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# Polymer-Based Additive Manufacturing Guidelines for Aircraft Design and Certification

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JAMS 2018 Technical Review
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# Polymer-Based Additive Manufacturing Guidelines for Aircraft Design and Certification

- Motivation and Key Issues
  - Additive Manufacturing is expanding at a high rate
  - Process sensitive material (like composites) → Variability and repeatability are common issues not well understood
  - Process control has shown to be an issue across all platform types
  - Sources of variability are both material and process based
  - No substantial database exists

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# The NCAMP Approach for Polymer AM

- Additive Manufacturing is quickly moving from development → production
  - Reliable design allowables are required
  - Process for generating allowables is critical
  - Working with industry and regulators provides a unique perspective on allowable development, status and issues.
- NCAMP is a proven process for allowables
- Equivalency aspect allows manufacturers to qualify installations

**No public qualification of an additive material exists to date.**

# Objectives and Technical Approach

- Develop a framework to advance polymer-based additively manufactured materials into the aerospace industry.
- Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.
- Assess the validity with equivalency testing.
- *Note: Program is in collaboration with America Makes (see objectives on following slide)*

**TASK 1:** Establish Steering Committee

**TASK 2A:** Develop Qualification Framework

**TASK 2B: Validate framework with selected Polymer AM material**

**TASK 3:** Establish statistical guidelines

**TASK 4:** Transition
-Data and guidance to CMH-17
- Specifications to SAE

# America Makes - Project Overview

- **Problem Statement:** ULTEM™ 9085 is a polyetherimide high performance thermoplastic material with application acceptable strength-to-weight ratio and flame, smoke and toxicity (FST) rating. This material is often used in aerospace where a high strength thermoplastic material is needed. As this material is one of the only high performance thermoplastic materials available for Fused Deposition Modeling, it is important to establish a complete database of material properties to further enable use in various commercial and government applications. Such a database is a minimum requirement for deployment of an additively manufactured solution in a production environment.

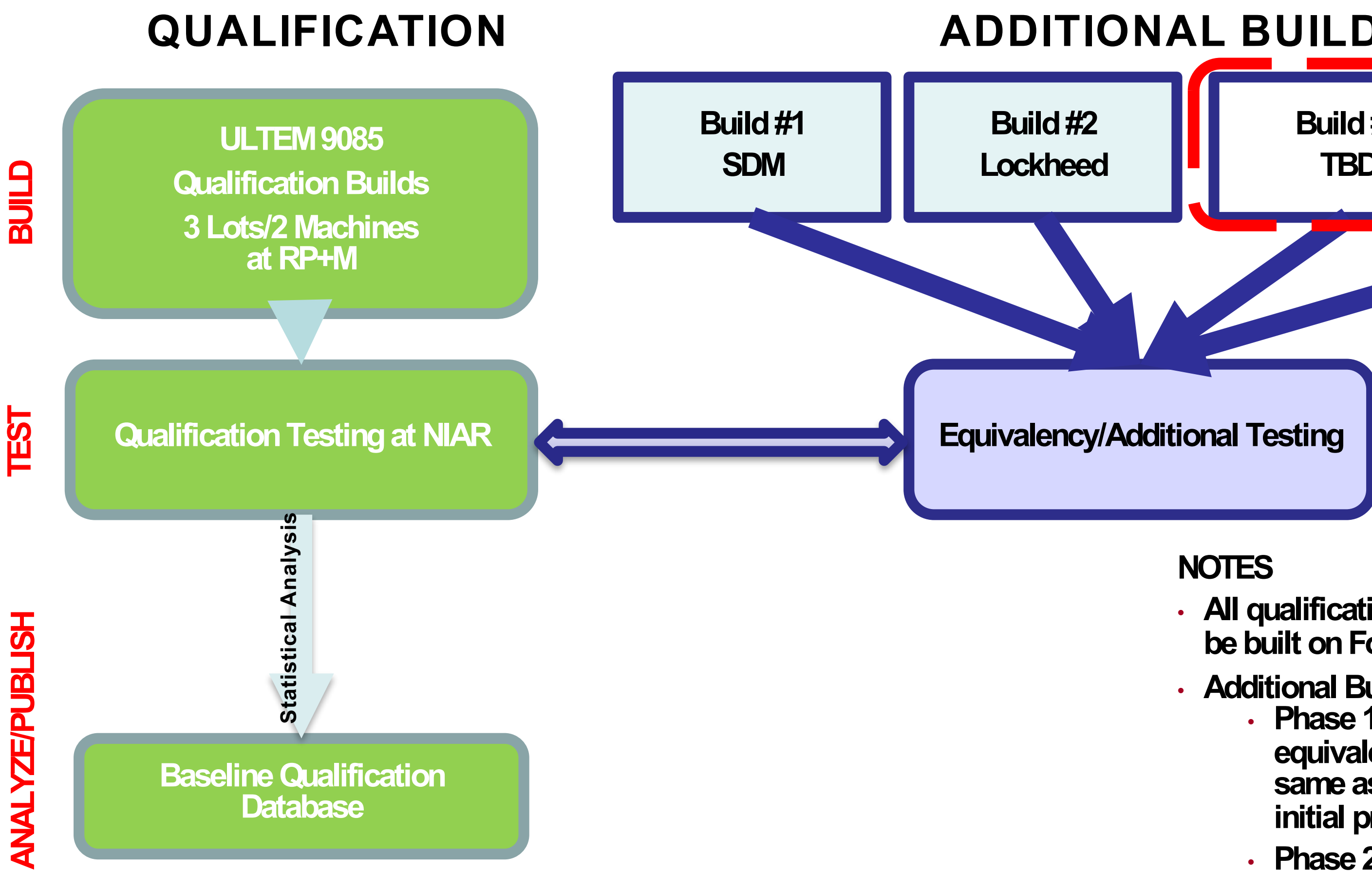
- **Objectives:** 1) Ensure Process Control and create documentation; 2) Identity and publish appropriate test matrix for process/material combination; 3) Fabricate test coupons; 4) Complete testing and publish results.

- **Project Benefits:** Completed database to allow membership to exploit for commercial applications; Framework for future materials/processes will be completed and available to membership; Equivalency process will be defined for membership to utilize outcomes in house.

# TASK 1: Steering Committee

- **Initial meeting/workshop**: St. Paul – August 2016
  - Material for initial qualification was selected: ULTEM 9085
  - Discussion on specifications and overall plan
- **Collaboration** with America Makes/AFRL/rp+m program
  - Shared resources
  - Deliverables and overall reporting are not changing
- **Material Partner**: Stratasys - Certified ULTEM 9085
  - Polyetherimide high performance thermoplastic
  - Good smoke and toxicity rating
  - Ability to withstand high temperatures – common use in aerospace and automotive duct work

# TASK 2: Qualification & Equivalency Overview

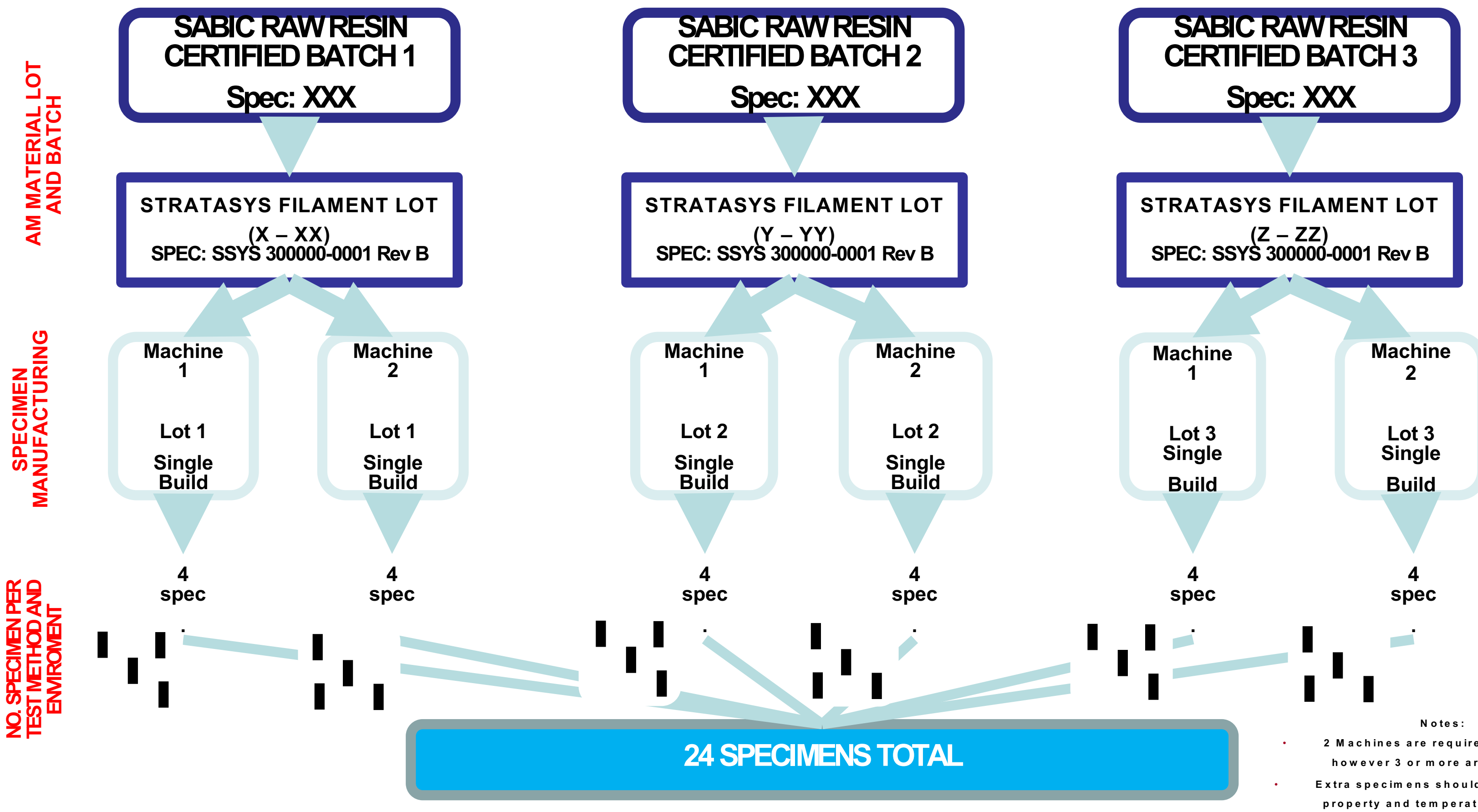



* Outside of current project scope, but NIAR project deliverable will allow or equivalency process for future use by any party with the appropriate equipment and process.

NOTES

- All qualification and equivalency coupons to be built on Fortus 900 MC machines.
- Additional Builds
  - Phase 1 = Equivalency: Standard equivalency matrix, 1 lot only, will be same as one of the original lots for initial program
  - Phase 2 = Additional Testing: Tests not part of qualification database

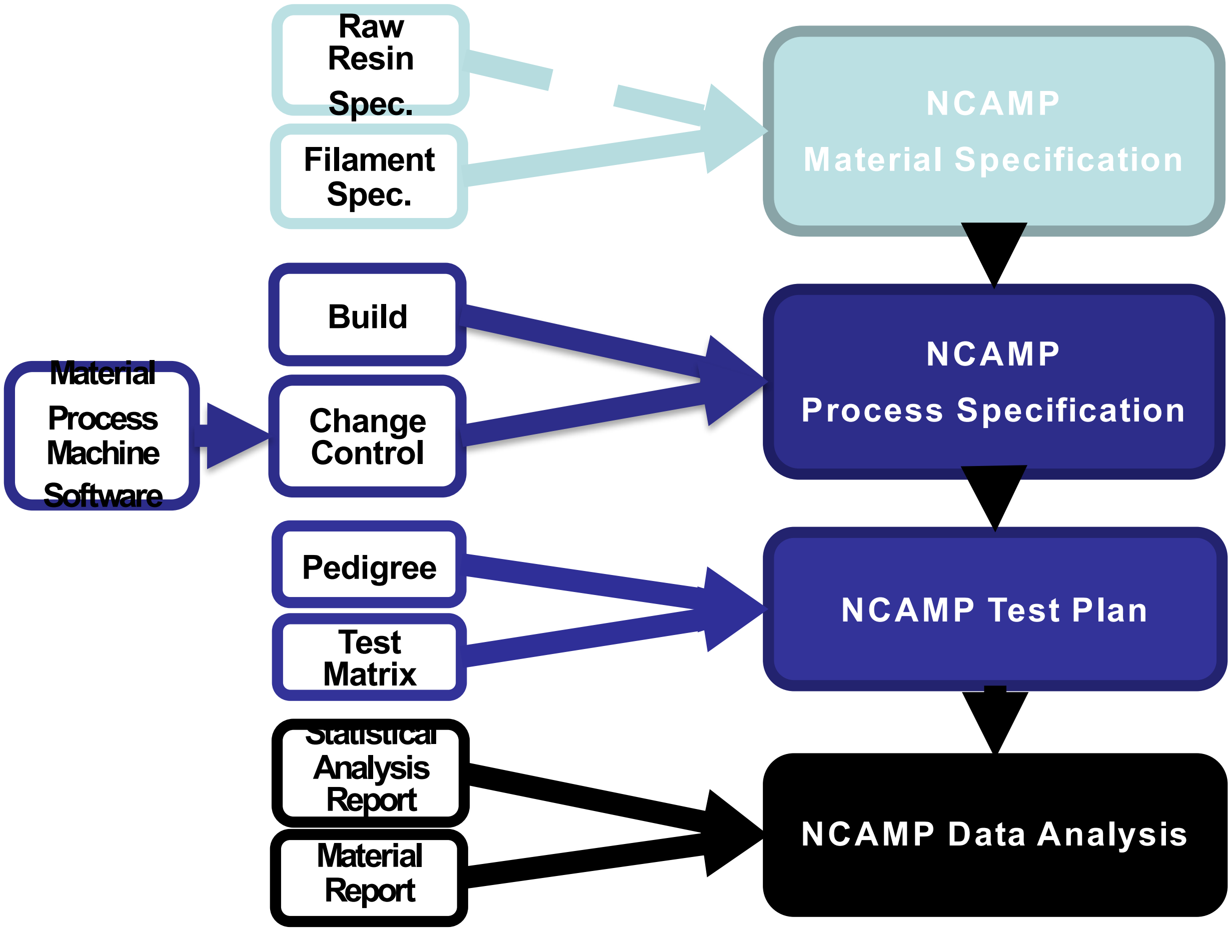
# TASK 2: Qualification Methodology




Notes:

- 2 Machines are required for qualification however 3 or more are recommended.
- Extra specimens should be tested for each property and temperature as "spares" to ensure desired quantity (min of 3 specimens).

# NCAMP DOCUMENTATION STATUS



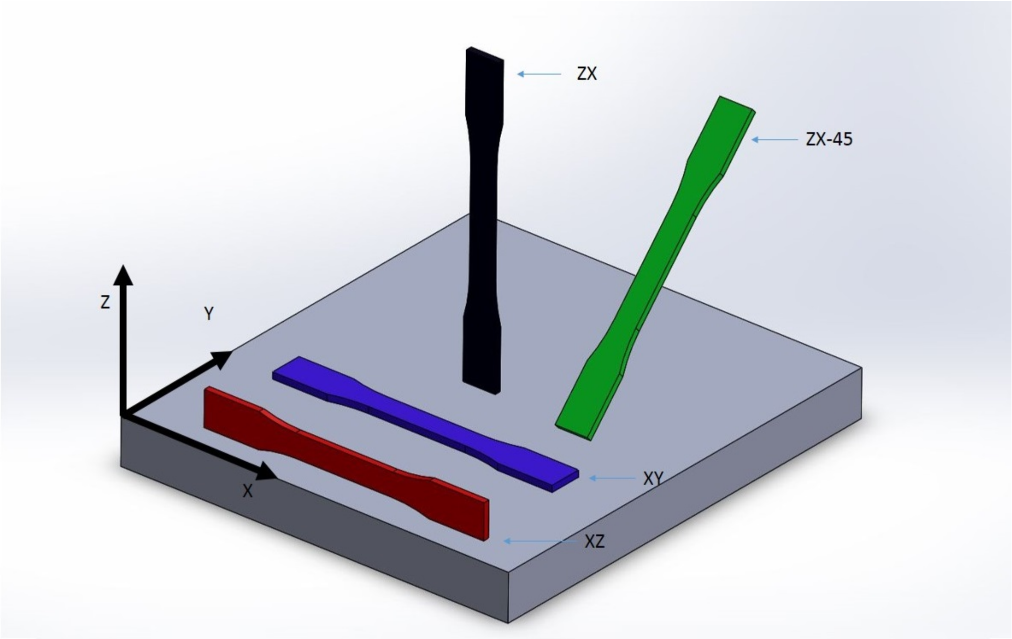

**STATUS**

- Final drafts of material and process specs - complete
- Build and Pack files included to reduce variation.

- Qual and Equiv. Test Plans finalized
- Site Inspections
  - Qual.: complete
  - Equiv.: complete

*Controlling the process is essential to success.*

# Build Orientation Investigation



# Test Matrix

| QUALIFICATION TESTS | EQUIVALENCY | "EXTRAS" |
|---|---|---|
| Tensile Strength | Tensile Strength | Tension-Tension Fatigue |
| Compressive Strength | Compressive Strength | ~~Tensile Creep~~ |
| Flexural Strength | Flexural Strength | |
| Shear | Shear | |
| Open Hole Tension | Open Hole Tension | |
| Filled Hole Tension | Open Hole Compression | |
| Open Hole Compression | IZOD Impact | |
| Filled Hole Compression | | |
| Single Shear Bearing Strength | | |
| IZOD Impact | | |

***Tests performed at CTD, RTD, RTW, ETW conditions.**

**Varying specimen thickness is also incorporated into the test plan.**

**Trial studies were conducted to define shear and compression test methods with ISC input.**

# NCAMP Test Plans

**NCAMP**

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| **Material Supplier Contact:** | **Specimen Fabricator Contact:** |
|---|---|
| Stratasys<br>7665 Commerce Way<br>Eden Prairie, MN. 55344<br>1-952-937-3000 | RP+M<br>33490 Pin Oak Pkwy<br>Avon Lake, OH. 44012<br>1-440-930-2015 |

**Document No.: NTP AM-P-001**

**Material Property Data Acquisition and Qualification Test Plan For**

- NCAMP has created formal test plans for Qualification Sites
- …for Equivalency Sites

# TASK 2: Qualification and Equivalency Printing

SubTask 1: Audit of Material Specification (@ Stratasys Inc. filament facility), Process Specification, Process Control Documentation (@ Rapid Prototype and Manufacturing LLC)

Date: March 28-30, 2017

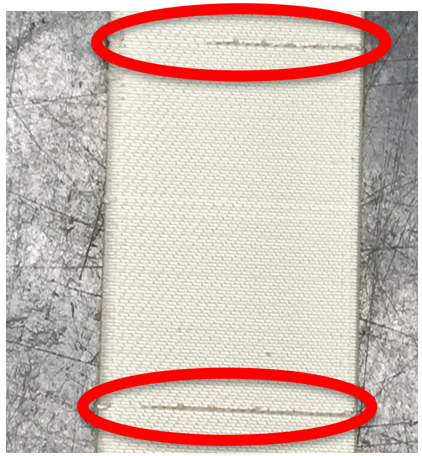
Status: Complete with minor corrective actions closed.

Outcomes:
Material specification passed quality audit.
Process specification passed quality audit.
Process Control Documentation passed quality audit.
rp+m AS9100C QMS passed quality audit.
Printing of qualification specimens began March 31, 2017.

# TASK 2: Examples – Dispositioned versus Acceptable Specimens

## Dispositioned

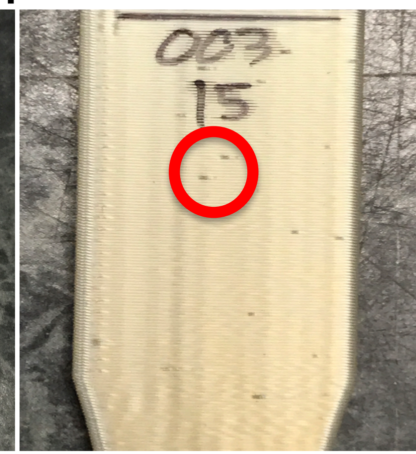
**Embedded Support**



**Extrusion Lagging and Purge Blobs**

## Acceptable

**Color Striation**




**Bubbles**

***Sample dispositioning has occurred at all 3 printing locations throughout the coupon manufacturing process.**

# TASK 2: Qualification and Equivalency Printing

## Qualification Specimens: (2846 specimens) - Complete

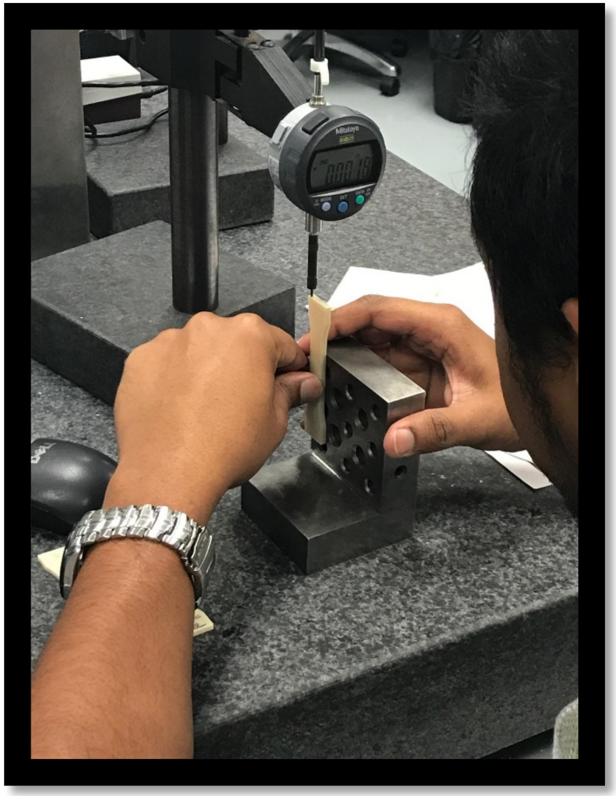
2 Major set backs (one on each machine) pushed back forecasted timeline considerably

- Issue #1: Machine 1 – tip and tip wipe setup errors
- Issue #2: Machine 4 – under filled specimens due to head output issues
- Testing results suggest we will have to complete some reprints.

## Equivalency Printing: (504 specimens each) - Complete

- Site 1: Stratasys Direct Manufacturing
- Site 2: Lockheed Martin MFC Orlando
- Some reprints will be required from each site.

# Coupon Gauging and Inspection @ NIAR



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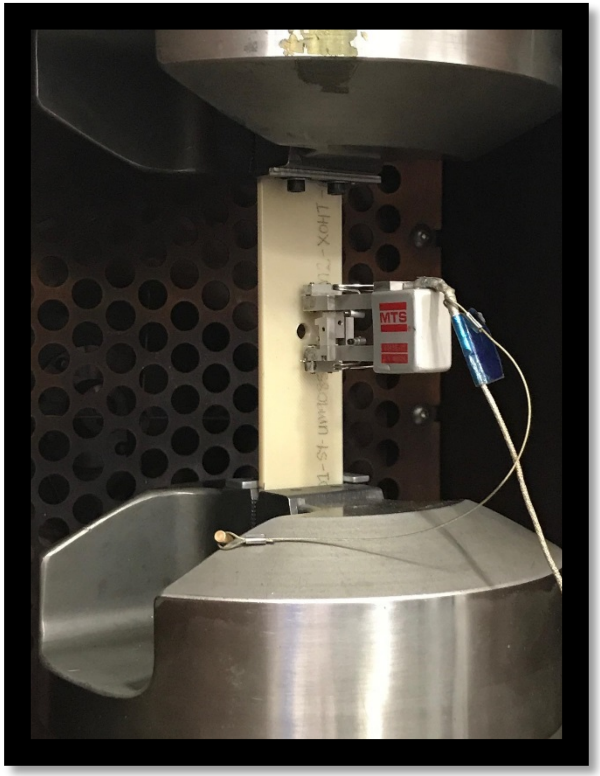
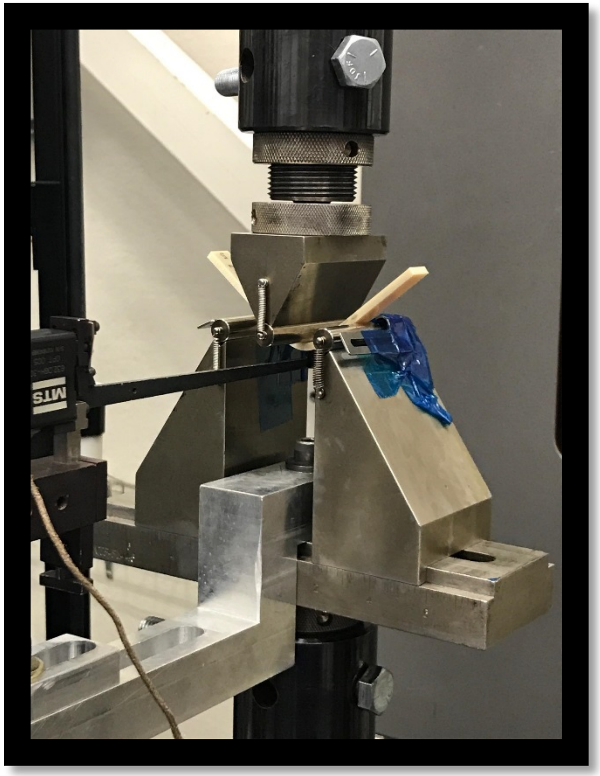
# Coupon Testing

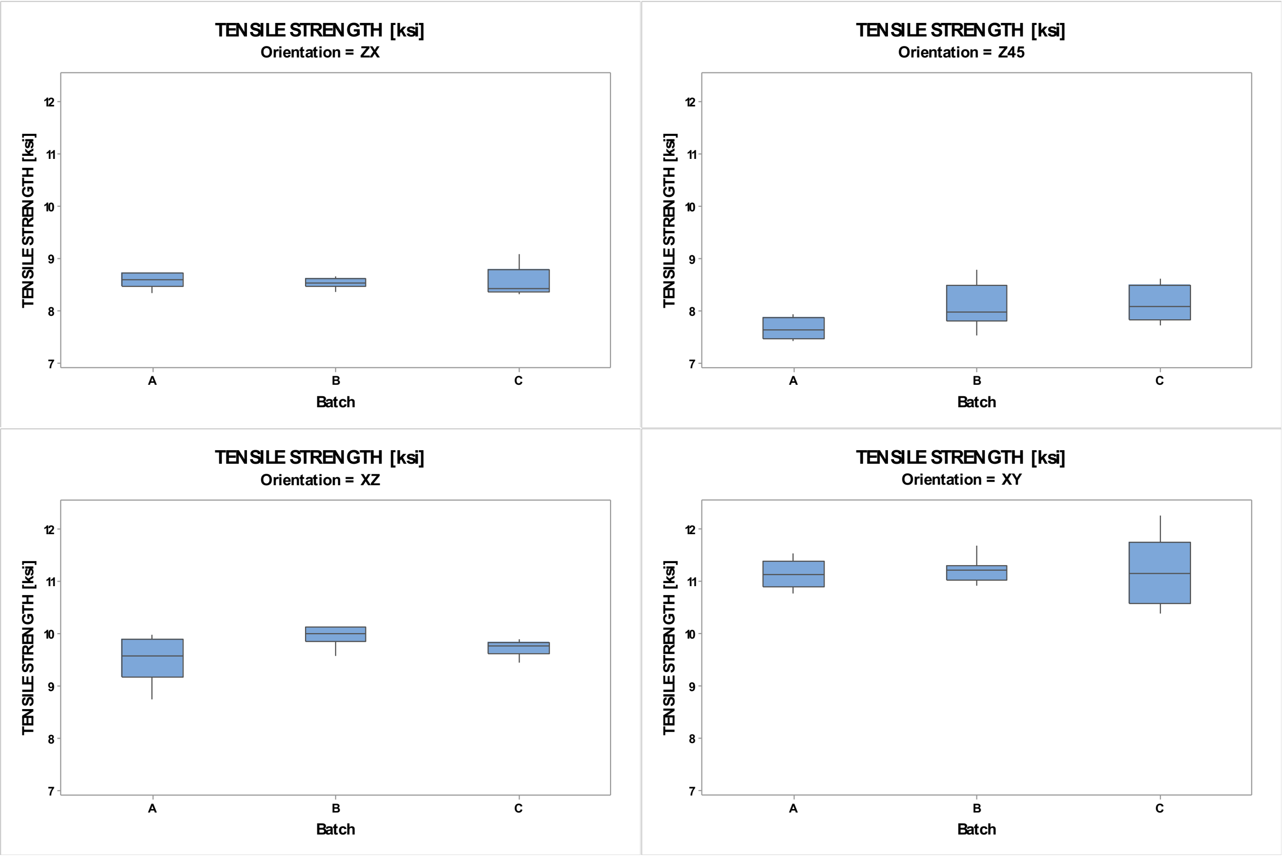


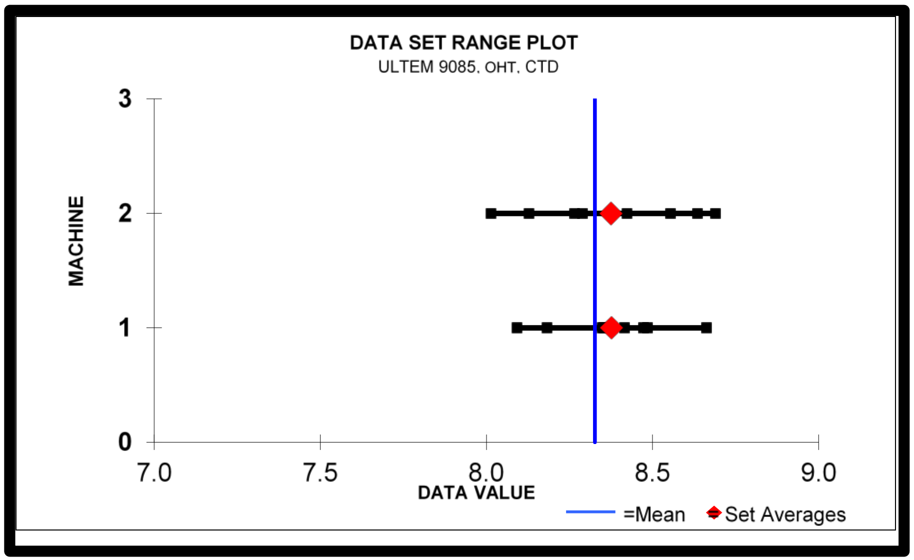
# Tension Data – Example of Compiled Data

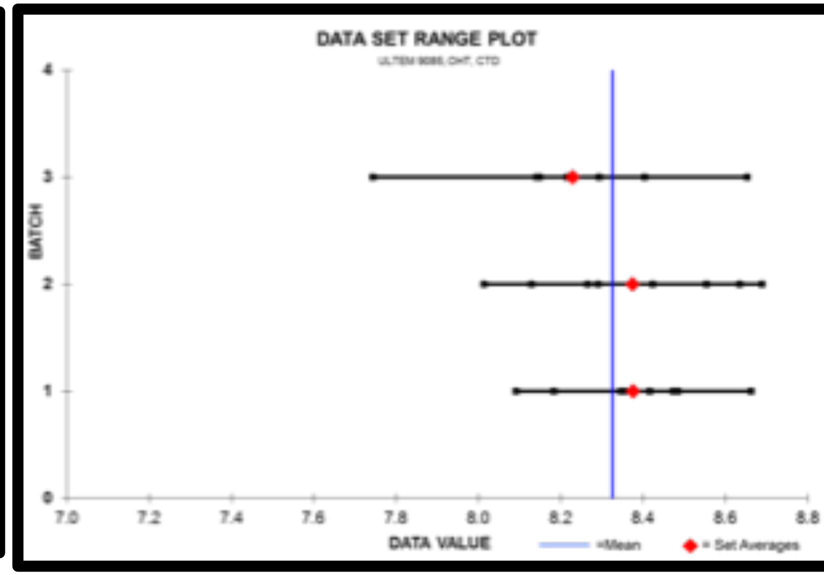
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Material: | Stratasys Certified ULTEM™ 9085 | | | | | | | | |
| Test Method: | ASTM D638 | | | | | | | Tension, Type 1<br>Fortus 900mc<br>As Built, -45/45 | |
| | | CTD | | | | RTD | | | |
| Test Temperature [F]<br>Moisture Condition<br>Equilibrium at T, RH | | -65 | | | | 70 | | | |
| Print Orientation: | | XY | XZ | Z45 | ZX | XY | XZ | Z45 | ZX |
| Tension Strength (ksi) | Mean | 12.96 | 13.59 | 9.77 | 10.59 | 9.73 | 11.18 | 7.96 | 8.55 |
| | Minimum | 11.47 | 11.58 | 8.85 | 7.88 | 8.74 | 10.39 | 7.41 | 8.31 |
| | Maximum | 14.50 | 15.05 | 10.88 | 11.88 | 10.14 | 12.27 | 8.79 | 9.08 |
| | C.V.(%) | 5.13 | 6.81 | 4.77 | 8.32 | 3.37 | 3.82 | 4.91 | 2.13 |
| | No. Specimens | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| | No. Batches | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Tension 0.2% Yield Strength (ksi) | Mean | 6.71 | 7.79 | 6.61 | 6.83 | 5.54 | 6.56 | 5.37 | 5.54 |
| | Minimum | 5.56 | 6.76 | 5.84 | 6.19 | 4.89 | 5.93 | 4.98 | 5.25 |
| | Maximum | 8.92 | 8.58 | 7.78 | 7.61 | 5.98 | 7.13 | 6.13 | 5.83 |
| | C.V.(%) | 10.58 | 6.41 | 8.31 | 6.29 | 4.55 | 5.01 | 5.47 | 2.51 |
| | No. Specimens | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| | No. Batches | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Tension Modulus (Msi) | Mean | 0.39 | 0.43 | 0.39 | 0.39 | 0.34 | 0.38 | 0.34 | 0.35 |
| | Minimum | 0.36 | 0.41 | 0.35 | 0.38 | 0.32 | 0.37 | 0.30 | 0.34 |
| | Maximum | 0.42 | 0.46 | 0.42 | 0.41 | 0.36 | 0.39 | 0.36 | 0.36 |
| | C.V.(%) | 4.60 | 2.37 | 4.81 | 2.53 | 2.51 | 1.52 | 3.97 | 1.84 |
| | No. Specimens | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| | No. Batches | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Poisson Ratio | Mean | | | | | | | | |
| | No. Specimens | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| | No. Batches | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

# Tension Data – Room Temperature Dry



# Variability – Machine, Batch




***NOTE: Batches and machines can be pooled.***

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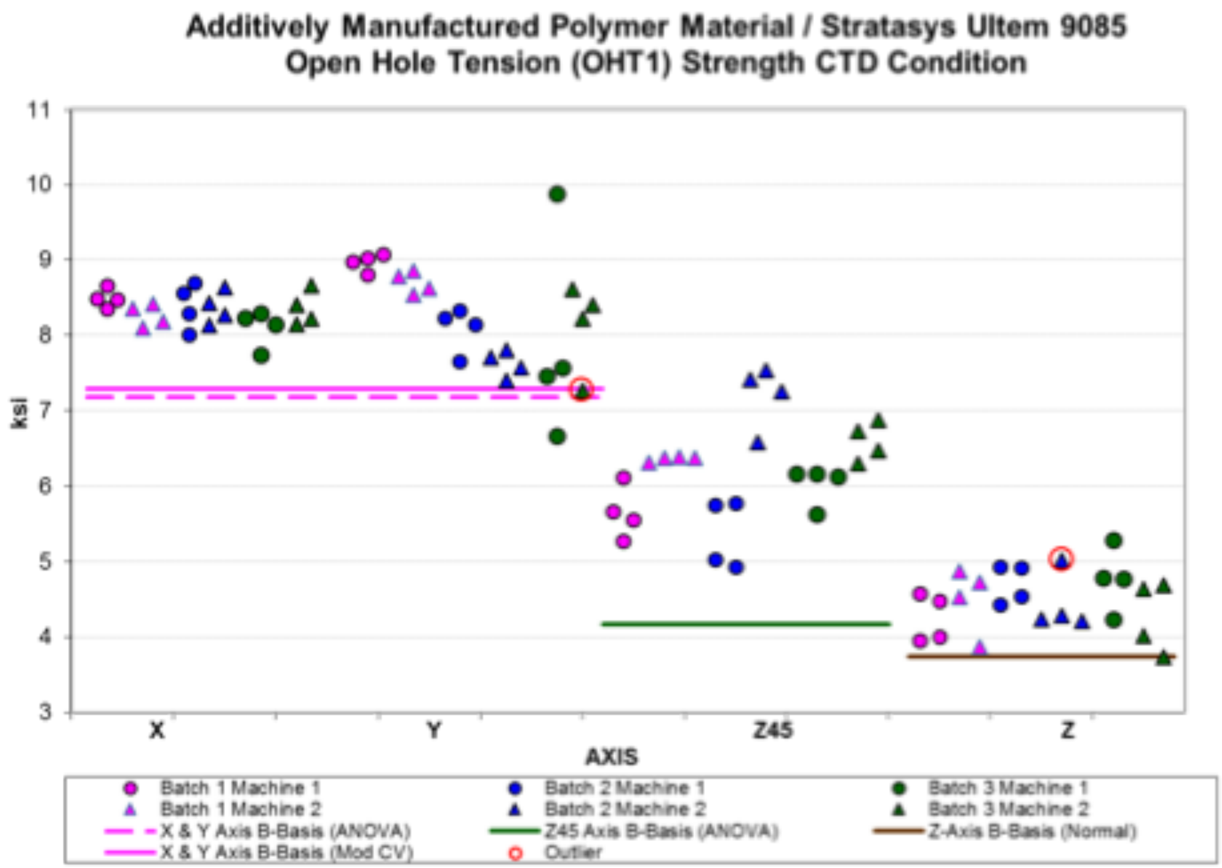
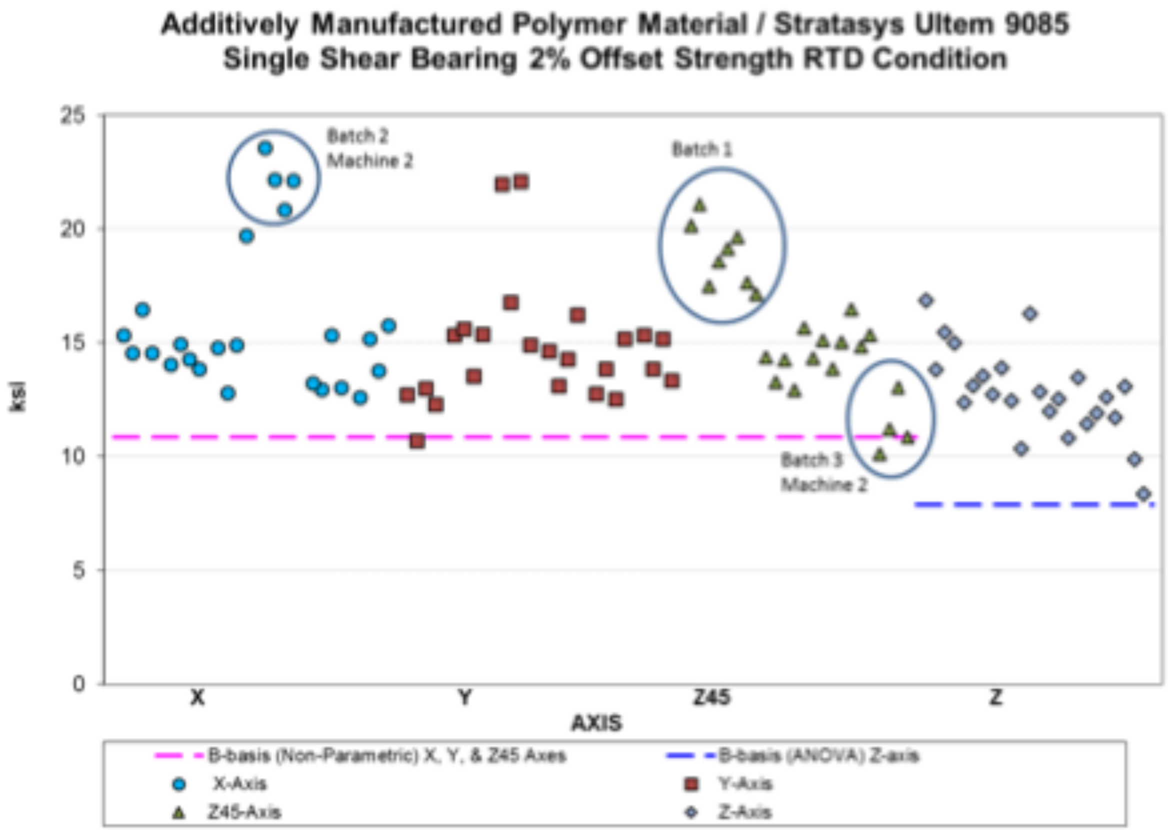
# Sample Results – OHT, CTD condition




- CVs: 3 – 9%
- X and Y build directions are poolable
- Few outliers

# Sample Results – SSB, RTD condition




- Higher CVs
- X, Y and Z45 are poolable
- Batch to batch variability seen

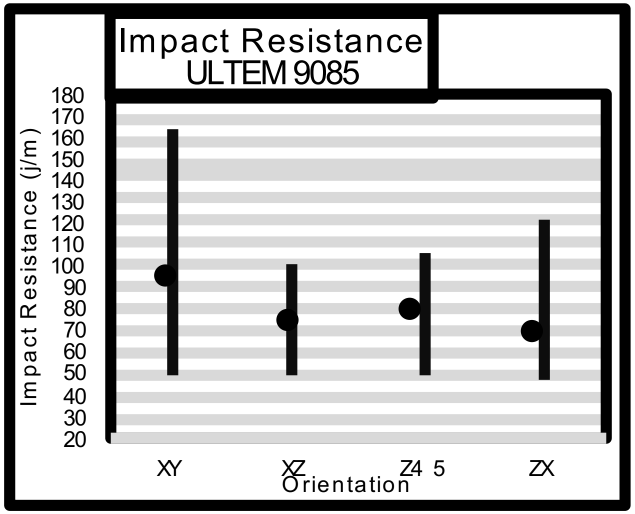
# IZOD Impact Resistance Data – Example of Variation within Data

**IZOD Impact**

**Fortus 900mc**
**Unnotched**

**-45/45**

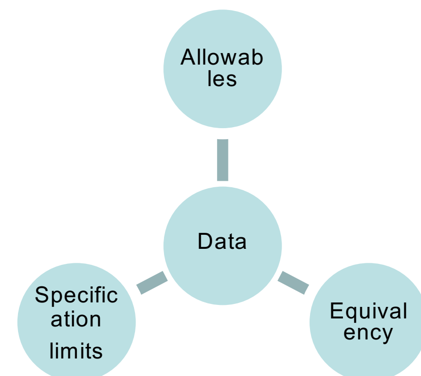
| | | | | | |
|---|---|---|---|---|---|
| Material: | | Stratasys Certified ULTEM™ 9085 | | | |
| Test Method: | | ASTM D6742 | | | |
| | | RTD | | | |
| Test Temperature [F] Moisture Condition Equilibrium at T, RH | | 70 | | | |
| Print Orientation: | | XY | XZ | Z45 | ZX |
| | Mean | 94.91 | 73.73 | 78.99 | 69.31 |
| | Minimum | 49.54 | 49.39 | 50.15 | 47.15 |
| Impact | Maximum | 163.69 | 98.48 | 106.97 | 122.52 |
| Resistance | C.V.(%) | | | | |
| (joules/meter) | | 30.67 | 14.22 | 19.29 | 26.66 |
| | No. Specimens | 24 | 24 | 24 | 24 |
| | No. Batches | 3 | 3 | 3 | 3 |



# Task 3: Development of statistical guidelines

*GOAL: Understanding of how parameters interact and affect variability as well as final allowables.*

- Establish qualification statistical requirements. The factors affecting variability will be assessed during this task.
- Establish equivalency requirements including specification minimums for acceptance.



# Task 4: Guidelines and Recommendations

*GOAL: To provide guidance to industry for the collection of statistically meaningful critical data that designers need to utilize polymer-based additive manufacturing materials potentially including:*

- Creation of a shared polymer AM database including test data, material and process specifications and statistical analysis methods.
- Development of handbook data and guidelines (i.e., CMH-17) – *new Volume*
- Coordinate with SAE to develop specifications from this program.
- Coordinate with ASTM and NIST on test method development and modification
- Collaborate with other organizations involved – ongoing

# SAE AMS-AM Committee

- Formed in 2015 by request of FAA - *to assist the FAA in developing guidance material for AM certification.*
- **Scope**
  - To develop and maintain aerospace material and process specifications for additive manufacturing.
  - Tied to the appropriate shared material property database.
  - Ensure material specifications are controlled and traceable.
- Currently: 480+ members, 8 specs and 4 guidance documents in development
- First Polymer AM Spec = ULTEM 9085 and ULTEM 1010

U.S. Department of Transportation
Federal Aviation Administration

800 Independence Avenue S.W.
Washington, DC 20591

OCT 30 2015

Bruce L. Mahone
SAE International
1200 G. Street N.W., Suite 800
Washington, DC 20005

Dear Mr. Mahone:

Additive manufacturing (AM) technology offers many potential benefits, such as reducing material costs, requiring fewer parts for fabrication, and its ability to manufacture complex designs. Therefore, it is expected to rapidly proliferate in the aerospace industry. The Federal Aviation Administration (FAA) Design, Manufacturing, & Airworthiness Division (AIR-100) is aware of various current and forthcoming type certification, production certification, and parts manufacturer approval activities that use AM, as well as the gradual increase in criticality of such applications.

Despite this growing use of AM technology, aerospace companies, engineering associations, and Government agencies have made little attempt to collaborate in developing acceptable industry-wide aerospace standards and qualification/certification guidelines for AM materials and processes, or for the design, manufacture, and maintenance/repair of aircraft and engine components produced using AM. This lack of collaboration may result in inadequate or inconsistent approaches to AM qualification/certification methodologies and the design, manufacture, and maintenance/repair of AM parts.

To address this issue, the FAA is requesting that SAE International form a committee to develop Aerospace Materials Specifications, process standards, Aerospace Recommended Practices, and other related standards. This action will assist the FAA in developing guidance material for AM certification.

If you have any questions, please contact Jim Kabbara, Electrical and Mechanical Equipment Section, AIR-133, at (202) 267-1575.

Sincerely,

Susan J. M. Cabler
Acting Manager, Design, Manufacturing, &
Airworthiness Division
Aircraft Certification Service

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# Significance of Qualification Program

RESULTS

- First publically available Material Allowables for the FDM Process and ULTEM 9085
- Repeatability proven for the first time – *process is controlled*
- Understood to be a *Mature Process* widely utilized by industry
- Control demonstrates machine repeatability through process specification implementation
- Quantify material variability through process
- Quantify other design variables through process

***Several process controlled parameters addressed variability***

# Status – Based on FY2017 Deliverables

| | Activity | Completion Date | Milestone / Deliverable | |
|---|---|---|---|---|
| 1.1 | Hold kick-off meeting on PBAM | 8/24/2016 | Milestone | ✓ |
| 1.2 | Industry Steering Committee<br>- Establish group of participants<br>- Create online portal for document sharing and data repository | 9/30/2016 | Milestone | ✓ |
| 1.3 | Preliminary drafts of qualification framework<br>- Material and process specifications<br>- Test plan<br>- Conformity documentation | 3/31/2017 | Deliverable | ✓ |
| 1.4 | Qualification Builds<br>- Site audit complete<br>- Coupons builds complete and delivered to NIAR | 10/15/2017 | Milestone | ✓ |

# Status – Based on FY2017 Deliverables

| | Activity | Target Date | Milestone / Deliverable | Complete? |
|---|---|---|---|---|
| 1.1 | Literature Review<br>- Conduct a literature review of relevant PBAM Research.<br>- Document results of the review in a technical report. | 11/30/2017 | Deliverable | ✓ |
| 1.2 | Equivalency Builds<br>- Site audit complete<br>- Coupon builds complete and delivered to NIAR | 3/1/2018 | Milestone | ✓ |
| 1.3 | Qualification Testing<br>- Perform physical and mechanical testing on qualification builds.<br>– Generate test data for qualification program. | 7/1/2018 | Milestone | ✓ |
| 1.4 | Equivalency Testing<br>- Perform physical and mechanical testing on equivalency builds.<br>– Generate test data for equivalency program. | 8/1/2018 | Milestone | |
| 1.5 | Develop Statistical Guidelines based on qualification data | 10/1/2018 | Milestone | |
| 1.6 | Develop Equivalency Guidelines based on qualification data | 12/31/2018 | Milestone | |
| 1.7 | NCAMP Reports on Qualification Data<br>- Material technical report<br>- Statistical analysis technical report | 2/28/2019 | Deliverable | |
| 1.8 | CMH-17<br>- Submit content, data, and protocols to Composite Materials Handbook 17 (CMH-17) | 5/31/2019 | Deliverable | |
| 1.9 | Final Report<br>- Final Technical Report on the Guidelines for PBAM Qualification. | 8/30/2019 | Deliverable | |

# Looking forward

- Benefit to Aviation
  - First AM qualification database with M&P specs
  - Understanding of relevant considerations – how to qualify an AM process, parameters, sources of variability
- Future needs
  - Perform qualification on other AM materials, including filled/reinforced AM or other processes
  - Determine if framework can be pulled to metallic AM
  - Machine Variability – machine type investigation
  - Building Block – how do coupon properties correlate to part properties

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