ADVANCED COMPOSITES TECHNOLOGY DEVELOPMENT AT THE NASA LANGLEY RESEARCH CENTER

John W. Connell, Ph.D.

Senior Materials Research Engineer

Advanced Materials and Processing Branch

NASA Langley Research Center

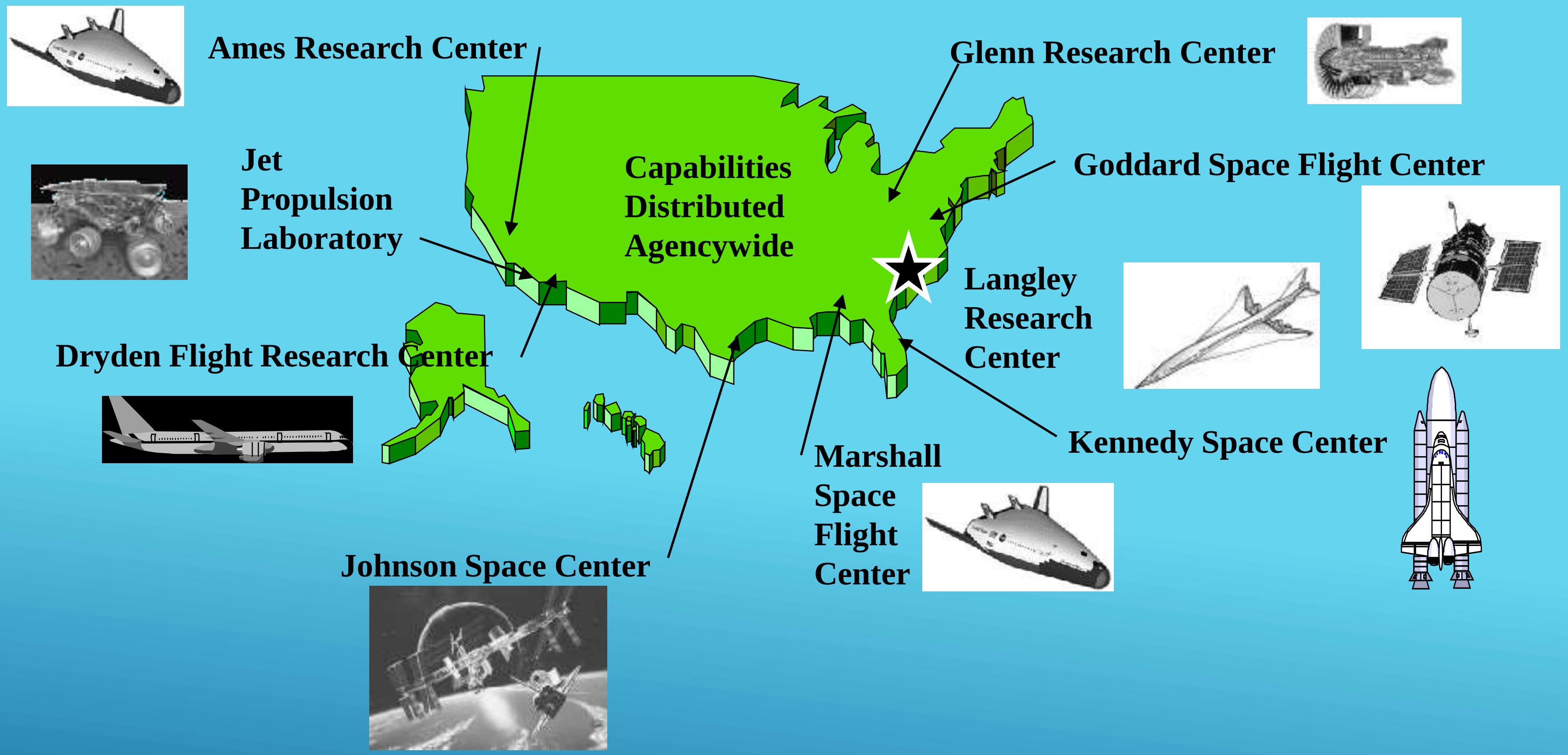
Hampton, VA 23681-2199

Presented at the Airtec 2014 9th International Aerospace Supply Fair
October 28-30, 2014 Frankfurt, Germany

Outline of Presentation

- Brief overview of Langley Research Center
- NASA's Advanced Composite Project
- Focus on adhesive bonding aspects
  - Energetic, automated surface treatment processes
    - Plasma
    - Laser
- Concluding Remarks

NASA Field Centers



Ames Research Center

Jet
Propulsion
Laboratory

Dryden Flight Research Center

Johnson Space Center

Capabilities
Distributed
Agencywide

Marshall
Space
Flight
Center

Glenn Research Center

Goddard Space Flight Center

Langley
Research
Center

Kennedy Space Center

NASA Langley Research Center

Hampton, Virginia

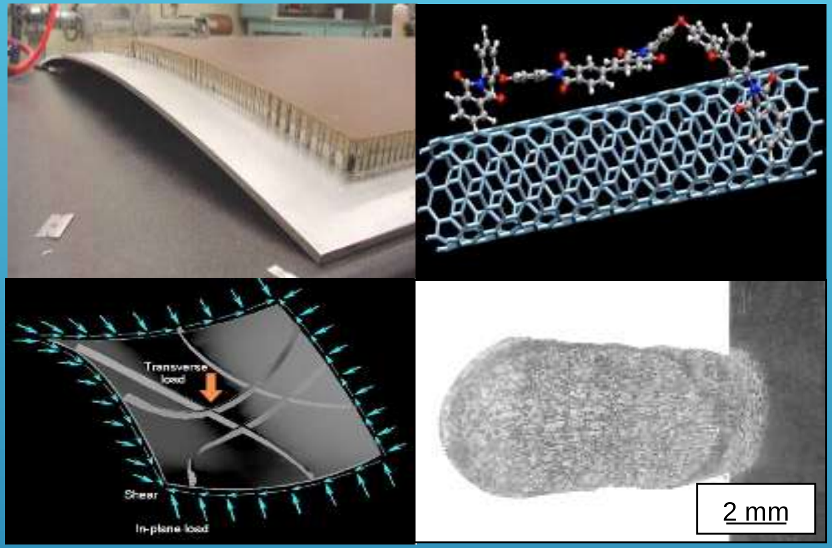
Founded in 1917: first civil aeronautical research laboratory

Facilities: $4 billion replacement value

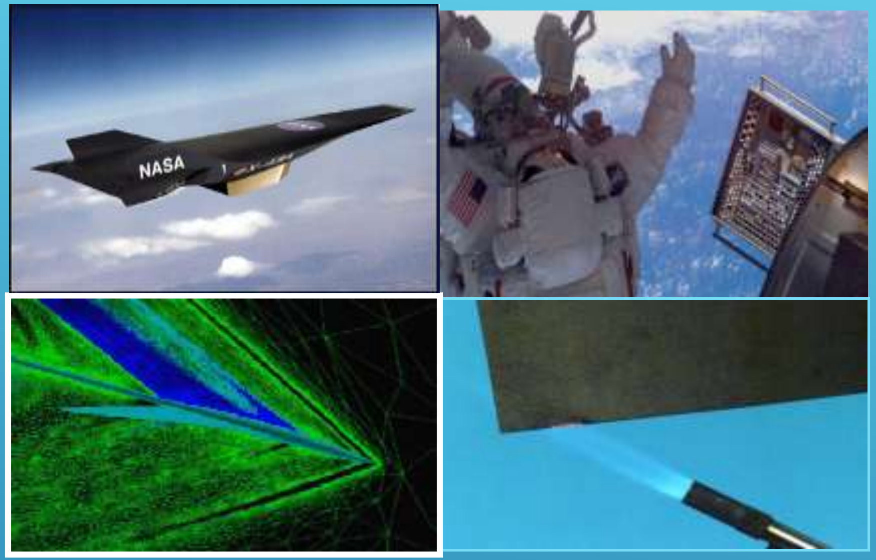
People: 2000 Civil Servants ; 1700 Contractors

ADVANCED MATERIALS AND PROCESSING BRANCH

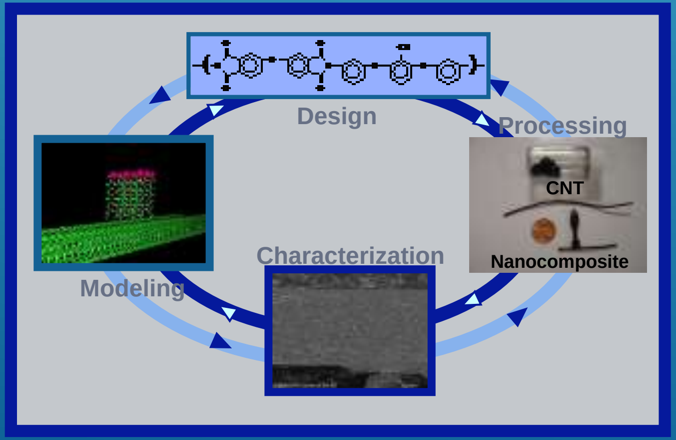
Advanced Material Systems



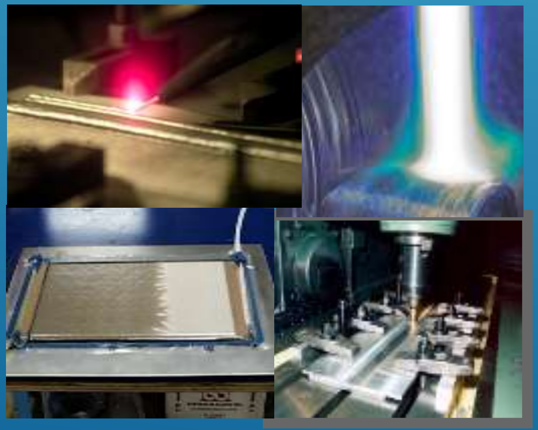
Materials for Extreme Environments



Materials Design



Innovative Materials Processing



Materials Testing

ADVANCED MATERIALS AND PROCESSING BRANCH

- 20,000 sq ft facility, 11 polymer synthesis laboratories with 22 chemical fume hoods
- Polymer characterization labs for complete spectrum of thermal, molecular weight and mechanical properties
- Comprehensive microscopy and spectroscopy facilities
- Processing equipment includes two autoclaves (700°F 400 psi), four vacuum presses, a modular prepreg machine, vacuum assisted resin transfer molding (VARTM), high-temperature VARTM, vacuum bag processing, various size ovens, and a heated head automated tape placement (ATP) facility

NASA LANGLEY CAPABILITY

“EXTRAORDINARY PLATFORM FOR COMPOSITES MANUFACTURING ”

- Highly-flexible automated manufacturing capability
- Appropriate scale for research activities & support of NASA missions
- Great opportunity to establish NASA leadership role in composites
- Top training ground for young talent – hands on exposure/experience
- Opportunity for government and industry stronger collaboration
- Goals: innovation, leadership, collaboration, competitiveness

Goal: To increase the use of composites in NASA missions

FULLY INTEGRATED RESEARCH ACROSS TRL SPECTRUM

TRL 1-3

Develop
New Resins
and Fibers

Pre-Pregging of
Composite Tows

Develop Advanced
Manufacturing and
and NDE Processes

TRL 4-6

Design and Manufacture of
Composite Structures

Post-Cure, In-Situ NDE
of Composite Structures

Testing and Analyses of
Composite Structures

TRL 7+

Fabrication of
Smaller Flight
Structures

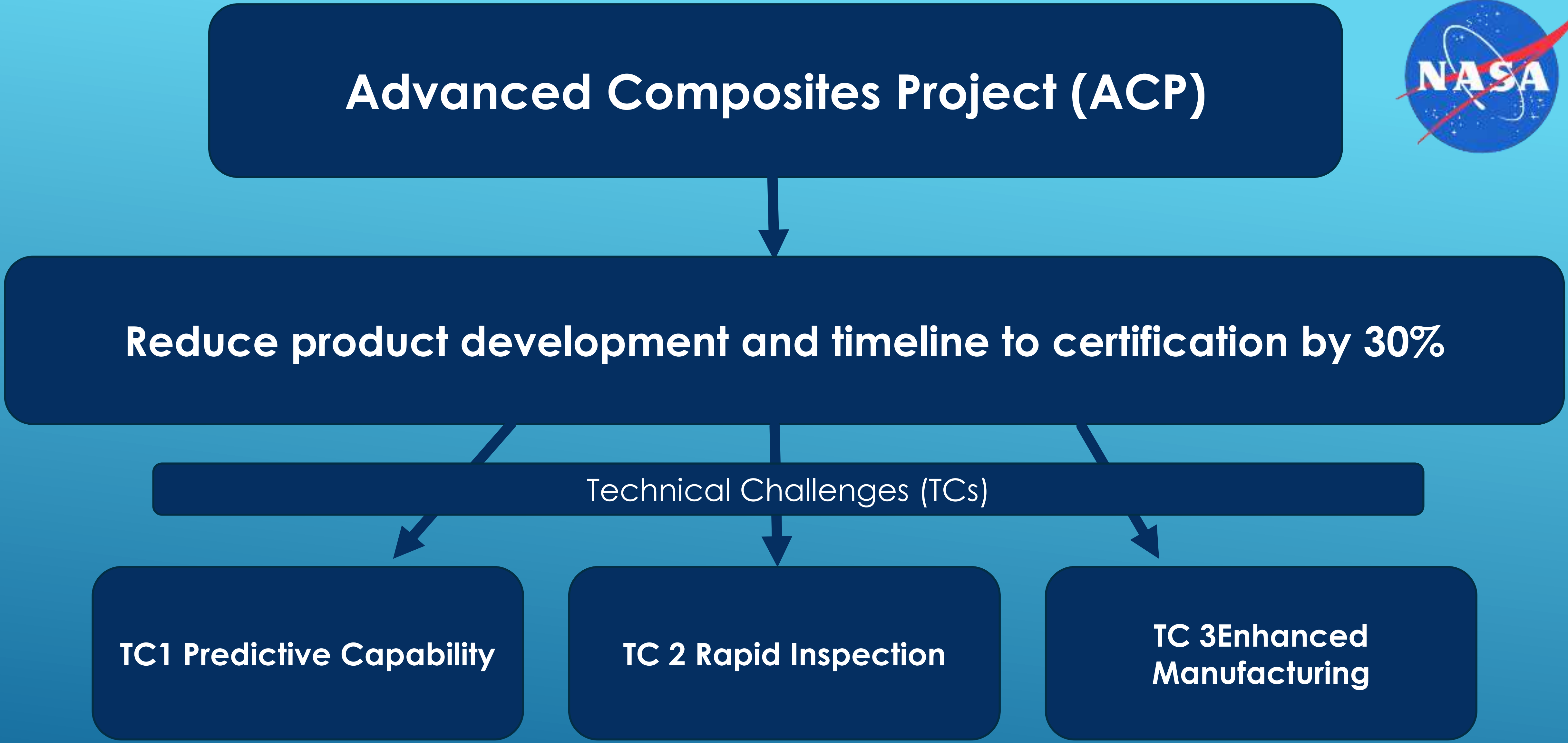
Aeronautics Research Mission Directorate
Advanced Air Vehicles Program
Advanced Composites Project

PI, Dr. Richard Young
PM, Dr. Stanley Smeltzer

Industry Partners

- Bell Helicopter Textron Inc. of Fort Worth, Texas
- GE Aviation of Cincinnati
- Lockheed Martin Aeronautics Company of Palmdale, Calif.
- Northrop Grumman Aerospace Systems of Redondo Beach, Calif.
- Boeing Research & Technology of St. Louis
- United Technologies Corporation and subsidiary Pratt & Whitney of Hartford, Conn.

The six firms were chosen for their technical expertise, willingness and ability to share in costs, certification experience with government agencies, focused technology areas and partnership histories.



Advanced Composites Project (ACP)

Reduce product development and timeline to certification by 30%

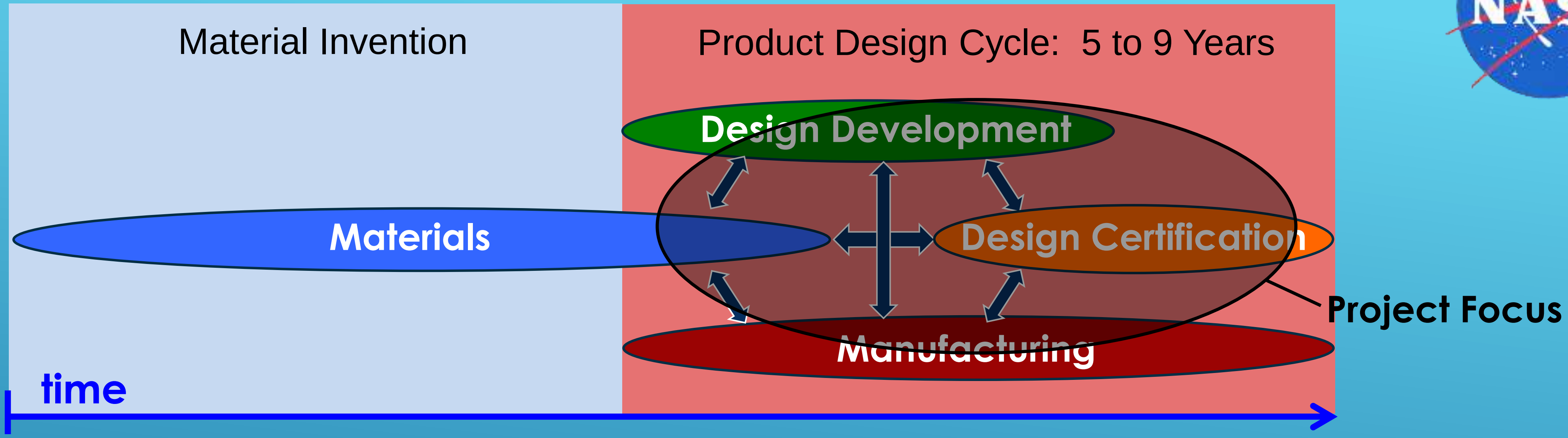
Technical Challenges (TCs)

TC1 Predictive Capability

TC 2 Rapid Inspection

TC 3Enhanced Manufacturing

PROJECT GOAL



Why Slow

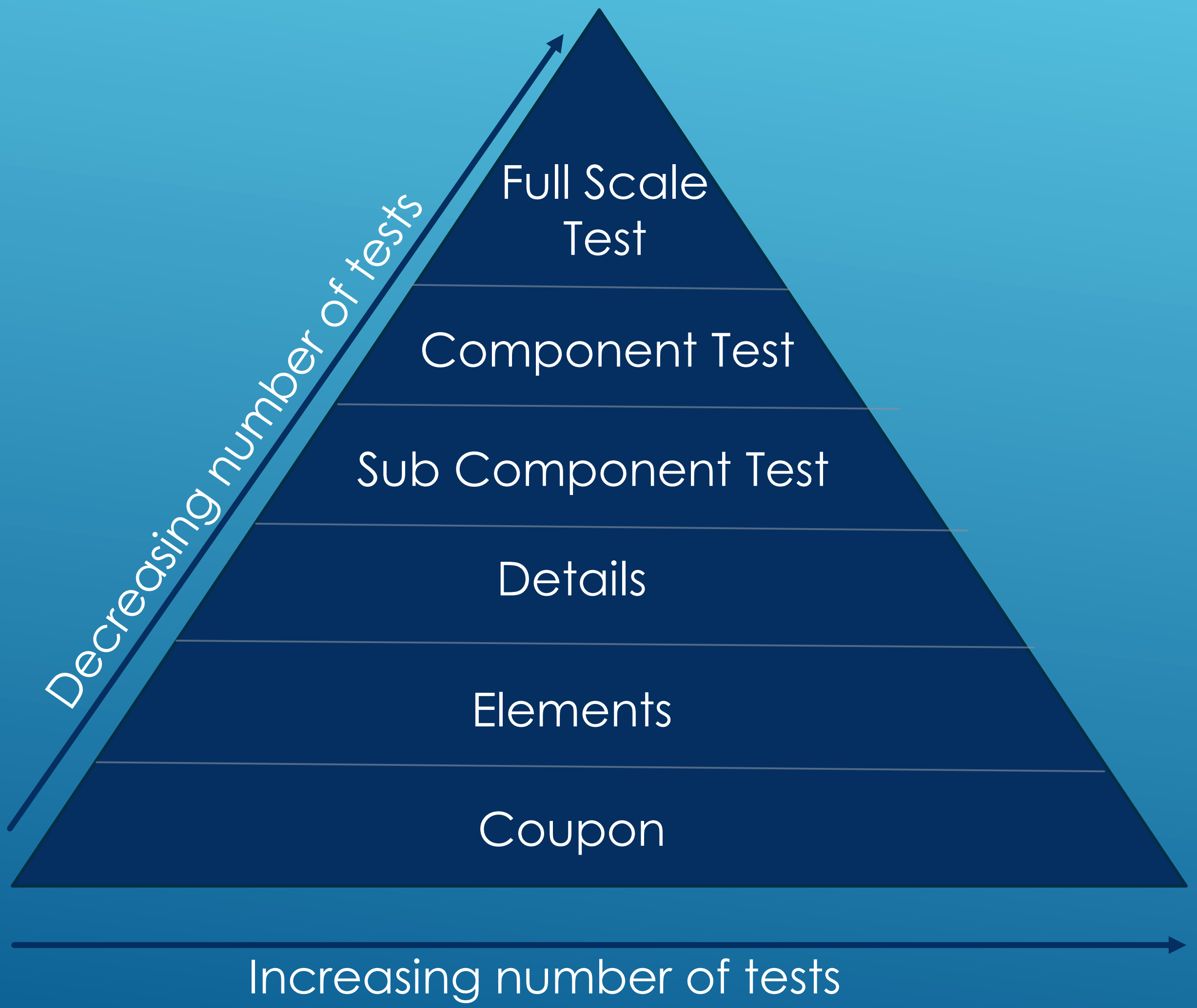
- Complexity:
  construction, failure modes, variability
- Strength and life not predicted reliably
- Design and manufacturing coupled
- Empirical and iterative methods

Goal: Reduce product development and certification timeline by 30%

- Baseline Model
- Tall Poles: validate with case studies sub-component / component level
- Systems Analysis

Project Goal

Traditional building block approach



Full Scale Test

Component Test

Sub Component Test

Details

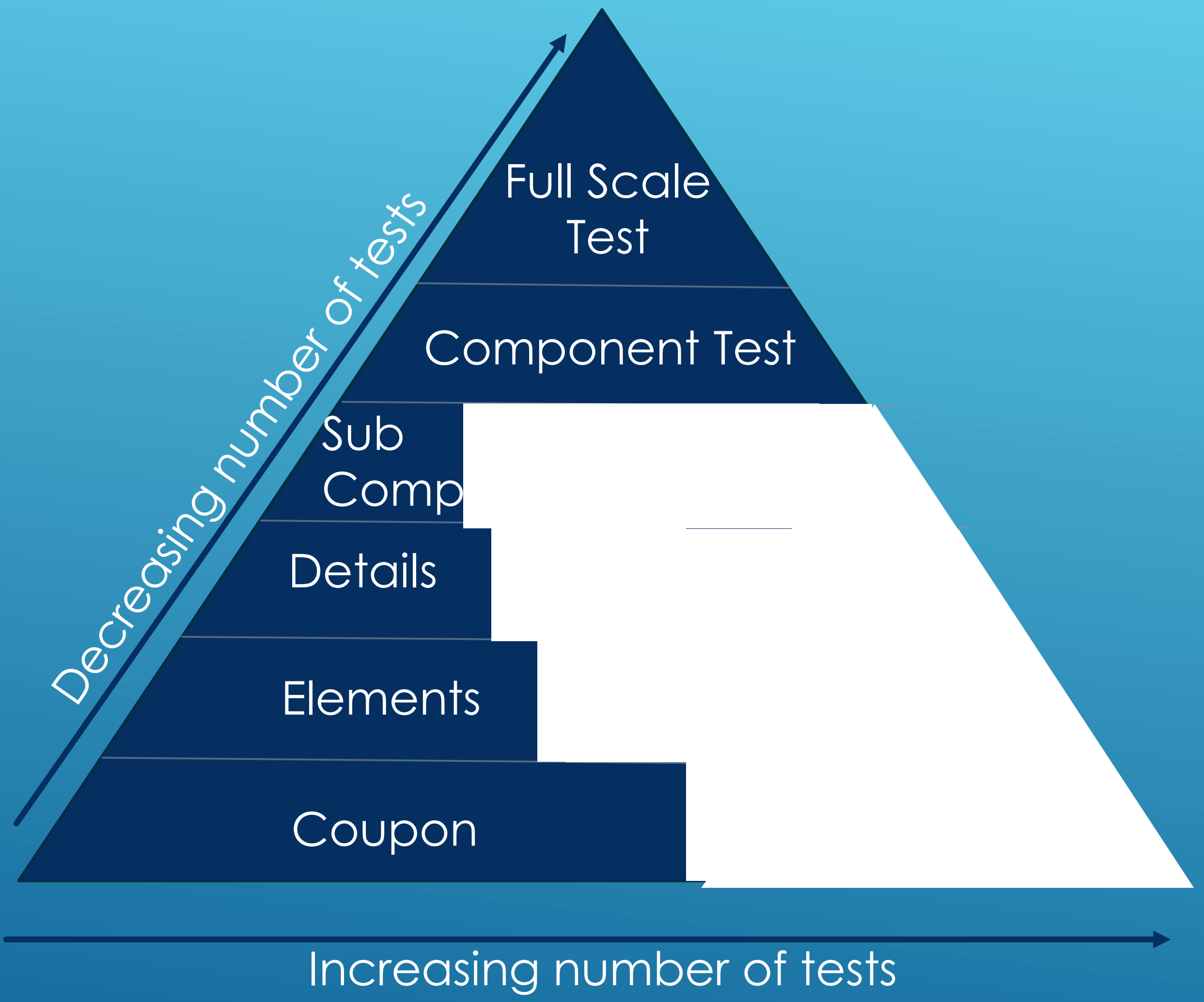
Elements

Coupon

Decreasing number of tests

Increasing number of tests

Future predictive and simulation approach



Full Scale Test

Component Test

Sub Comp

Details

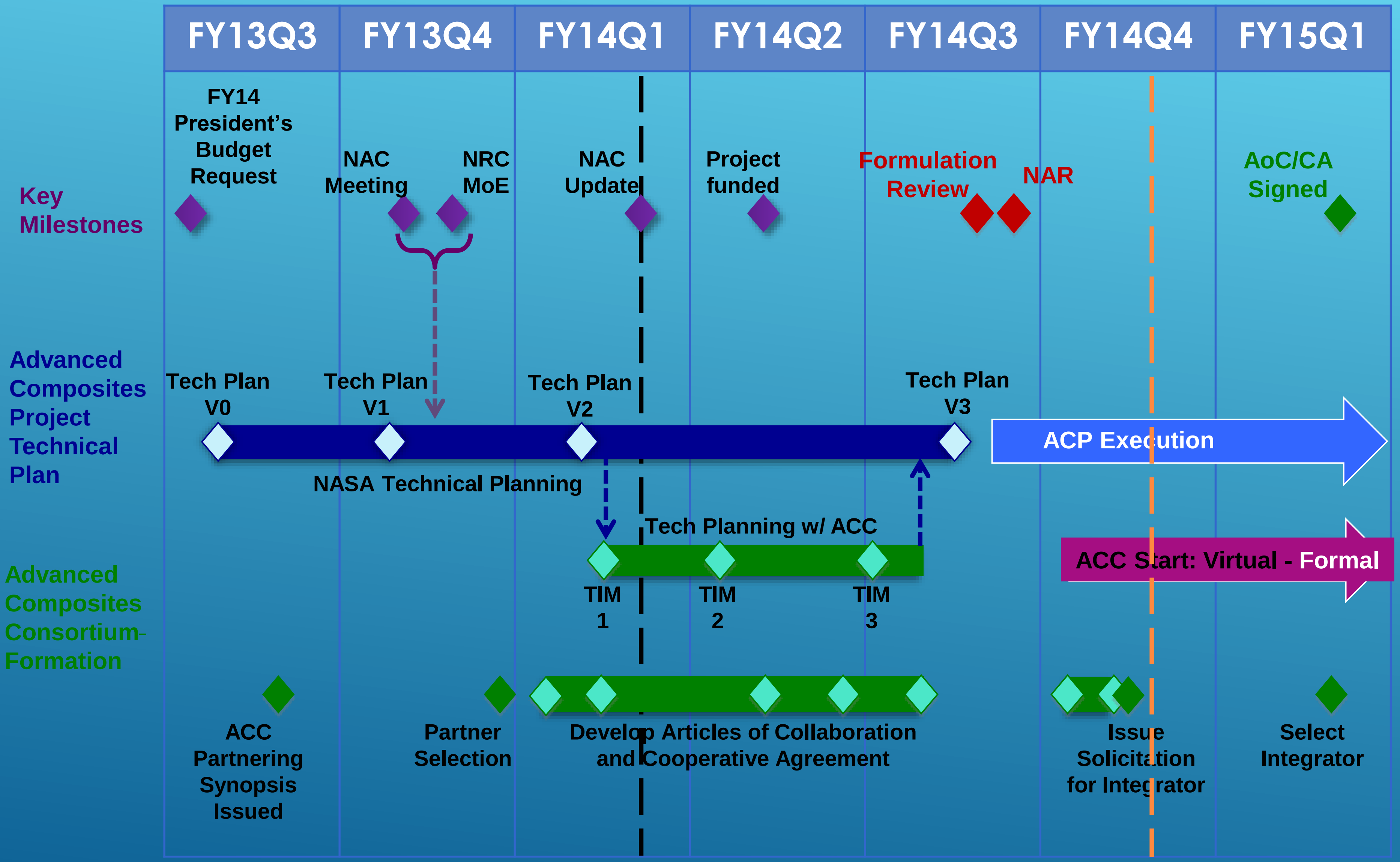
Elements

Coupon

Decreasing number of tests

Increasing number of tests

ACP / ACC FORMATION



FY13Q3 | FY13Q4 | FY14Q1 | FY14Q2 | FY14Q3 | FY14Q4 | FY15Q1

Key Milestones

FY14 President's Budget Request

NAC Meeting

NRC MoE

NAC Update

Project funded

Formulation Review

NAR

AoC/CA Signed

Advanced Composites Project Technical Plan

Tech Plan V0

Tech Plan V1

Tech Plan V2

Tech Plan V3

NASA Technical Planning

ACP Execution

Advanced Composites Consortium-Formation

Tech Planning w/ ACC

TIM 1

TIM 2

TIM 3

ACC Start: Virtual - Formal

ACC Partnering Synopsis Issued

Partner Selection

Develop Articles of Collaboration and Cooperative Agreement

Issue Solicitation for Integrator

Select Integrator

NASA Project Planning with Partner Input

Portfolio Formulation

Community Needs

1. Material qualification databases
2. Progressive damage modeling
3. Design coupled to manufacturing
4. Bonding and bond qualification
5. Manufacturing tooling and molds
6. Accelerated certification approaches
7. Material durability and aging
8. Education of workforce

- Systems Engineering

Apply Filters

Tech Challenges (v1)

1. Efficient Design
2. Streamlined Certification
3. Progressive Damage Modeling
4. Enhanced Manufacturing
5. Systems Assessment

Vet & Refine

Tech Challenges (v2)

1. Predictive Capability
2. Rapid Inspection
3. Manufacturing Process & Simulation

Team Validation & Tech Roadmaps

TC 1

TC 2

TC 3

- Content, ROM $, time

Phase I Execution

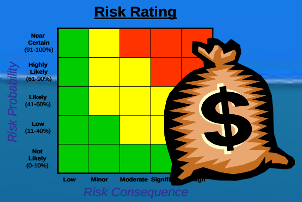
Team-Developed Detailed Technical Work Packages

Execute & Evaluate

- Fabricate
- Test
- Analysis
- Timeline model

Manage Portfolio

- Cost/Benefit/Risk Analysis
- Down-select



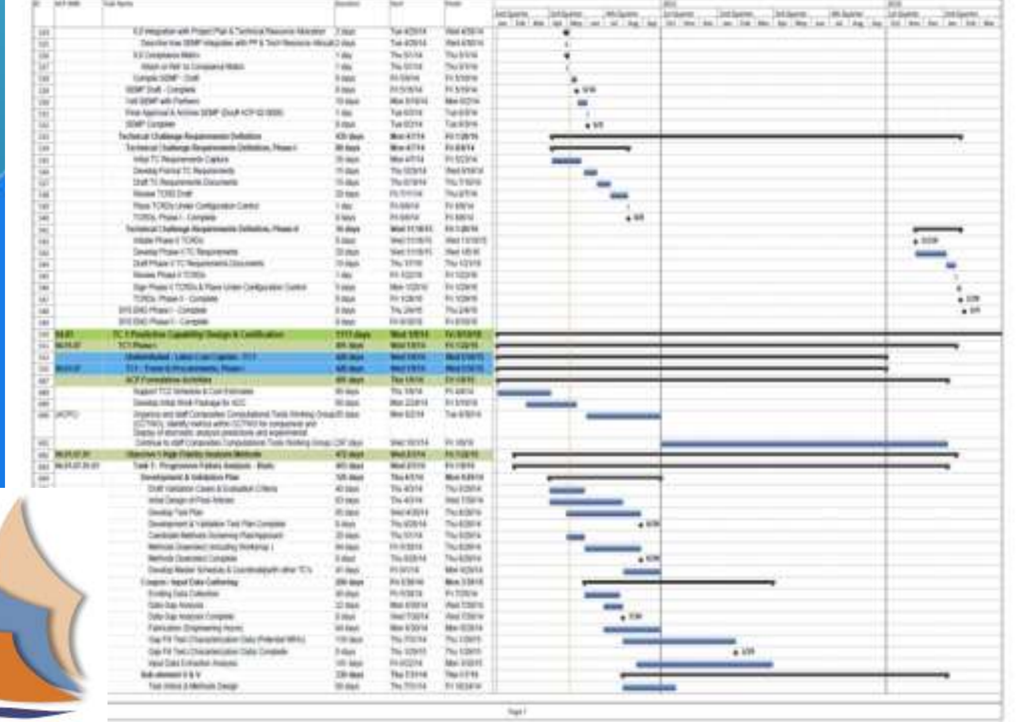
Team Validation and Technology Roadmaps

Portfolio Formulation

Community Needs

1. Material qualification databases
2. Progressive damage modeling
3. Design coupled to manufacturing
4. Bonding and bond qualification
5. Manufacturing tooling and molds
6. Accelerated certification approaches
7. Material durability and aging
8. Education of workforce

- Systems Engineering



Apply Filters

Tech Challenges (v1)

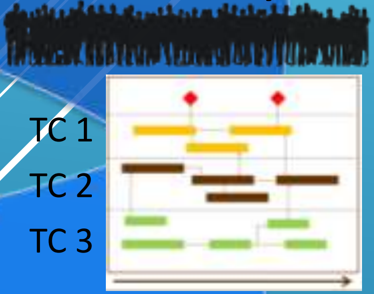
1. Efficient Design
2. Streamlined Certification
3. Progressive Damage Modeling
4. Enhanced Manufacturing
5. Systems Assessment

Vet & Refine

Tech Challenges (v2)

1. Predictive Capability
2. Rapid Inspection
3. Manufacturing Process & Simulation

Team Validation & Tech Roadmaps

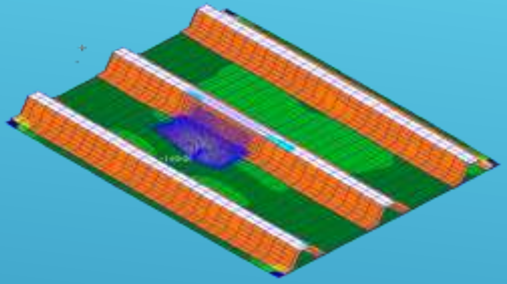


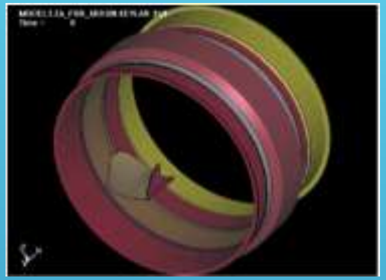
- Content, ROM $, time

TECHNICAL CHALLENGES

TC1 Predictive Capabilities

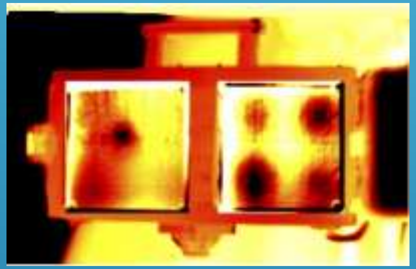
- Robust analysis reducing physical testing
- Better prelim design, fewer redesigns





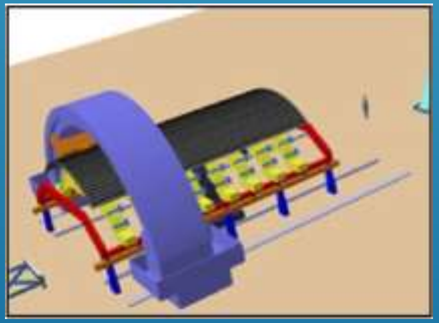
TC2 Rapid Inspection

- Increase inspection throughput
- Quantitative characterization of defects
- Automated inspection



TC 3 Manufacturing Process & Simulation

- Reduce manufacture development time
- Improve quality control
- Fiber placement and cure process models



TC3, OBJECTIVE 2 “BONDED STRUCTURE”

Description: Develop bonding process methods leading to improved manufacturing quality control for co-bond and co-cured structure.

State of current practice: Process development of sandwich structure requires empirical trial and error testing. Effects of process parameters of sandwich structure are not fully understood. Bonded joints require labor intensive, time consuming surface preparation that can be inconsistent and difficult to certify.

Benefits over current practice:

1. Science based process model that eliminates/ reduces trial and error testing
2. Better control of process parameters leading to more consistent / repeatable bond quality.
3. Automated, reproducible surface preparation techniques leading to more consistent / repeatable bond quality.

Reduces current development and certification timeline

1. Process model reduces the bonded structure build cycle time
2. Repeatable surface preparation process leads to reduced process development time and certification time.

TC3 OBJ2, Bonded Structure- Automated Surface Treatment Methodology
Importance of Surface Treatment to Adhesive Bonding

- The main driver to obtain FAA certification for adhesive bonding of primary airframe structure is to reduce weight, and cost and complexity of manufacturing by eliminating rivets. It will also expand aircraft design flexibility.

- Restrictions on the application of adhesively bonded joints in commercial aircraft stem from a lack of control in current bonding methods [1] [2].

- The premature or unexpected failure of an adhesive bond can usually be traced to defects in the preparation of the faying surface [3] [4].

- Current surface treatment techniques based on mechanical abrasion such as grit blasting or sanding, or peel-ply have limited control with respect to precision and reproducibility, create waste, and can leave behind contamination that reduces bond performance.

[1] R. Bossi and M. Piehl, *Manufacturing Engineering*, pp. 101-109, March 2011.

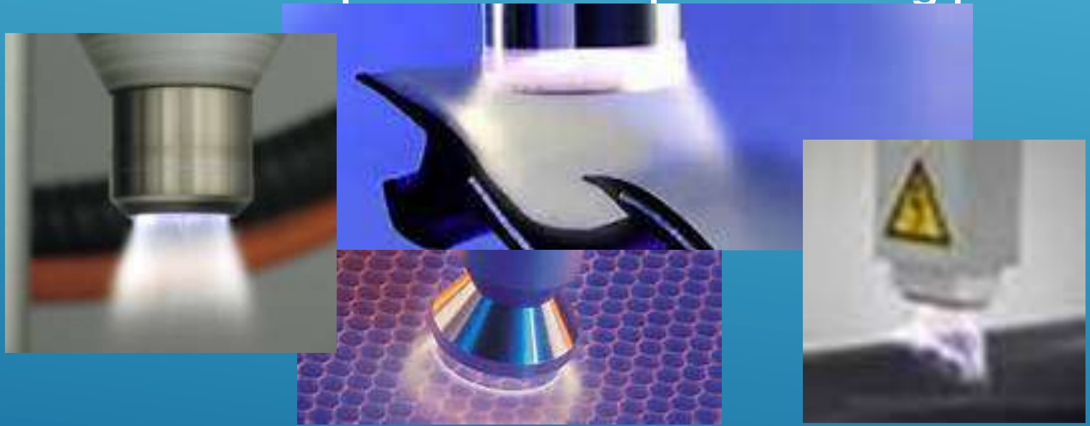
[2] M. Perton, *Journal of Physics D: Applied Physics*, vol. 44, pp. 1-12, 2011.

[3] G. Davis, *Surface and Interface Analysis*, vol. 20, pp. 368-372, 1993.

[4] M. Davis and D. Bond, *International Journal of Adhesion and Adhesives*, vol. 19, pp. 91-105, 1999.

TC3 OBJ2, Bonded Structure- Automated Surface Treatment Methodology

The FAA specifically calls out the need for " ... strict in process control and post-bond inspections .. " in the document Bonded Joints and Structures-Technical Issues and Certification Considerations, PS ACE-2005-10038 as part of the manufacturing quality management. This " process control mentality" is further emphasized in AC 20-107B. The concern is with the final strength of a bonded joint, which depends upon the proper completion of a number of steps that make up the bonding process.



Objective: Develop a high precision, reproducible surface treatment process for aerospace structural metal alloys and carbon fiber reinforced composites (CFRPs) that is amenable to automation and scale-up that becomes part of an overall bonding process leading to the certification of primary bonded structure on commercial aircraft.

Approach: Investigate the use of laser ablation as a high precision process for surface treatment of aerospace Al and Ti alloys, and CFRPs for adhesive bonding.

Justification: Process control is a critical component needed to enable a FAA approved certification methodology for adhesive bonded primary commercial transport aircraft structure.

SURFACE TREATMENT FOR ADHESIVE BONDING OF COMPOSITES

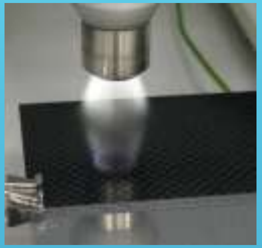
- To generate chemical functional groups that can react with the adhesive
  - This is the primary basis for durable adhesion
  - Chemical bond formation is essential to provide strength and durability

- To remove any contaminants on the surface prior to adhesive bonding
  - Contaminates can be from the manufacturing process (i.e. mold release, release plys, coated breather cloths, etc., or from human interactions)

- Composites fabricated by different techniques may have different types of contaminants, and may have different surface characteristics (i.e. autoclave processed parts may have more of a resin rich surface than a part fabricated by AFP.

A.J. Kinlock, Adhesion and Adhesives, Chapman and Hall, p. 78 1987.

ENERGETIC SURFACE TREATMENTS



Plasma Surface Treatment

- Variety of open air (atmospheric pressure) types available
- May require a carrier gas
- Creates oxygenated surface (oxygen gas or open air) species and removes contaminates
- Affects about top 5 nm of surface, no topography introduced
- Must be within 0.5 inches of surface to be effective
- Exposure to plasma is generally not harmful
- Not effective for metallic alloys
- Amenable to rapid throughput and automation

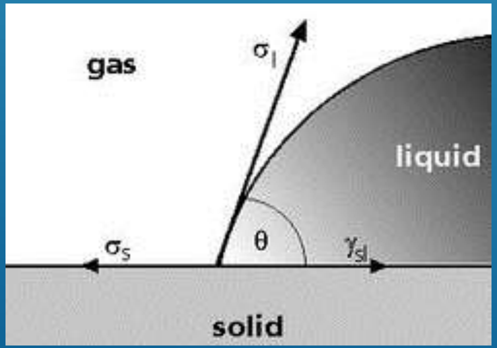
Laser Surface Treatment

- Variety of laser types
- Can create oxygenated surface (open air) species and remove contaminates
- Penetration depth can be customized for specific part types by adjusting power, frequency
- Topography can be introduced
- Effective for Al and Ti alloys, can remove chemical dip steps
- Requires safety measures for operation
- Amenable to rapid throughput and automation

RAPID INSPECTION SURFACE CHARACTERIZATION TECHNIQUES

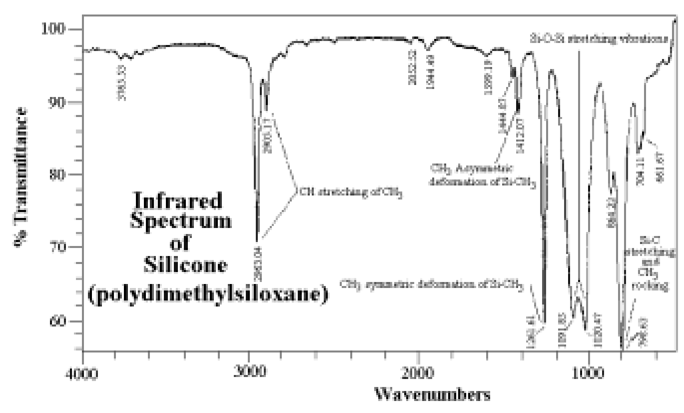
Hand Held Water Contact Angle Measurement

- Places a water droplet on a surface, and measures contact angle in real time
- Measures a relatively small area
- Contact angle can be used to **infer** surface energy and wettability
- Rapid, amenable to in-line QC
- Does not give any chemical or molecular level information
- As a single test, reliability it is likely insufficient



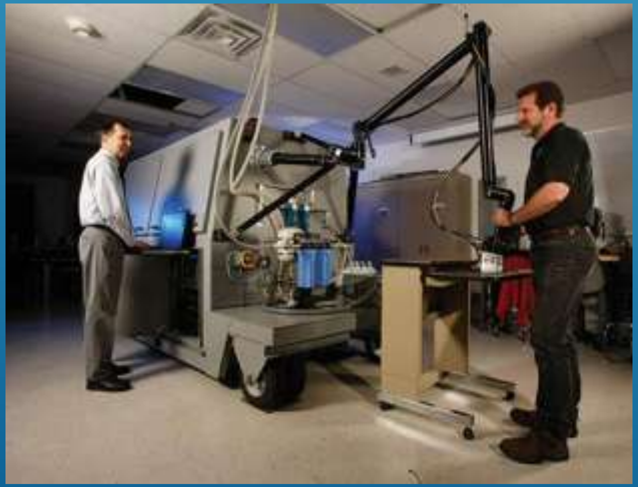
Hand Held Fourier transform Infrared Spectroscopy

- Scans a surface rapidly and produces a spectra that identifies specific chemical functional groups and species
- Measures a relatively small area
- Rapid, amenable to in-line QC
- Applicable to many different composite types, although some customization will likely be needed



WHAT ELSE IS NEEDED?

- FAA Part 21 advisory circular planned for FY 16 to FY20 includes certification efficiency 7 “bonded structure guidance”
- Maturation of non destructive inspection techniques to detect weak bonds
- Rapid, portable and high precision
  - FAA would really like to have an NDI method that measures bond strength
- Closest method available that meets these criteria is the laser bond inspection system (LBID)



- Device sends a well-controlled dynamic stress to the adhesive bond that propagates through the composite structure and stresses bond lines
- The application of the dynamic stress on the composite material has no effect on the integrity of the material or bond when it is properly constructed
- When the bond is substandard (i.e. below design strength as a result of improper surface preparation or kissing bond), these defects can be identified

Summary

- NASA's ACP is underway with strong participation from industry partners
- Goal is to reduce product development and time to certification by 30% by focusing on predictive capabilities, rapid inspection and manufacturing process and simulation

- Energetic surface treatment processes and inspection tools are under development and evaluation
- Optimization of process parameters and energies to achieve reproducible performance and minimize production costs is still required
- While differences exist between the methods, parameters can be adjusted to achieve acceptable results for both plasma and laser based methods
- Specific material systems, and specific part fabrication techniques will likely require customization of these processes to achieve desirable performance in adhesive bonding
- The ability to control the application parameters of the energetic methods combined with high fidelity, molecular level, rapid inspection techniques provides a pathway for achieving robust durable bonded systems
- Ultimately an acceptable NDI technique to assess bond integrity will likely be needed to achieve certification for primary airframe structure

BACK-UP CHARTS

TC1, OBJECTIVE 1 “HIGH FIDELITY PDA MODELING TOOLS”

Description: Develop and validate high fidelity composite damage prediction methods sufficiently reliable to enable reduction of the element and subcomponent testing necessary for design development and certification.

State of current practice: Progressive damage methods and transient dynamic methods are not capable of reliably predicting all failure modes. Applicability and utility of progressive damage methods and transient dynamic methods, either alone or in combination, may depend on the material form and application. Few, if any, of these tools have been thoroughly validated. Hence, there is currently more reliance on testing relative to analysis for certification.

Benefits over current practice:

1. Develop industry standard validation framework
2. Establish Best Practices for new product certification
3. Improved manufacturing yield by ability to assess effects of defects
4. Enable expanded design space

Reduces current development and certification timeline

1. Element and subcomponent testing represent a substantial time and cost, and could be replaced by better analysis
2. Reduce incidences of redesign late in development cycle

TC1, OBJECTIVE 2 “RAPID DESIGN TOOLS”

Description: Develop rapid design tools to reduce preliminary design timeline and reduce redesign. Tools are needed to make design architecture and material selection decisions, to conduct trade studies and optimizations.

State of current practice: Gaps exist in the rapid design tools for simulating complex failure modes, which results in additional testing. Examples of gaps include post-buckled skin stringer analysis, damage tolerance analysis, and warpage residual stresses.

Benefits over current practice:

- More accurate preliminary designs

Reduces current development and certification timeline

- Reduce incidences of redesign late in development cycle

TC2, OBJECTIVE 1 “RAPID QUANTITATIVE CHARACTERIZATION OF DEFECTS”

Description: Identify defect types of most interest to industry and then develop methods to find, quantify, and efficiently pass composite specific defect data back for analysis in a digital environment.

State of current practice: Current inspection methods are not sufficient to quantify all the composite specific defects i.e., micro-cracks, subsurface wrinkles, bond strength, etc. In addition, current methods for handling inspection data do not allow for efficient use and rapid disposition of defects.

Benefits over current practice:

1. Effectively addressing composites specific defects more efficiently
2. Facilitates rapid disposition of quantified defects via progressive damage analysis
3. Manufacturing can more effectively use inspection data for improved manufacturing processes

Reduces current development and certification timeline

1. More accurately and quickly characterizes test articles used for development and certification and reduces the number of required tests
2. More quickly identifies the manufacturing issues responsible for the defect

TC2, OBJECTIVE 2 "DEVELOPMENT OF AUTOMATED INSPECTION TECHNIQUES"

Description: Identify automated inspection and analysis opportunities of most interest to industry by establishing a baseline of current practice for comparison of improvements, identifying and ranking candidate techniques. Develop high priority measurement and analysis techniques into validated methods for inspection automation.

State of current practice: Current inspection and analysis methods are time and labor intensive. They generate large data sets requiring highly skilled/subjective interpretation and don't allow for automated data fusion opportunities.

Benefits over current practice:

1. Reduces subjective interpretation of inspection data
2. More effective and efficient use of inspection information
3. Comprehensive automated tracking of structural health during the life of the component

Reduces current development and certification timeline

1. More accurately and quickly characterizes test articles used for development and certification and reduces the number of required tests
2. More quickly identifies the manufacturing issues responsible for the defect

TC3, OBJECTIVE 1 “PREDICTIVE TOOLS FOR AUTOMATED FABRICATION”

Description: Develop Predictive tools to streamline the design, analysis, and fabrication cycle time, predict automated fiber placement (AFP) induced defects, re-defining defect thresholds, and improve processability for fiber placed structures.

State of current practice: Current design and analysis is not linked to AFP processing and fabrication. AFP induced defects are reduced through time-consuming trial and error; AFP process models are non-existent. Induced defects require substantial rework, increasing cycle time and production certification. Current industry rework specifications are, in most cases, not based on supporting data. Close loop control of current Hot Air and IR heating systems cannot be achieved.

Benefits over current practice:

1. DFM will reduce the time consuming iterative process of design, analysis, and fabrication development
2. AFP process models will reduce trial-and-error development iterations and decreases production development time.
3. Better understanding of the effects of AFP defects will decrease production down-time related rework of defects
4. Closed loop control of the material placement temperature provides more accurate and precise control over tape surface temperature and heated zone.

Reduces current development and certification timeline

1. DFM will reduces the design–analysis and AFP build cycle time.
2. The ability to predict defects related to AFP will reduce fabrication development and reduce re-work..
3. Closed loop control of the material placement temperature reduces development and production time

TC3, OBJECTIVE 3 “PHYSICS-BASED CURE PROCESS MODELS”

Description: Develop cure process models with the goal of predicting laminate quality and reducing manufacturing rework due to defects, which often occur during the composite matrix cure.

State of current practice: Cure process models have been developed to accurately predict residual stress due the cure process. These physics-based process models are not currently capable of predicting common cure-induced defects, such as porosity and wrinkling, or accounting for the effects of raw material variability on cure-induced defects.

Benefits over current practice:

1. Physics based cure process model that predicts defects will reduce the SOA trial and error process associated with part fabrication development.
2. In-situ process sensors have potential to provide better understanding of cure process defect evolution.
3. Better control of critical incoming material properties will lead to more consistent composite part quality.

Reduces current development and certification timeline

1. A reduction in the trial and error iterative process directly translates to a reduced production process development timeline.
2. The work proposed will result in reduced part quality variability which reduces the timeline for production certification.

TC3 , OBJ 1 – Physics-based AFP Process Modeling

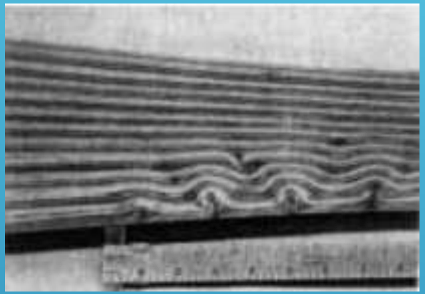
AFP Composites Manufacturing

Automated fiber placement has rapidly evolved to become the predominant manufacturing technology to efficiently fabricate both complex fixed–wing and rotorcraft airframe primary structure. Processing defects resulting during AFP contribute to significant production down-time due to the lack of understanding of how these defects occur and their effect on structural performance.

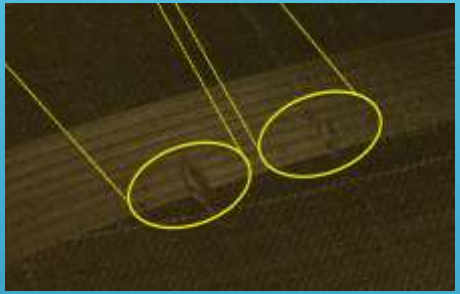
Today the certification of primary flight structures is largely an empirical enterprise with analysis serving in only a supporting role and this has led to resource intensive certification processes with enormous commitments of time to experimental tests. This commitment to an experiment dominated certification process is a significant barrier to innovation in both products and materials systems. The development of new analysis methods, such as physics-based processing models utilized with enhanced computational capacity, provide the framework upon which certification by analysis, supported by experiments can be realized.

Approach: Develop physics-based process models to predict defects resulting from the manufacturing process and material interaction which knock-down laminate performance. Exploit these models to reduce the trial-and-error approach currently utilized to reach production certification.

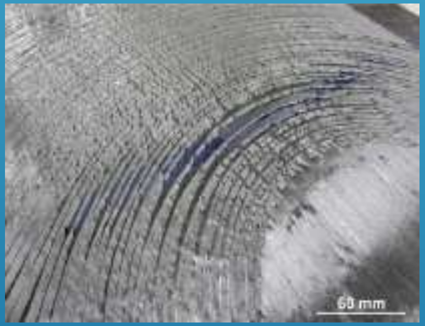
AFP Induced Defects



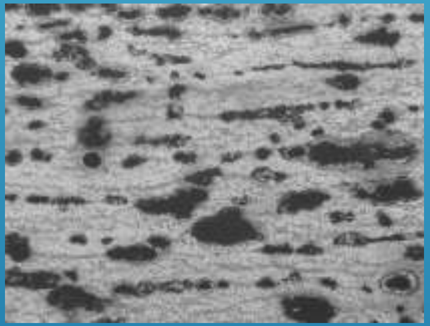
Ply Waviness



Wrinkles



Puckering



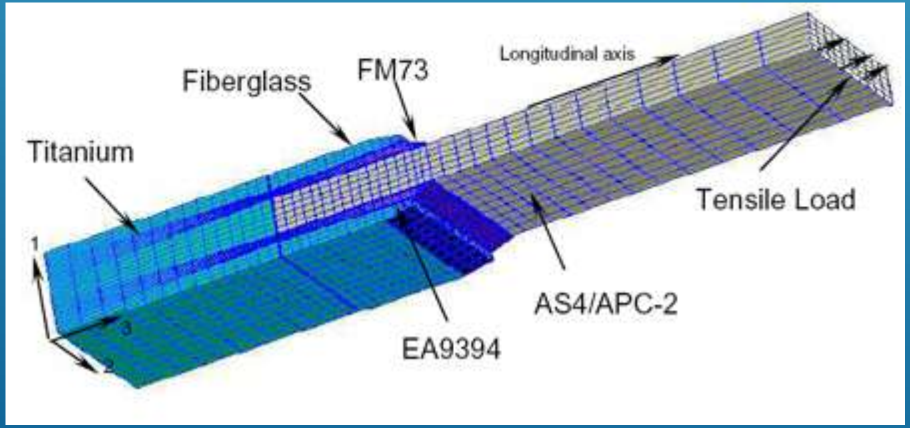
Elevated Porosity

Justification: Process control is a critical component of a FAA approved certification methodology for composite primary commercial transport aircraft structure.

TC3 OBJ2 Bonded Structure-Automated Surface Treatment Methodology

Laser surface treatment method is applicable to:

- Aerospace alloys (Ti6AL4V, Al 2024 T3 and 7075 T6)
- Carbon fiber reinforced composites (T800/3900-2)
- OEM bonded parts
- Co-cured bonds and joints
- Repairs

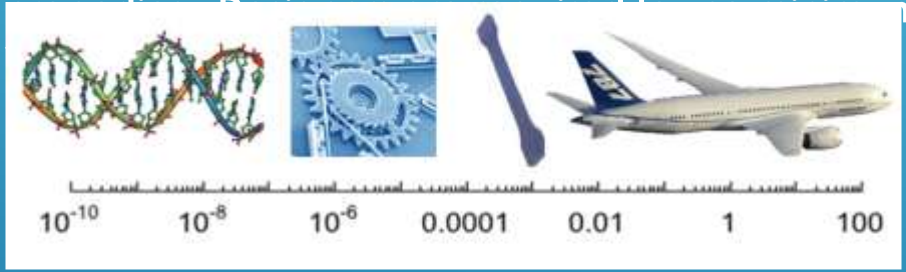


Automated Surface Treatment Methodology

- Critical component to enable certification of primary bonded airframe structure
- Simplifies airframe design and construction (no rivets, secondary arrest features)
- Achieve greater application of bonded structure

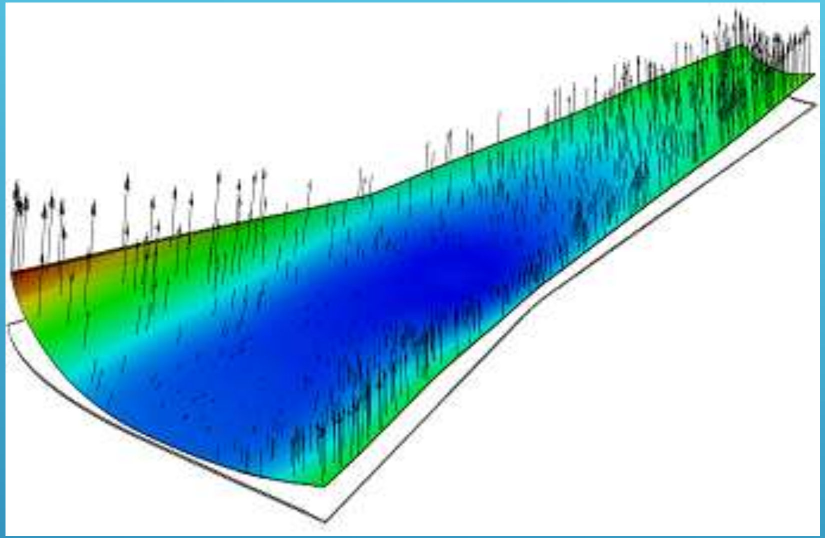
TC3 , OBJ 3 – Cure Process Modeling

Carbon fiber composite structures are built by a multi-layer additive fabrication process whereby the structural properties are developed during manufacturing. For automated tape placement (ATP), the complete process includes: 1) matrix synthesis 2) prepregging 3) tape lay-down and 4) consolidation/cure with temperature and pressure. For infusion processes, steps 2 and 3 are replaced by fabric preform development and resin impregnation, respectively. Variability in any of these steps produces a range in mechanical



Objective: Improve process efficiency by development of a physics -based process model to predict defects and laminate performance due to cure/consolidation and raw material variation, specifically as it applies to thick parts and complex geometries.. Exploit these models to reduce material development and manufacturing times and provide real-time corrections to off -nominal process conditions.

Approach: Improve the capabilities of COTS cure process models to predict defects such as porosity and fiber waviness related to the composite structure cure process



Cure Spring-in Simulation

Justification: Process control is a critical component of a FAA approved certification methodology for composite primary commercial transport aircraft structure. The FAA highlights computational analysis of process development as critical to further understanding of defects and sites a study where as little as 1.2% porosity can result in a 40% knockdown in laminate mechanical performance analysis