involve all relevant disciplines (i.e., engineering, manufacturing, and quality control). A reliable quality control system should be in place to address special engineering requirements that arise in individual panels or parts or areas as a result of potential failure modes, damage tolerance and flaw growth requirements, loadings, inspectability, and local sensitivities to manufacture and assembly (FAA, 2010).

The following areas should be reviewed and monitoring procedures instituted.

- Equipment—All equipment requirements requiring verification should be listed for inspection. Calibration frequency is also defined.

- Materials—All material requirements requiring verification should be listed for inspection. This would include cold storage temperature, storage life, out-time at time of backing material removal, collation, consolidation, performance of receiving inspection tests, use of approved consumable materials, and batch numbers.
- Facilities—All facility requirements requiring verification should be listed for inspection. This would include clean room temperature and humidity and cleaning schedule.
- Tooling—All tooling requirements requiring verification should be listed for inspection. This would include performance of thermal surveys to document temperature uniformity during the consolidation or sinter cycles, performance of tool visual inspections, and monitoring of storage conditions.

2.9.4 Documentation

All information required to be recorded and reported should be listed in the documentation section. Per AC 20-108B, thorough manufacturing records are needed to support parts acceptance and allowable discrepancies (defects, damage, and anomalies). Substantiating data is needed to justify all known defects, damage, and anomalies allowed to remain in service without rework or repair. Manufacturing records are also needed for all substantiated design and process changes (FAA, 2010). The time span all process records should be retained must also be specified. A period of 7 years is recommended unless other guidance is provided by regulatory bodies or certifying agencies.

2.10 Shipping section

This section provides requirements for shipping the processed panels or parts. For material qualification and equivalency purposes, it may be necessary to send the panels to a designated test lab as specified in the applicable test plan. The panel or part shipping instruction should also be included in the applicable test plan.

2.11 Notes section

This section is reserved for explanatory and other notes not already addressed in other sections. Definitions specific to processing ox/ox CMCs may also be included in this section.

2.12 Revisions section

Process specification revision control is essential to the control and traceability of ox/ox CMC manufacturing processes and of the panels and parts manufactured according to the process

specification. A list of document revisions including a revision identifier (e.g., number or letter), date of revision, and a summary description of the revision should be maintained in the process specification.

3 Producibility validation guidelines

Certification and qualification test programs typically concentrate on the validation of mechanical properties and allowables, as is discussed in DOT/FAA/TC-25/27. Of equal importance, however, is the validation of processing parameters and part producibility. This section presents recommended producibility validation guidelines, which address (1) verification of material characteristics that affect producibility and (2) qualification and verification of fabricator processes to ensure the part meets the expected properties.

3.1 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 prepreg that govern the material's producibility. Some of the material characteristics that influence producibility are fabric drape, matrix tack, level of impregnation, and matrix flow properties.

In addition to validating the influence of prepreg characteristics, 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 laminate thickness, part area, internal ply drop-off features, or the non-uniform influence of debulks on matrix content and porosity. 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. But these effects can have a major impact on producibility of large-scale components and thus the structural performance of the component.

There typically exists a need for a panel design that will discriminate these material characteristics and their ability or robustness to accommodate scale-up effects. This panel can then be fabricated as part of the qualification test program and is often referred to as a "discriminator panel." The objective of the discriminator panel is to distinguish one material from another similar (or like) material by exposing their differences as related to producibility. The difference in material characteristics is often quantified by the density or amount of porosity

within the discriminator panel. For example, significant porosity may occur when the material is used to fabricate complex, contoured components even though small test panels made with the same material were void-free. In another example, the debulk frequency, time, and duration needed to achieve conformance to complex layup tooling pulls out excess matrix and reduces the end part density when similarly applied to a small, thin panel. Therefore, the discriminator panel needs to be representative of the intended application. It must be representative in thickness and contour and contain ply drop-off features representative of the proposed component designs. It must be fabricated with procedures representative of production methods.

Instead of fabricating a discriminator panel, an actual part can be fabricated to address prepreg material processing characteristics. 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 or optical microscopy, physical tests such as thickness, density, porosity, fiber volume fraction, or mechanical property tests used in the qualification program or required by the material specification. 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 impregnation processing parameters, the discriminator panel often will be more discerning to the changes than mechanical properties from test panels.

3.2 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 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.

3.2.1 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 from the same statistical population as the qualification and allowables dataset. The process of validating the material properties for an alternate process or facility is termed equivalency testing (see DOT/FAA/TC-25/27 and DOT/FAA/TC-25/44). An audit to verify compliance with the process specification requirements is also recommended as part of the fabricator qualification process.

3.2.2 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 elements and subcomponents 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 typically 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 laminate physical properties (matrix content, density, and thickness), and
- verify fiber path continuity within joints and complicated geometries (typically features that cannot be verified through a discriminator panel or by NDI).

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 if a repair procedure has been developed and validated for the ox/ox CMC material as part of a separate effort. The most likely defects will vary based on part geometry and processing

procedures, and should be evaluated for each unique part. Typical defects to place within the destruct article may include:

- Porosity, voids, or bridged fibers
- Thickness variation
- Delamination
- Wrinkles or ply waviness
- Tool mark off (matrix ridge or surface wrinkle)
- Foreign inclusions

The destructive inspection process typically includes:

- Full dimensional inspection
- NDI
- Section cuts through areas indicted by the NDI and areas of complex geometry, layup or thickness variations. Section cuts through co-processed joint regions, if co-processing methods have been tested and validated for the ox/ox CMC material
- Excising coupons for physical and mechanical property testing

Coupon types typically excised for physical property assessment include density, porosity, fiber volume fraction, sintered ply thickness, and matrix content. Small sections excised for optical microscopy to visually evaluate stacking sequence or laminate quality may be of interest as well. XRD coupons may also be excised, if the end user and prepreg supplier agree that it is acceptable for this data to be collected. Coupon types excised for mechanical property assessment will depend on end-use application and previous testing conducted as part of either an original material qualification or an equivalency. Such tests may include, but are not limited to, short beam strength and tensile, compression, and flexural properties. Elevated temperature mechanical property testing may also be necessary or desirable based on the ox/ox CMC material characteristics and the end-use application. If possible, element or joint specimens should also be excised for testing, which is supported by the requirements in AC 20-107B that the static strength of the composite design should be demonstrated through a program of component ultimate load tests in the appropriate environment, and that the strength of composite structure should be reliably established, incrementally, through a program of analysis and a series of tests

conducted using specimens of varying levels of complexity (the building block approach) (FAA, 2010).

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 report but should be included in the destructive inspection process.

Destructive inspections should be performed on part families. A typical part family might be all compression seals and another might be all mechanically fastened assemblies. 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, material, 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 first full-scale article.

3.2.3 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 its engineering design of 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, numbers, and locations of physical measurements beyond those identified as key characteristics. Each part type should go through the FAI process.

4 Conclusions

This research report provides a set of guidelines for the development of process specifications for continuous fiber-reinforced oxide/oxide (ox/ox) ceramic matrix composite (CMC) prepreg and an approach for the validation of ox/ox CMC fabrication processes used during the certification of composite aircraft structure, which are presented as producibility validation guidelines. This report describes a process with which to develop controls on manufacturing processes and outlines the necessary sections and content for process specification generation. The framework for development of ox/ox CMC process specifications is still being studied, and it is anticipated that revisions to strengthen or adjust the recommendations provided herein will be available in the future. This research report provides the current recommendations for ox/ox CMC process specifications until and unless additional research or experience that points towards alternative guidelines is developed. These recommendations, paired with recommendations for the generation of material specifications as described in DOT/FAA/TC-25/45 and recommendations for conducting material qualification and equivalency activities as described in DOT/FAA/TC-25/27, provide a framework for the qualification, use, and control of ox/ox CMCs for structural applications including in aircraft products and engines.

5 References

BSI. (2001). *Cleanrooms and Associated Controlled Environments—Part 1: Classification of Air Cleanliness, ISO 14644-1.* British Standards Institution on ERC Specs and Standards. International Organization for Standardization.

FAA. (2010). *AC 20-107B, Composite Aircraft Structure, Change 1.* Department of Transportation. Federal Aviation Administration.

Horner, A. L., Andrulonis, R. M., & Opliger, M. S. (2025). *Processing-Property Relationship of Oxide/Oxide Composites.* FAA Report DOT/FAA/TC-25/16.

Horner, A. L., Andrulonis, R. M., Opliger, M. S., & Tomblin, J. S. (2026a). *Guidelines and Recommended Criteria for the Development of a Material Specification for Oxide/Oxide Ceramic Matrix Composite Prepregs.* FAA Report DOT/FAA/TC-25/45.

Horner, A. L., Andrulonis, R. M., Opliger, M. S., & Tomblin, J. S. (2026b). *Material Qualification and Equivalency for Ceramic Matrix Composite Systems.* FAA Report DOT/FAA/TC-25/27.

SAE. (2024). *AMS2750 Rev. H, Pyrometry.* SAE International Material Specification. doi:https://doi.org/10.4271/AMS2750H