Comparison of Failure Modes in 2-D and 3-D Woven Carbon Phenolic Systems

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Woven TPS Background and Motivation

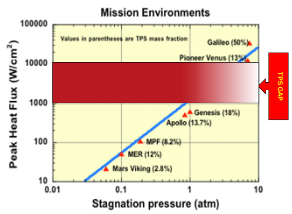

Figure 1: Current TPS Gap

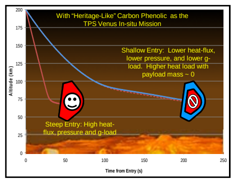

Figure 2: Mission Constraints of Carbon Phenolic

- **Thermal Protection Systems (TPS) Background**
  - o Thermal Protection Systems (TPS) protect an atmospheric entry vehicle from the harsh aerothermodynamic environment of re-entry
- **Introduction to 3D Woven TPS (3D WTPS)**
  - **Vision:** Close TPS Gap & enable future missions with TPS that is not mission constraining but enabling
  - **Project Goal:** Explore feasibility and establish manufacturing of TPS using the textile industry and resin infusion techniques.
- **What is 3D Woven TPS**
  - o 3D Woven TPS is an approach to the design and manufacturing of **ablative** TPS
  - o Combination of weaving precise placement of fibers in an optimized 3D woven manner and then resin transfer molding when needed
  - o Ability to design TPS for a specific mission requirements
  - o Tailor material composition by weaving together different types of fibers (e.g. carbon, ceramic, glass, polymeric)
  - o One-step process for making a mid density dry woven TPS
  - o Ability to infiltrate woven structure with a polymeric resin to meet more demanding thermal r**Heritage Like 2D Carbon Phenolic (2D CP)**
  - o Mission concepts have had no other option but to baseline Carbon Phenolic (CP)
  - o CP is very capable and robust
  - o CP enabled Galileo and is flight proven
  - o CP is the only option (no mid-high density TPS)
- **Carbon Phenolic is mission constraining**
  - o Mission design with CP and acceptable payload mass leads to:
    - Steeper trajectories
    - High heat-flux, high pressure and high g-loads

Woven TPS Design and Manufacturing Process

Current Woven TPS Design Process

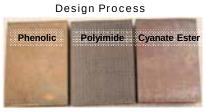

Figure 3: Fully Dense 3D Woven TPS Preforms with Various Resins

Optimized Woven TPS Design Loop

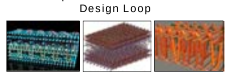
Figure 4: 3D Woven TPS Modeling Tools

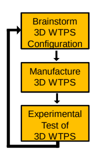

Figure 5: Current Design Loop

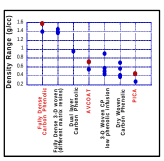

Figure 6: Potential Woven TPS Densities

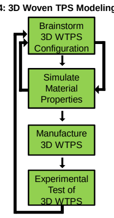

Figure 7: Optimized Design Loop

- **Goal of Direct TPS Comparison Experiment**
  - o Evaluate thermal response and failure mode evolution in both 3D WTPS and traditional 2D Carbon Phenolic TPS materials
  - o Two 2 in x 2 in samples at 0°ply angles were cut and tested under similar conditions in the mARC Jet Facility to analyze thermal- material performance
  - o Failure modes will be examined if they occur
  - o Test hypotheses that 3D Woven TPS is a viable TPS and a potential carbon phenolic replacement material
- **Potential Woven TPS Density Trade Space**
  - o Woven TPS shows its tailorability in Figure 6 by providing TPS options at many density ranges including mid-density TPS options
- **Current Woven TPS Design Loop Disadvantages**
  - o Relies solely on experiments for decision-making
- **Optimized Woven TPS Design Advantages**
  - o Simulates material properties of candidate WTPS designs for quick initial screening
  - o Large cost savings from reduced test samples
  - o Converge on final design faster

3D WTPS Experimental Comparison to 2D CP


Figure 8: NASA Ames mARC Jet Facility


Figure 9: mARC Gardon Gauge Insertion

Figure 10: mARC Labeled Diagram

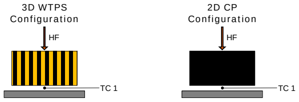

Figure 11: Test Sample Thermocouple Configurations

Table 1: mARC Testing Conditions

mARC Testing Condition	3D Woven TPS	2D Carbon Phenolic
Sample Ply Angle	0 deg	0 deg
Run Duration	61.6 s	60.6 s
Column Pressure	348 mbar	374 mbar
Chamber Pressure	21 mbar	22 mbar
Heat Flux	837 W/cm^2	808 W/cm^2
Nozzle Diameter	0.403 in.	0.403 in.
Nozzle Distance to Surface	30 mm	30 mm

- **Introduction to the mARC Jet Facility**
  - o Small-scale arc jet that heats flow by running current between electrodes in the arc chamber
- **mARC Testing Capabilities**
  - o Approx. 30 kW of power and 0.45 g/s mass flow rate of air
  - o 3D WTPS and 2D CP samples tested and compared
  - o Table 1 shows that all testing conditions were matched
- **mARC Experiment Setup**
  - o Directly compare thermal response performance of 3D Woven TPS to 2D Carbon Phenolic
  - o Samples have nearly identical size, density, fiber volume fraction, ply-angle, and material composition and were bonded to an Al substrate
- **Thermocouple (TC) Configuration for Test Samples**
  - o TC's placed between sample backface and L-Bracket

References

- Stackpoole, M., "Request for Information: Analysis Tools for Textile Composites – Woven TPS (WTPS) and ADEPT Projects," NASA Ames Research Center, Moffett Field, CA, 94035, 2011.
- Stackpoole, M., Feldman, J., Venkatapathy, E., "Woven TPS – A New Approach to TPS Design and Manufacturing," NASA Ames Research Center, Moffett Field, CA, 94035, ERC Inc., Moffett Field, CA 94035.
- Nawaz, A., Philippidis, D., Ho, T., "Setup and Characterization of the 30kW Arc Jet Facility mARC", 44th AIAA Thermophysics Conference, San Diego CA, 2013.
- Stackpoole, M., Feldman, J., Venkatapathy, E., "Woven TPS-Enabling Missions Beyond Heritage Carbon Phenolic," Gordon Research Conference.

3D Woven TPS vs. 2D CP Pre-Test Photos

3D Woven TPS

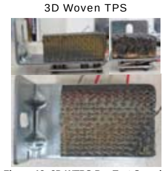
Figure 12: 3D WTPS Pre-Test Sample

2D Heritage Like Carbon Phenolic


Figure 13: 2D CP Pre-Test Sample


Figure 14: 3D WTPS mARC Jet Testing


Figure 15: 2D CP mARC Jet Testing

- **3D Woven TPS Pre-Test Characteristics**
  - o Weave consisted of coarser tows set in phenolic resin
  - o Through-thickness z-fibers (green-colored fibers) connect layers together forming a 3-D architecture
  - o Mechanically fastened to L-Bracket sting arm
- **2D Carbon Phenolic Pre-Test Characteristics**
  - o Finer tows set in phenolic resin
  - o 2D carbon fiber layers are laminated together
  - o Attached to L-Bracket sting arm with RTV sealant
  - o Surface observed to "puff up" and deflate during testing – attributed to pressure build up in material followed by delamination

3D Woven TPS vs. 2D CP Post-Test Photos

3D Woven TPS

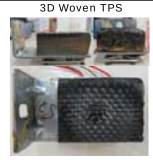
Figure 16: 3D WTPS Post-Test Sample

2D Heritage Like Carbon Phenolic


Figure 17: 2D CP Post-Test Sample

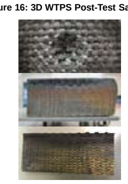
Figure 18: 3D WTPS ablated surface


Figure 19: 2D CP ablated surface highlighting delamination

- **3D Woven TPS Post-Test Characteristics**
  - o Smaller, more well contained defect area
  - o Evidence of free gas flow through sample
  - o No delamination observed – attributed to 3-D architecture
  - o Char, pyrolysis, and virgin zones clearly visible
- **2D Carbon Phenolic Post-Test Characteristics**
  - o Larger, more widespread defect area
  - o Gas build-up resulted in ply separation
  - o Clear delamination of surface and defect layers
  - o Catastrophic failure mode observed at 0°ply angle

3D Woven TPS vs. 2D CP Post-Test Analysis

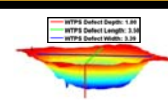

Figure 20: 3D WTPS Defect Analysis

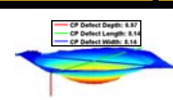

Figure 21: 2D CP Defect Analysis

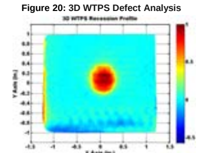

Figure 22: 3D WTPS Normalized Recession Profile

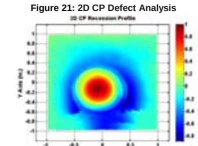

Figure 23: 2D CP Normalized Recession Profile

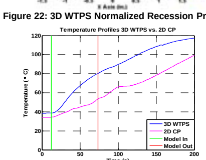

Figure 24: 3D WTPS and 2D CP backface T/C Profiles

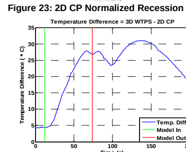

Figure 25: 3D WTPS and 2D CP backface T/C Profile Difference

Conclusions

- An un-optimized WTPS material was compared to a traditional 2D CP in the mARC facility at NASA Ames.
- At a 0° ply orientation the 2D Carbon Phenolic delaminated during the test while the 3D Woven TPS did not display the failure mode prevalent in 2D carbon phenolic
- 2D carbon phenolic must be tested at a certain ply angles to avoid delamination
- Depth analysis in Figure 20, Figure 21 shows a deeper defect depth for 3D WTPS than seen in 2D CP
- Recession analysis in Figure 22, Figure 23 shows a smaller defect area for 3D WTPS than seen in 2D CP
- Temperature response analysis in Figure 24 measured from embedded TC's shows a slightly higher temperature profile for 3D WTPS than seen in 2D CP, as a result of the higher conductivity fibers used in this weave
- Next steps including testing the 2D CP material at different shingle angles and testing different WTPS variants

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