Effects of New Jet Fuel Exposure on Aerospace Composites

Federal Aviation Administration

Presented by:

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MISSISSIPPI STATE UNIVERSITY

JAMS

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JAMS Technical Review

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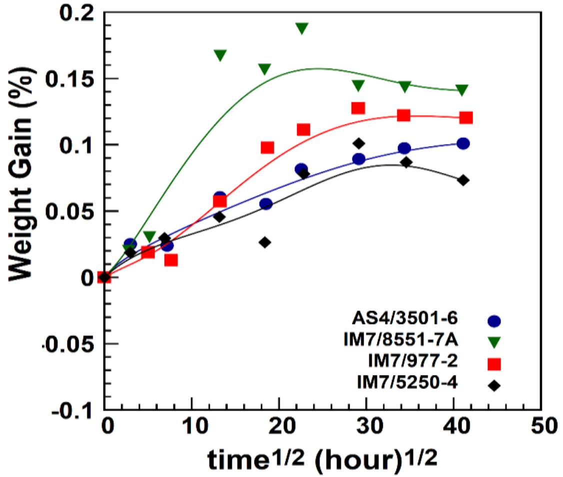
Introduction

- **Project Title: Effects of New Jet Fuel Exposure on Aerospace Composites**
- Project Participants
    - **Principal Investigators:** Santanu Kundu, Matthew W. Priddy, Thomas E. Lacy Jr., Charles U. Pittman Jr.
    - **Graduate Students:** Naoufal Harich
- FAA Technical Monitor
    - Dave Stanley
- Industry Partnerships/Other Collaborations: Aurora Flight Sciences, Advanced Composite Institute (MSU)
- Source of matching contribution for the current award: Aurora Flight Sciences, MSU, and TAMU

Background

- **Motivation and Key Issues**
  - The matrix phase of composites can absorb various fluids including fuels
  - Fuel absorption can lead to matrix swelling and matrix cracking
  - The degradation of thermal and mechanical properties of composites can occur because of fuel absorption
  - Alternative fuels can have similar effects as conventional Jet fuels, but not reported in the literature extensively
- **Objective and Scope**
  - Investigation of the effects of alternative fuels on carbon/epoxy composites
  - Evaluate the changes in thermal and mechanical properties
  - Compare the effects of alternative and conventional fuels absorption
  - Developing a modelling framework based on the experimental data that can be used for complex, real-life geometries
- **Approach**
  - Experimental investigation of fuel absorption of carbon/epoxy composites in conventional and alternative fuels
    - Track the weight gain with time to determine the amount of fuel absorbed
    - Investigate the changes in the dynamic and static mechanical properties after absorption
  - Modelling the diffusion process using Finite Element Method

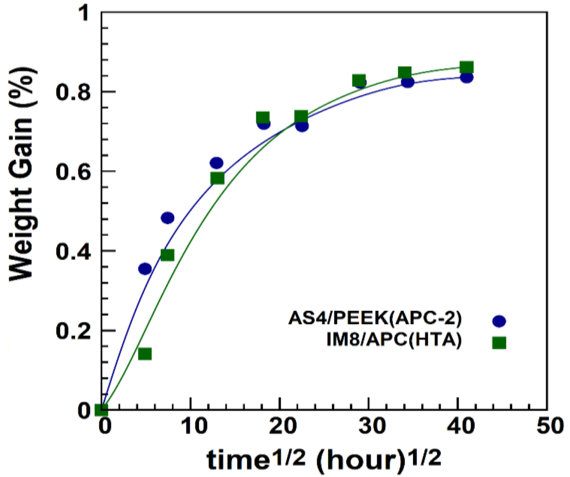
Literature Study: Effects of JP4 Fuel Uptake on Composites



% weight gain for composites with $[\pm45]_{2s}$ layup and thermoset matrix

- AS4/3501-6: carbon fiber with epoxy resin
- IM7/8551-7A: carbon fiber with epoxy resin
- IM7/977-2: carbon fiber with epoxy resin
- IM7/5250-4: carbon fiber with bismaleimide resin
- AS4/PEEK(APC-2): carbon fiber with polyetheretherketone resin
- IM8/APC (HTA): carbon fiber with aromatic polymer composite (high temperature amorphous)

Graphs reproduced from Ref 1



% weight gain for composites with $[\pm45]_{2s}$ layup and thermoplastic matrix

- Composites with a thermoset (cross-linked) matrix absorb less fuel than composites with a thermoplastic matrix
- The type of matrix and layup affect the fuel uptake

[1] Curliss, D.B., and Carlin, D., 1990, "Effect of jet-fuel exposure on advanced aerospace composites, II: Mechanical properties," Final Report, no. WRDC-TR-90-4064, Air Force Wright Research and Development Center, OH, USA.

Material Systems: Composites

- Three aerospace-grade carbon/epoxy composites were used:

Material system	Fiber type	Fabrication method	Layup
Hexcel SGP370-8H/8552	Eight harness woven carbon fabric	Autoclave cured	Cross-ply [0/90/90/0]
Hexcel SGP370-8H/8552	Eight harness woven carbon fabric	Autoclave cured	Quasi-isotropic [0/-45/45/90]
DMS2436/API-1078	Warp/knit carbon fabric	Resin-infused	[45/-45/0/90/0/-45/45]

- Specimens were cut from these composite panels into 2 (L) x 0.5 (W) in^2 dimensions

Red: carbon fibers

Blue: Epoxy

Material Systems: Fuels

- Conventional jet fuel **Jet A** was used
- The alternative fuels (AF) used in this work were:

AF blend used	Process used	Blending ratio with Jet A	Aromatic content
ATJ/Jet A	ATJ/SPK	50/50	0%
SPK/Jet A	HEFA/SPK	50/50	0-0.4%
Farnesane/Jet A	HFS/SIP	20/80	0%
S8/Jet A	FT/SPK	50/50	<0.2%

ATJ/SPK: Alcohol-to-Jet to Synthetic Paraffinic Kerosene

HEFA/SPK: Hydroprocessing Esters and Fatty Acids to Synthetic Paraffinic Kerosene

HFS/SIP: Hydroprocessed Fermented Sugars to Synthetic Isoparaffins

FT/SPK: Fischer-Tropsch to Synthetic Paraffinic Kerosene

Material Systems: Fuels

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ATJ/SPK: Alcohol-to-Jet to Synthetic Paraffinic Kerosene

Sugars/Cellulose → *Fermentation* → **Alcohols** → *Hydration* → **Olefins** → *Hydrogenation* → **Paraffins**

HEFA/SPK: Hydroprocessing Esters and Fatty Acids to Synthetic Paraffinic Kerosene

Plant based feedstock (*i.e.*, algae, jatropha etc.) → *Pressing* → **Oils** → *Deoxygenation / Hydroprocessing* → **SPK**

HFS/SIP: Hydroprocessed Fermented Sugars to Synthetic Isoparaffins

Sugars/Cellulose → *Fermentation* → **Farnesene** → *Hydroprocessing* → **Farnesane**

FT/SPK: Fischer-Tropsch to Synthetic Paraffinic Kerosene

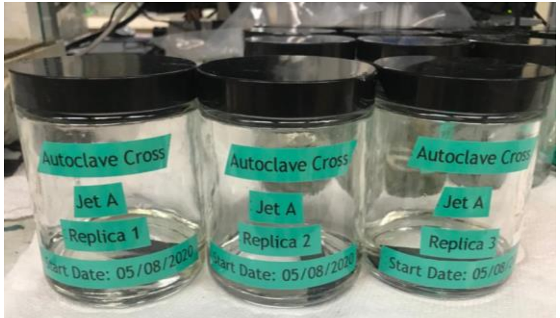
Biomass (*i.e.*, forestry residues, grasses, municipal solid waste etc.) → *Gasification* → **Syngas** → *Fischer-Tropsch* → **Alternative fuel**

Experimental Details: Preconditioning

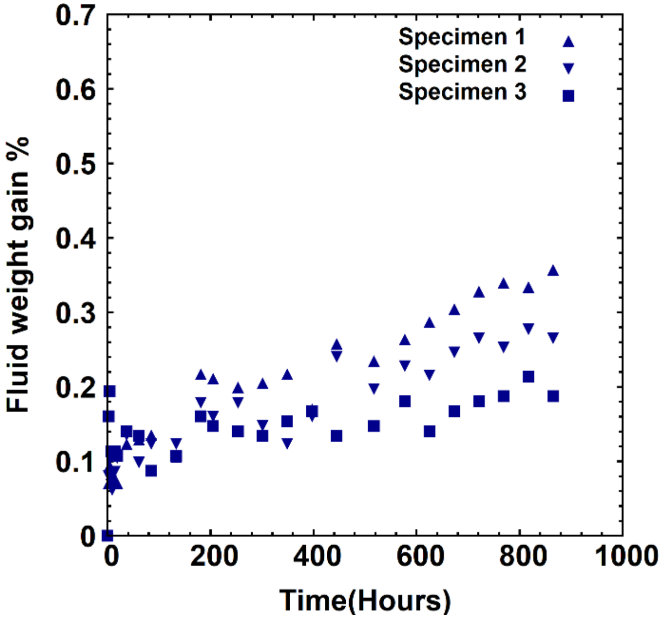
- **Preconditioning** used for **all specimens** studied in this work:
  - Samples were dried at room temperature under vacuum at 0.5 atm absolute pressure for at least 12 h
  - Held in a controlled humidity chamber at 50% relative humidity (RH) for a minimum of 12 h before fuel immersion.

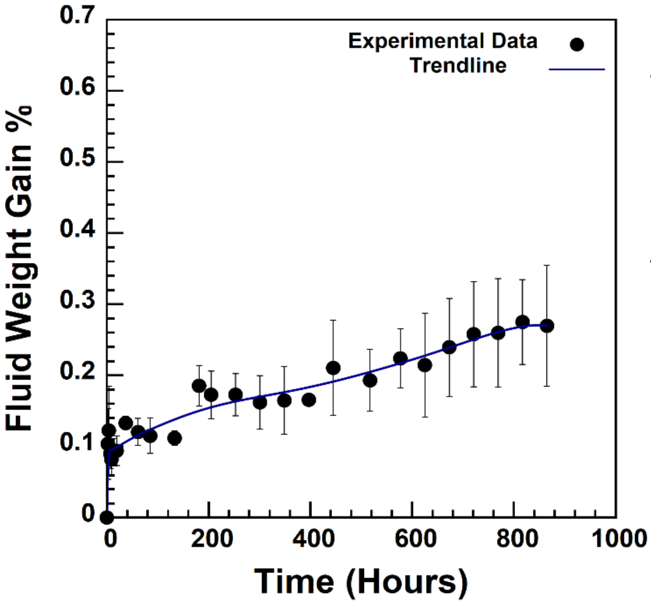
Experimental Details: Tracking Weight Gain

- **Weight gain** was tracked for each specimen as a function of time following these steps:
    - **Periodically removing** the specimens from the soaking bath
    - **Wiping** the specimens dry
    - **Weighing** the specimens to assess their fluid uptake
    - **Re-immersing** the specimens in the bath until the next weighing
- For each sample, **three replicas** were employed



Weight Gain with Time for Autoclave Quasi-Isotropic Hexcel SGP370-8H/8552 Carbon/Epoxy immersed in Jet A fuel

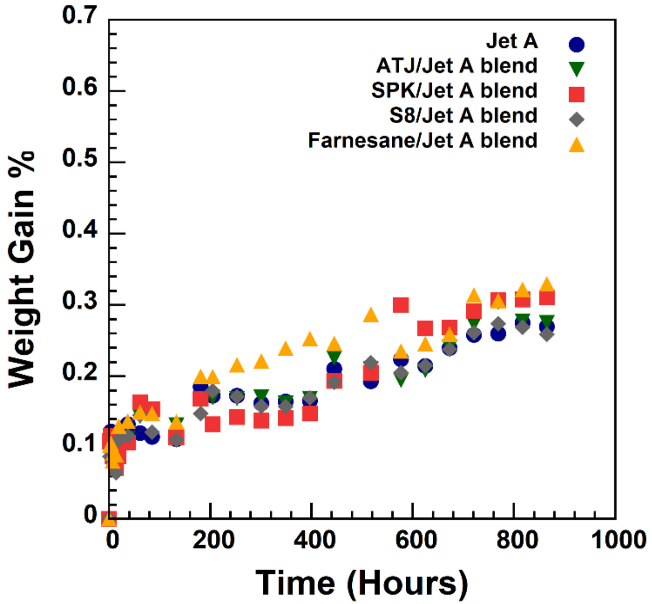




The ***average fuel uptake*** and a Bezier trendline. Error bars represent the standard deviation.

- Faster **absorption** in the **early stages** of the fuel immersion
- The equilibrium weight gain was of ≈0.27% and the range [L-H] of [0.18 - 0.35] %

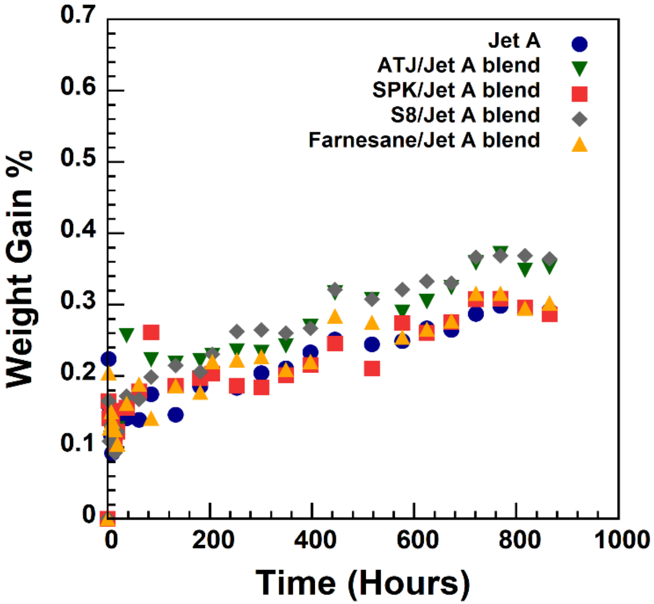
Average Weight Gain with Time for Autoclave *Quasi-Isotropic Hexcel SGP370-8H/8552* Carbon/Epoxy



Jet A fuel
50/50 ATJ/Jet A blend
50/50 SPK/Jet A blend
50/50 S8/Jet A blend
20/80 Farnesane/Jet A blend

- Faster **absorption** in the **early stages** of the fuel immersion
- The equilibrium weight gain for all specimens was in the range of 0.26-0.32%

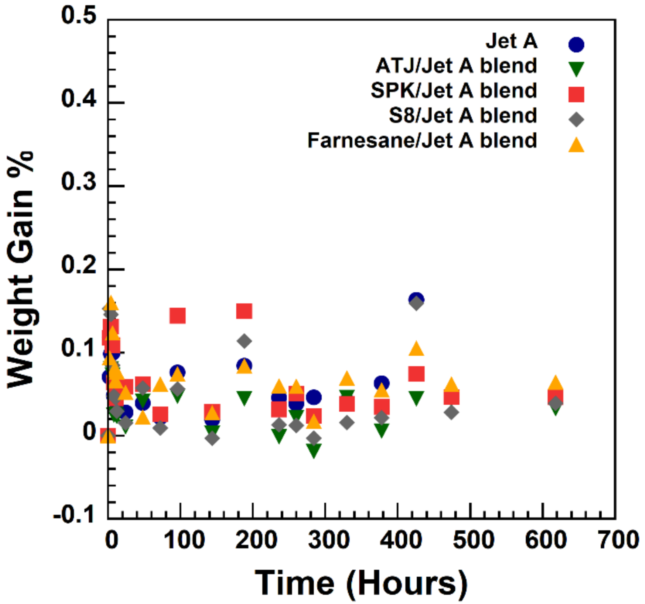
Average Weight Gain with Time for Autoclave *Cross-Ply Hexcel SGP370-8H/8552* Carbon/Epoxy



Jet A fuel
50/50 ATJ/Jet A blend
50/50 SPK/Jet A blend
50/50 S8/Jet A blend
20/80 Farnesane/Jet A blend

- Faster **absorption** in the **early stages** of the fuel immersion
- The equilibrium weight gain for all specimens was in the range of 0.28-0.36%

Average Percent Weight Gain with Time for Resin Infused DMS2436/API-1078 Carbon/Epoxy



Jet A fuel

50/50 ATJ/Jet A blend

50/50 SPK/Jet A blend

50/50 S8/Jet A blend

20/80 Farnesane/Jet A blend

- Faster **absorption** in the **early stages** of the fuel immersion
- The equilibrium weight gain for all specimens was in the range of 0.04-0.07%

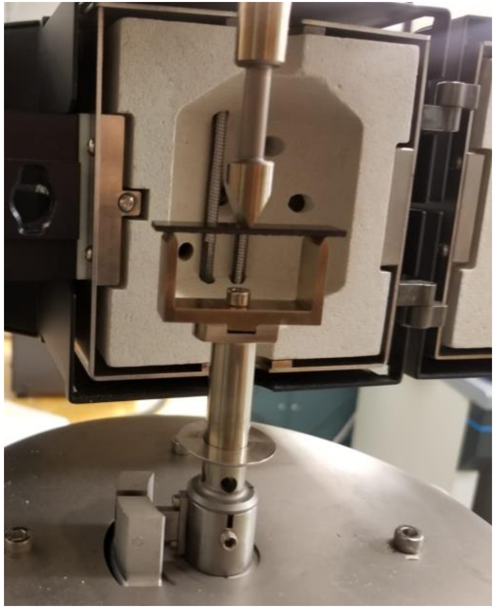
Summary of Average Weight Gain for All Specimens and Fuels Used

	%Equilibrium weight gain in different fuels				
Composite Type	100% Jet A	50/50 ATJ/Jet A blend	50/50 SPK/Jet A blend	50/50 S8/Jet A blend	20/80 Farnesane/Jet A blend
Autoclave Quasi-Isotropic Hexcel SGP370-8H/8552 Carbon/Epoxy Specimens	0.27 ± 0.08	0.26 ± 0.09	0.3 ± 0.06	0.26 ± 0.05	0.32 ± 0.04
Autoclave Cross-Ply Hexcel SGP370-8H/8552 Carbon/Epoxy Specimens	0.28 ± 0.04	0.36 ± 0.13	0.32 ± 0.09	0.36 ± 0.04	0.29 ± 0.10
Resin Infused DMS2436/API-1078 Carbon/Epoxy Specimens	0.04 ± 0.01	0.04 ± 0.05	0.05 ± 0.05	0.04 ± 0.03	0.07 ± 0.03

- **No significant difference** in **absorption** of **Jet A** compared to **alternative fuels**.
- **Hexcel carbon/epoxy** specimens **absorbed more** fuels than the **resin-infused specimens.**
- The **resin-infused specimens** have a **warp-knit fabric** making the **layers tightly stacked** than for the **woven fabric** used for **Hexcel specimens** likely resulted in lower fuel absorption.

Experimental Details: DMA

- **The effects** of fuel absorption on the **thermomechanical properties** of composites are studied using **Dynamic Mechanical Analysis (DMA)**.
- **DMA** was **performed** on **neat and fuel-immersed** specimens using an **RSA-G2 Solids Analyzer** with the **three-point bending** mode.
- The analysis was performed following the **ASTM D7028-07**.

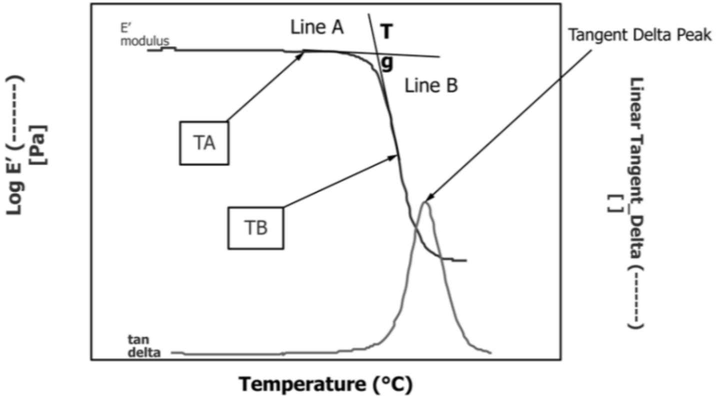


DMA parameters used

Test method	Frequency	Heating Rate
Three-point bending	1 Hz	5 °C/min

Experimental details: DMA (cont.)

- **Thermomechanical properties** of interest:
  - **Storage modulus E'** measures the **elastic response**
  - **Loss modulus E''** measures the **viscous response** (dissipation in the system)
  - **tan(δ)** is the **ratio of E''/E'**
- The **ASTM D7028-07**[3] define **two temperatures** of interest for the **glass transition temperature:**
  - The **intersection of the two tangent lines** from the storage modulus gives **DMA T_g**
  - The **maxima in the tan(δ)** curves is the glass transition temperature, T_t

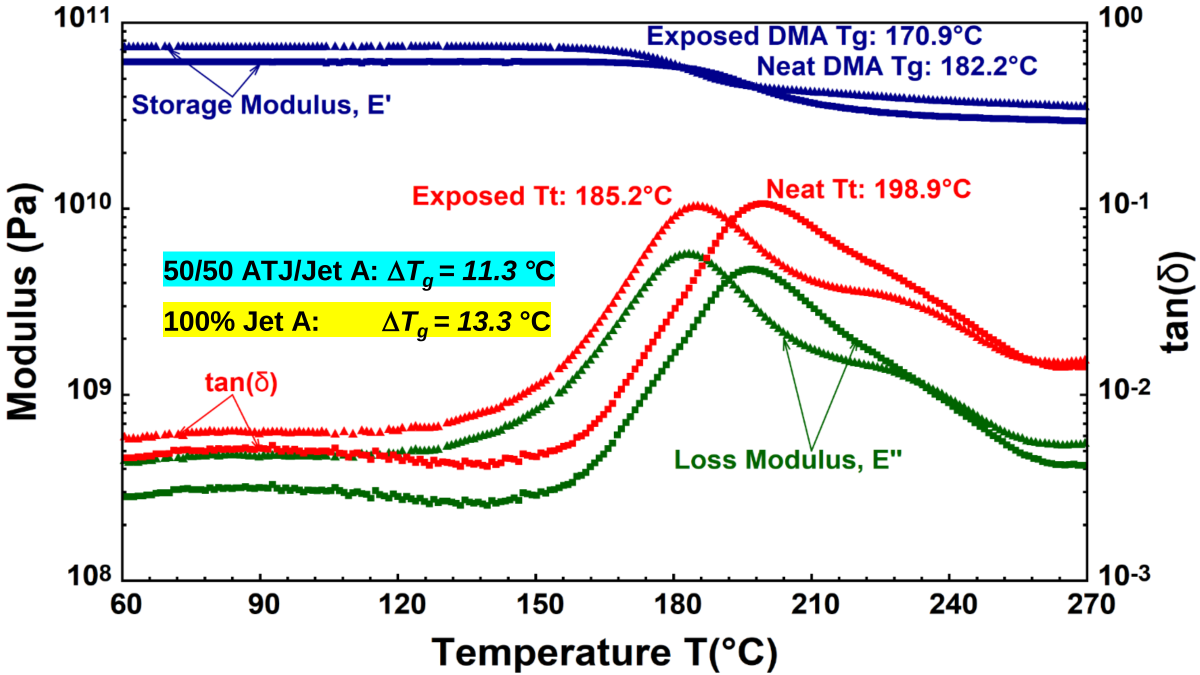


Obtained from ref [2]

[2] Sperling, L. H. (2005). *Introduction to physical polymer science*. John Wiley & Sons.

[3] ASTM International. (2007). ASTM D7028-07-Standard Test Method for Glass Transition Temperature (DMA Tg) of Polymer Matrix Composites by Dynamic Mechanical Analysis (DMA).

DMA Results for Autoclaved Cross-ply Hexcel SGP370-8H/8552 Carbon/Epoxy Specimens: Neat and Immersed in ATJ/Jet A Blend



- Both DMA T_g and T_t decreased after fuel absorption: $\Delta\mathbf{DMA}\ \boldsymbol{T_g} = \mathbf{11.3}$℃ and $\Delta \boldsymbol{T_t} = \mathbf{13.7}$℃

Average Values of DMA T_g and T_t

Specimen type	Property	Average values of DMA T_g and T_t of three replicates ± standard deviation.					
		Neat	100% Jet A	50/50 ATJ/Jet A blend	50/50 SPK/Jet A blend	50/50 S8/Jet A blend	20/80 Farnesane/Jet A blend
Autoclave Quasi-Isotropic Hexcel SGP370-8H/8552 Carbon-Epoxy Specimens	DMA T_g (°C)	187.1 ± 7.6	174 ± 1.5	173.5 ± 0.8	173.3 ± 0.9	173.5 ± 0.1	172.9 ± 0.9
	Tan(δ) peak T_t (°C)	200.6 ± 0.5	186.9 ± 0.8	187.9 ± 0.7	188.0 ± 0.15	187.4 ± 0.9	186.7 ± 1.3
Autoclave Cross-Ply Hexcel SGP370-8H/8552 Carbon-Epoxy Specimens	DMA T_g (°C)	182.3 ± 0.3	168.9 ± 0.4	170.1 ± 1.3	171.4 ± 0.3	170.6 ± 0.9	172.3 ± 0.7
	Tan(δ) peak T_t (°C)	198.9 ± 0	185.5 ± 2.1	184.5 ± 1.0	185.4 ± 0.9	183.4 ± 1.1	185.8 ± 0.3
Resin Infused DMS2436/API-1078 Carbon-Epoxy Specimens	DMA T_g (°C)	168.4 ± 0.5	165.3 ± 0	167.3 ± 0.2	168.2 ± 0.3	165.7 ± 0.6	166.3 ± 0.1
	Tan(δ) peak T_t (°C)	182.9 ± 0.1	182.55 ± 1.8	183.4 ± 0.4	182.5 ± 0.5	181.2 ± 0.1	183.1 ± 0.1

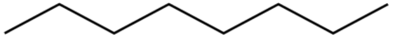
- **DMA T_g and T_t** for specimens **saturated** with **four alternative fuel/Jet A blends** were **impacted** to the **same extent** as those saturated with **100% Jet A fuel**.
- **Decrease of** DMA T_g and T_t for **Hexcel specimens' higher** than for the **resin-infused.**

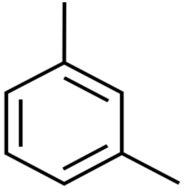
Absorption of Model Fluids

- MSU has limited access to alternative fluids, particularly unblended ones.
- **Model fluids** with **similar chemical structure** as the **pure alternative fuels** will be used.
- Use **100% (neat) alternative fuels** and investigate their **effects on carbon/epoxy specimens**.
- These **pure alternative fuels** are comprised **mostly of paraffins and olefins** and have almost **no aromatics.**
- **Sample thickness** will be **varied-** higher thickness leads to **slower diffusion.**
- **Accelerated absorption** using **different temperatures** will be performed on the **thicker specimens.**

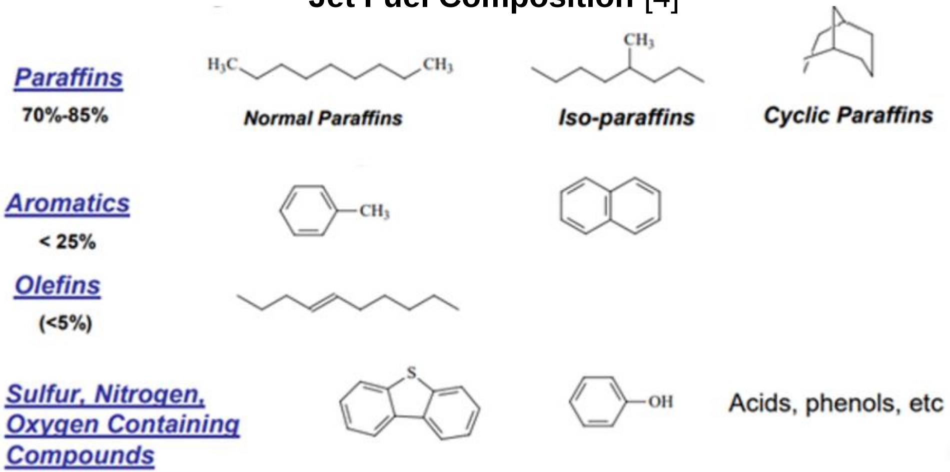
Material System: Model Fluids

- Model fluids to be used:





Jet Fuel Composition [4]



[4] Sustainable bio-derived synthetic paraffinic kerosene (Bio-SPK) jet fuel flights and engine tests program results. *9th AIAA aviation technology, integration, and operations conference (ATIO) and aircraft noise and emissions reduction symposium (ANERS)*, (p. 7002).

Preliminary Results: Absorption

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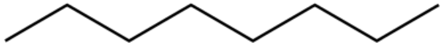
<u>Autoclave cured Hexcel SGP 370-8H/8552 quasi-isotropic</u> specimens after **~3500h**

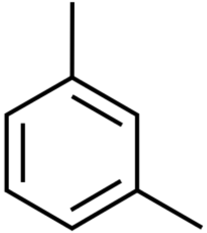


Octane

Average equilibrium weight gain: 0.21%

Nonane

Average equilibrium weight gain: 0.21%



Xylene

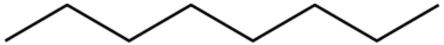
Average equilibrium weight gain: 0.22%

3 replicates each

- **Low** model fluids absorption**, similar to the** alternative fuels
- **Aromatic** and **aliphatic** model fluids display **similar** uptake values

Preliminary Results: Weight Tracking

<u>Autoclave cured Hexcel SGP 370-8H/8552 cross-ply</u> specimens at **~3500h**

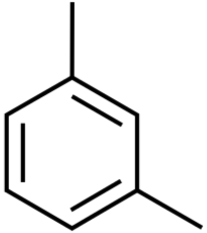


Octane

Average equilibrium weight gain: 0.09%

Nonane

Average equilibrium weight gain: 0.18%



Xylene

Average equilibrium weight gain: 0.16%

3 replicates each

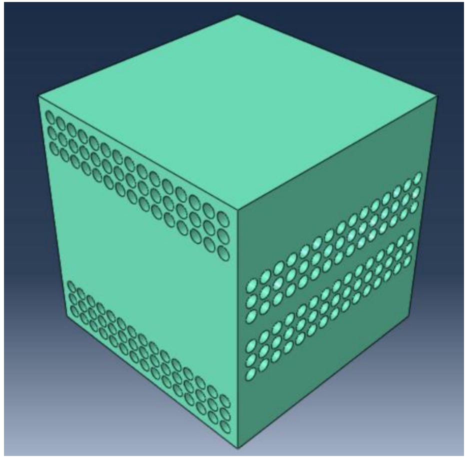
- **Low** model fluids absorption**, similar to the** alternative fuels
- **Aromatic** and **aliphatic** model fluids display **similar** uptake values

Diffusion Modelling

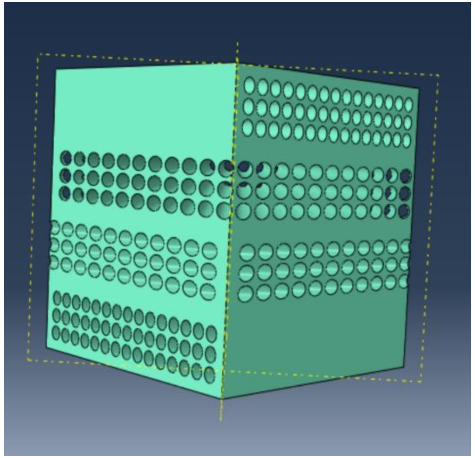
- The **diffusion study** for some composites can **require prolonged experimental** work to reach saturation and **complex experimental setup**.
- **Modelling of diffusion in composites** can be helpful in **predicting various outcomes** of the experimental work, (i.e., **time to reach saturation**, **equilibrium values**, etc.).
- Finite element software (**Abaqus**) is **used to model diffusion** through its **built-in mass diffusion** based on **Fickian diffusion** model.

Diffusion Modelling

- **Initial geometries** with **cross-ply** and **quasi-isotropic** layups are used.
- Specimens with the **exact dimensions and layers** will be **used and compared** with the **experimental results**.



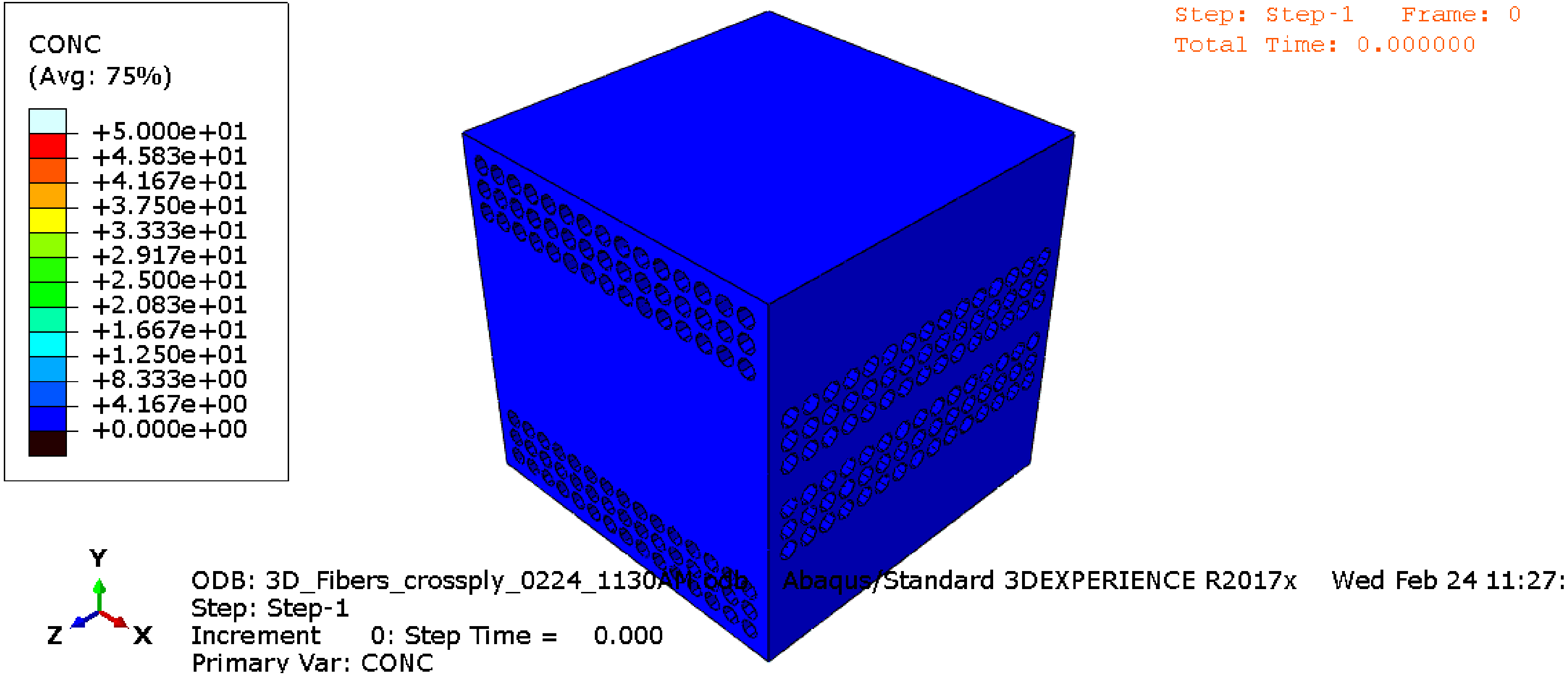
Cross-ply layup [0/90/90/0]



Quasi-Isotropic layup [0/-45/45/90]

Preliminary results

Animation for diffusion through a **cross-ply** specimen



Fiber Array Type Study

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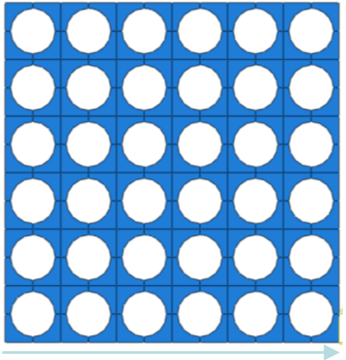
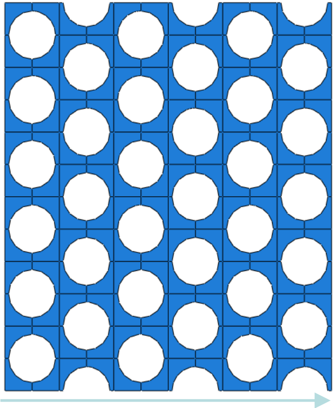
- The **fiber arrangement** of a composite specimen can **affect the diffusion**
- The **fibers** represent **obstacles the fluid** has to move around, **changing its path and slowing the diffusion.**
- Two fiber configurations are used:

Square Array



Diffusion direction

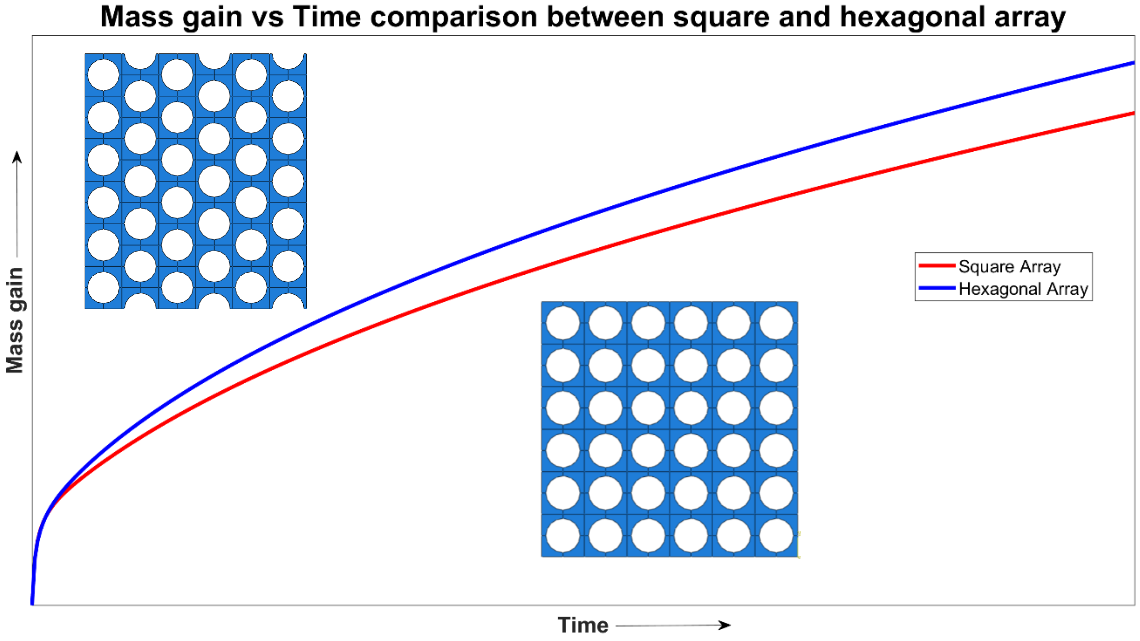
Hexagonal Array



Diffusion direction

- Same fiber and matrix volume fractions: $v_f = 50\%$
- Unit cell diffusion dimensions are different (S/Hx   1/0.93)

Preliminary Results: Fiber Array study



- Hexagonal array appears to have a faster diffusion rate than square array.

  - likely due to the difference in unit cell dimensions

- Both arrays will converge to the same equilibrium value since they have same matrix volume

Technical Publications

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- Bassou, R., Harich, N., Kundu, S., Priddy, M. W., Lacy, T. E., & Pittman, C. U. (2019). DOT/FAA/TC-20/22 - Effect of Jet Fuels Exposure on Aerospace Composites - Literature Review. Federal Aviation Administration. Atlantic City International Airport, NJ: FAA William J. Hughes Technical Center.
- Harich, N., Bassou, R., Kundu, S., Priddy, M. W., Lacy, T. E., & Pittman, C. U. (2020). **DOT/FAA/TC-20/22** - Effects of New Jet Fuel Exposure on Aerospace Composites - Phase 1 Final Report. Federal Aviation Administration. Atlantic City International Airport, NJ: FAA William J. Hughes Technical Center.
- Harich, N., Bassou, R., Priddy, M. W., Lacy, T. E., & Pittman, C. U. Kundu, S. *“Effects of alternative jet fuel blends on aerospace-grade carbon/epoxy composites”* **(To be submitted)**