Mechanical and Thermal Material Properties of Restraint Filaments for Use in Low Cost Satellites

Joseph Severino, Naoki Oishi

CubeSat Developer's Workshop 2018
April 30 2018 – May 2, 2018

Outline

- Background/Motivation
- Materials Introduction-Fiber Types
- Mechanical Properties
- Thermal Cutting
  - *DMA (Table/Scatter Plot)*
  - *Heating Coil (Air/Vac)*
- Friction Coefficients
- CTE under Load
- Conclusion

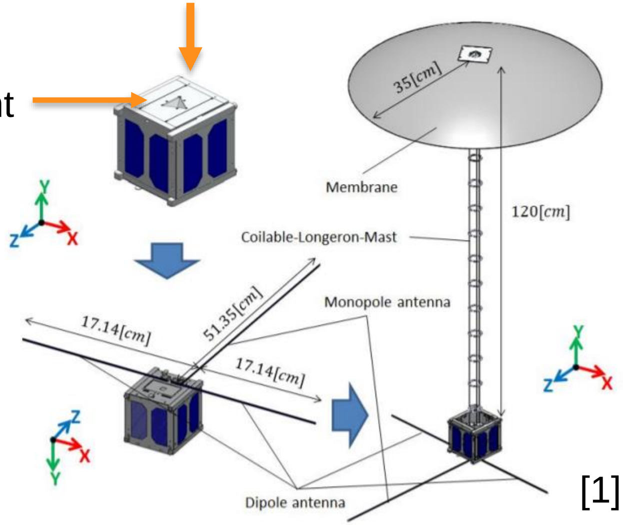
Background/Motivation

- Complexity of CubeSats is expanding with new deployable structures
  - *Antenna* -- *Booms*
  - *Solar panels* -- *Others*
- Lightweight and compact actuating mechanisms necessary to fit into restrictive cube format.
  - *Shape memory alloy latches*
  - *Paired CTE alloys*
  - ***Nichrome burn wires***
    - low mass | compact | simple
- Various configurations of burn wires
  - *all rely on melting a thermoplastic filament that restrains components*

- Goal here was to evaluate the materials properties of various low cost filament materials (fishing line) used in CubeSats to determine the advantages and disadvantages of their application.

Japanese Waseda-SAT3

Filament



[1]

Filament

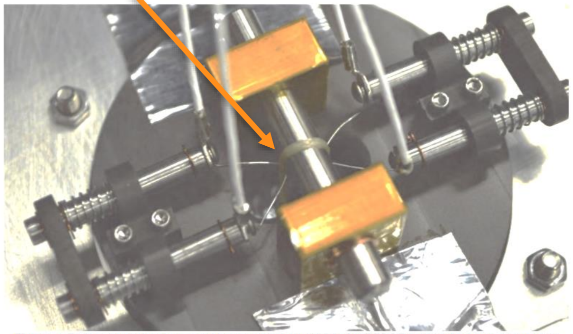


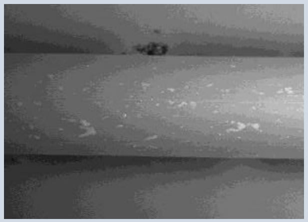
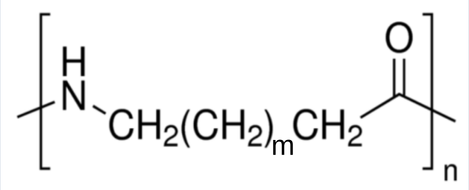
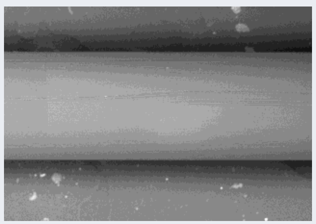
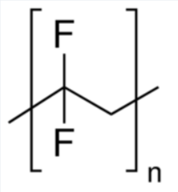
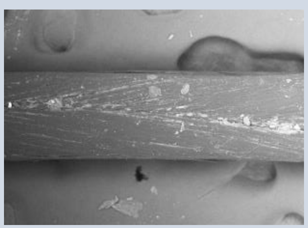
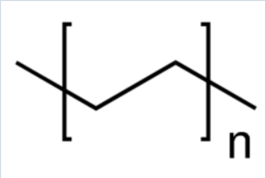
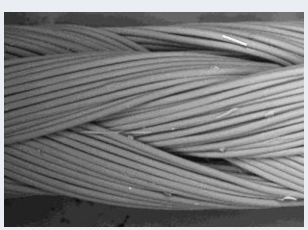
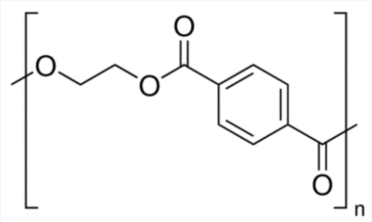
Figure 4. Release mechanisms on Vectran tie down cable for TEPCE tether deployment system

[2][3]

Patented nichrome cutting mechanism

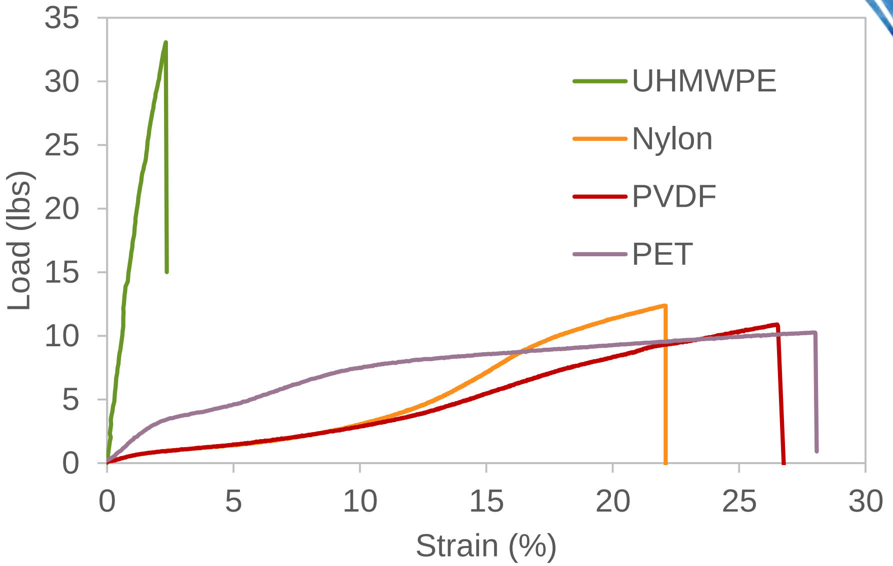
[1] Miyashita et al. Expansion and Measurement of Spiral Folded Membrane by Small Satellite. 55th AIAA Aerospace Sciences Meeting, Grapevine, Texas, January 9 - 13 2017
[2] Thurn et al. A Nichrome Burn Wire Release Mechanism for CubeSats. Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18, 2012
[3] US20150102172A1, Burn Wire Release Mechanism for Spacecraft and Terrestrial Applications

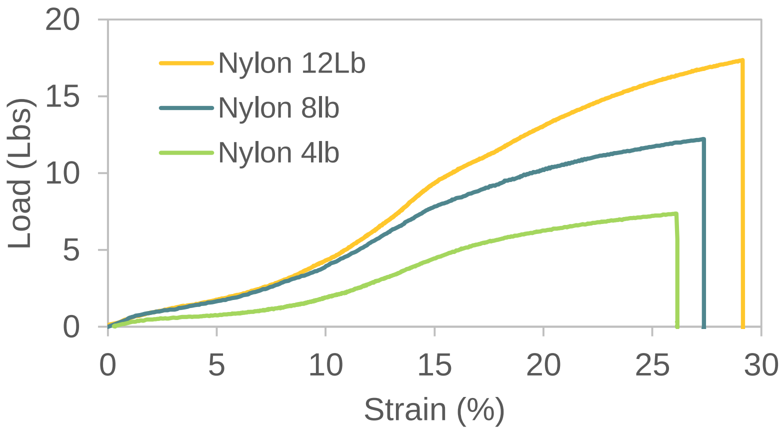
Materials

	Trade Name	Material	Formula
	Monofilament	Polyamide (Nylon)	
	Fluorocarbon	Polyvinylidene fluoride (PVDF)	
	Braid	Polyethylene (UHMWPE)	
	Dacron	Polyethylene terephthalate PET	

Mechanical Properties

- Compared the 4 types of filaments
  - *UHMWPE far out performs rating*
  - *PET underperforms but has low scatter*
- Compared filament rating of common Nylon
  - *Properties similar but failure load increases*
  - *Congruent to increase in filament diameter*

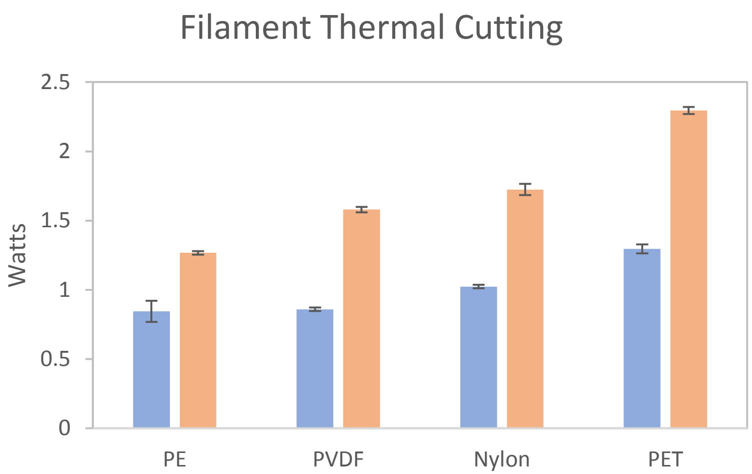


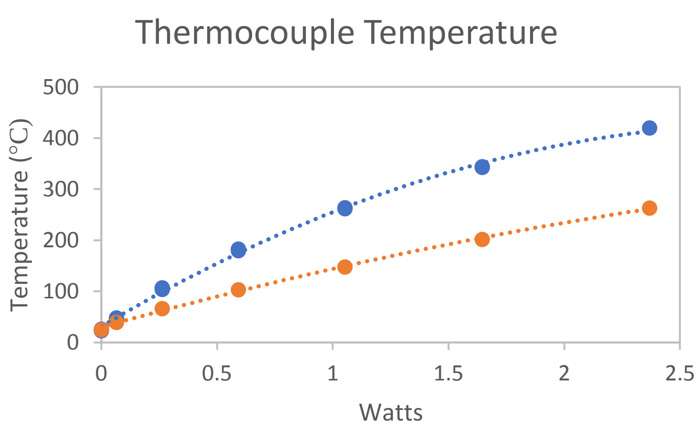


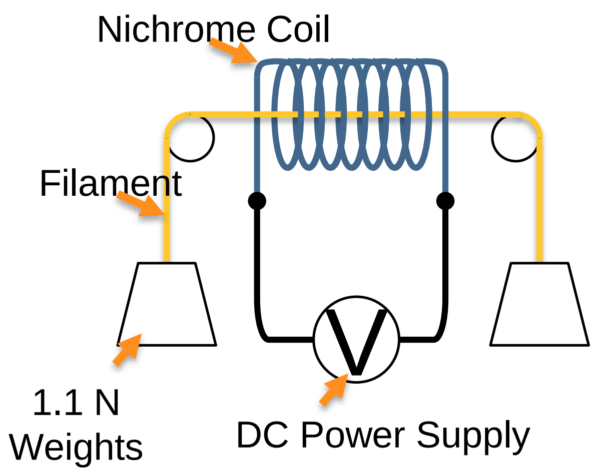
Material	Rating Lbs	Failure Load Lbs	Failure Strain %	Diameter mil
UHMWPE	10	32.3 ± 3.2	2.7 ± 0.4	8
PVDF	10	10.7 ± 0.5	26.5 ± 2.8	11
PET	12	10.2 ± 0.1	27.0 ± 0.6	15
Nylon	4	7.2 ± 0.2	24.9 ± 1.4	8
Nylon	8	11.9 ± 0.9	23.7 ± 3.2	11
Nylon	10	13.4 ± 0.6	24.1 ± 2.0	12
Nylon	12	16.7 ± 0.5	26.1 ± 2.8	13

Only UHMWPE has significantly different stiffness and strength within group

Nichrome Coiled Wire Cutting



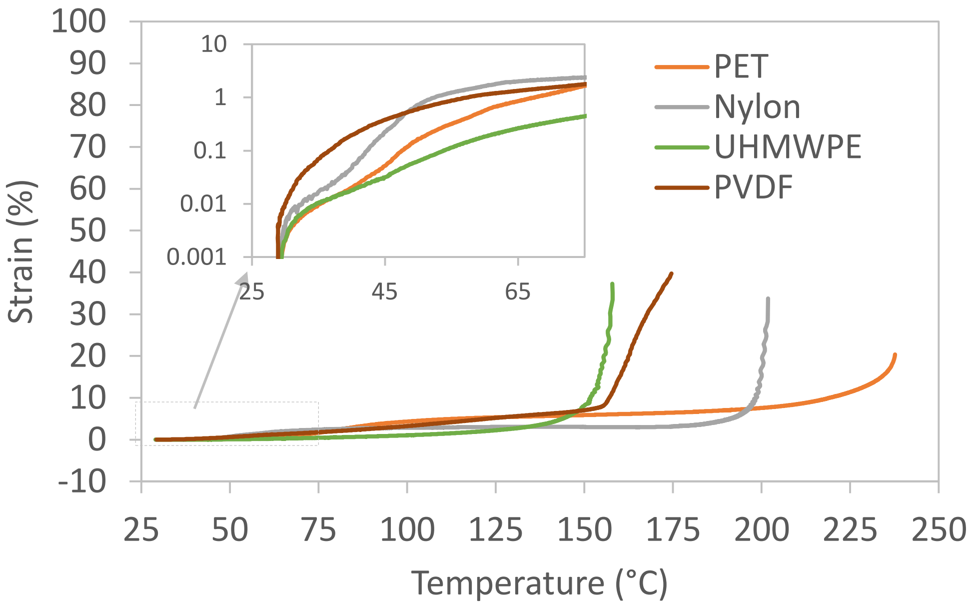


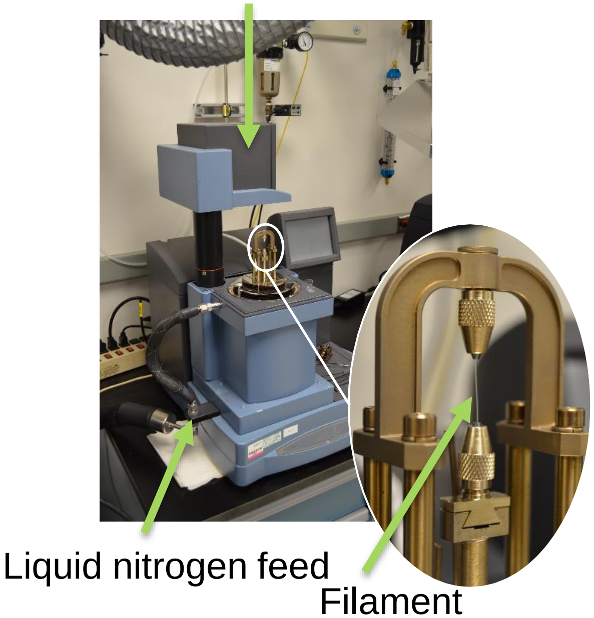


- Investigated hot wire filament cutting in air and vacuum
- Voltage ramped at 5 V/min until filament break
- Wattage recorded at fiber break
  - *Breaks were instantaneous*
  - *Filament could consistently withstand load when 0.01 Watts below breaking point*
- Excessive power (wire glowing red hot) was not necessary to cut any of the filaments
  - *Nichrome incandescence at ~550 °C*

Filaments cut instantaneously well below incandescence of nichrome wire

Thermal Cutting



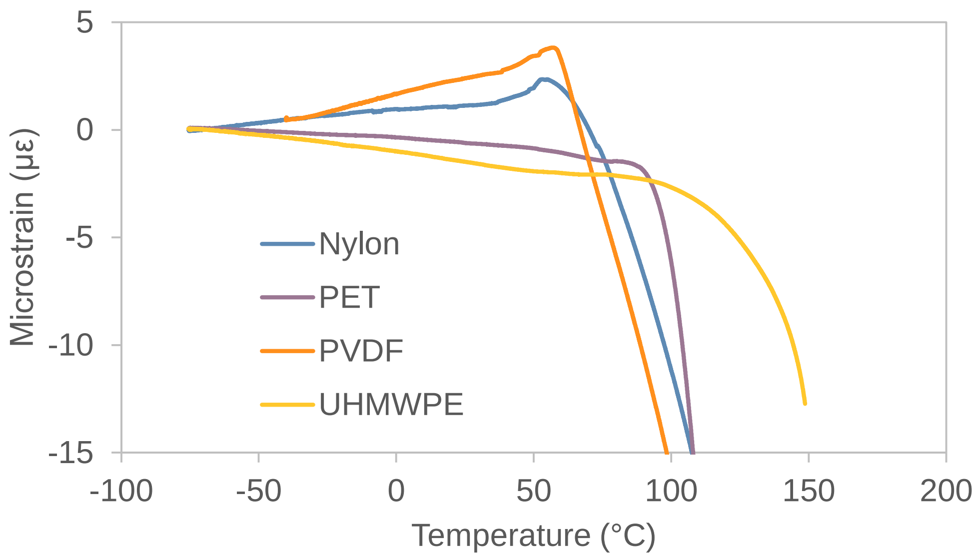


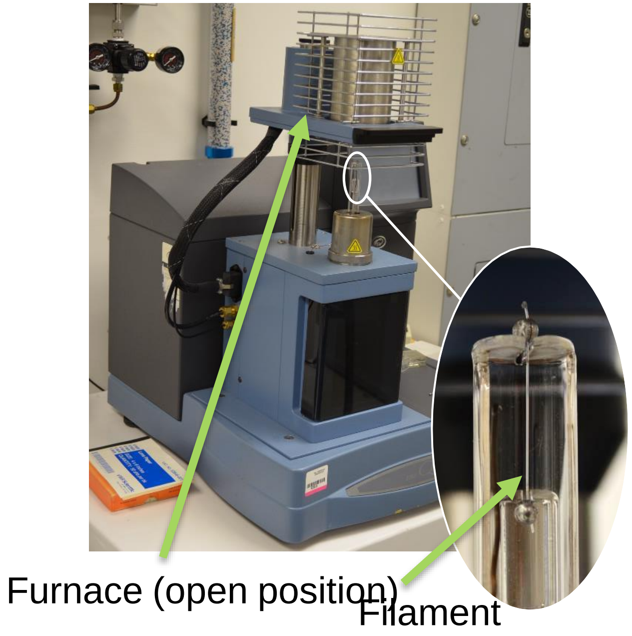
- Directly measured breaking temperature with thermal ramp/creep test
  - *5 °C/min | 4 N tension*
- Breaking temperature corresponded to melting point
- Minor inflection around 40 °C
  - *Glass transition of Nylon 25 to 45 °C*

Filament	DSC Melting Point (°C)
UHMWPE	156
PVDF	164
Nylon	160
PET	254

Filament breaking temperature dominated by melting point

Coefficient of Thermal Expansion





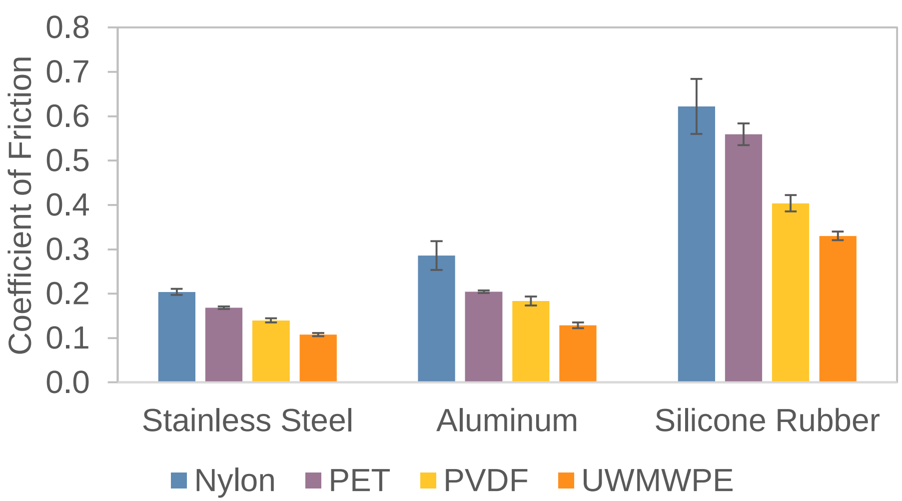
- Observed thermal expansion of filaments with 0.1 N load using TMA system
- All filaments shrunk at elevated temperature in contrast to measurements made at 4N
  - *Low loads here*
  - *Polymer softening*
  - *Entropy*

Filament	CTE (με/°C)
UHMWPE	-22.5
PVDF	30.0
Nylon	23.3
PET	-7.0

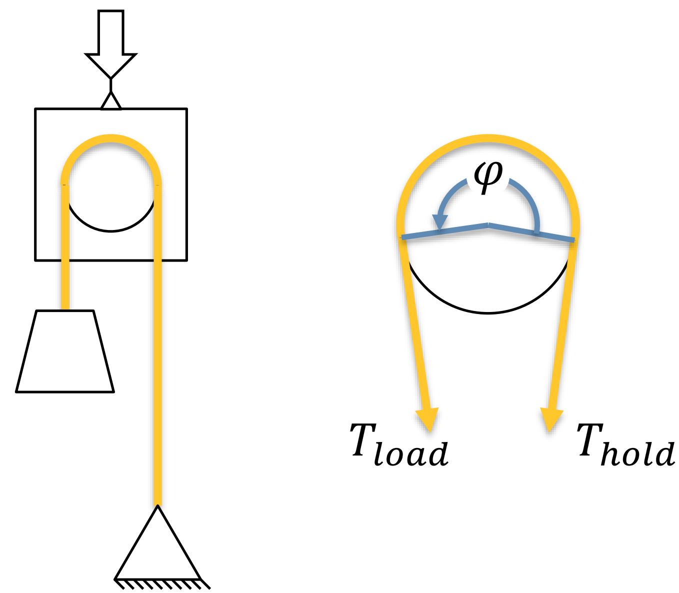
CTE can be negative or positive and structure changes well before melting/break

Coefficient of Friction

- Used a capstan approach to measure sliding friction of the fibers on 3 materials
  - *Stainless steel | aluminum | silicone rubber*
- Consideration for complex routing or termination approaches



Test Arrangement

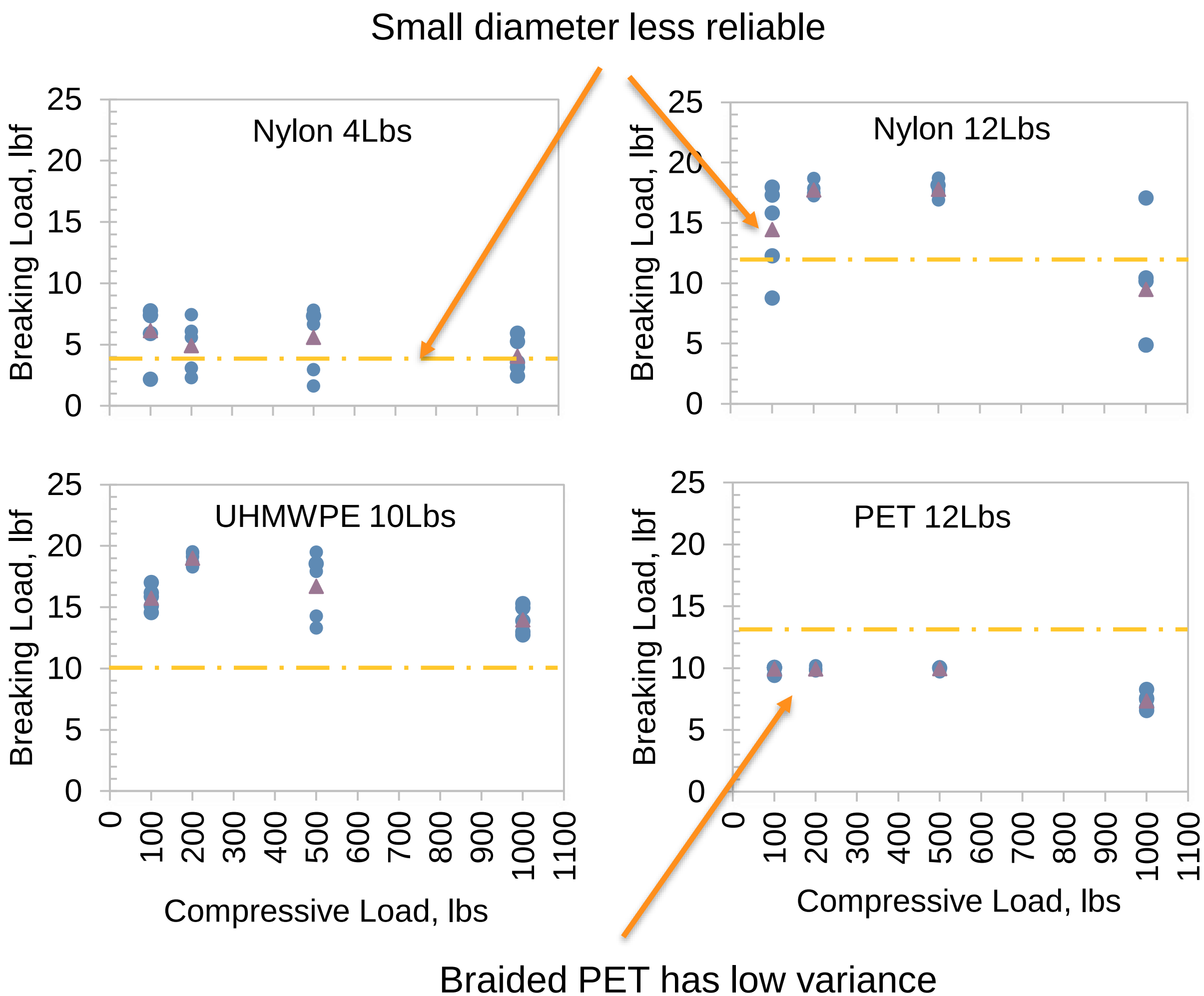


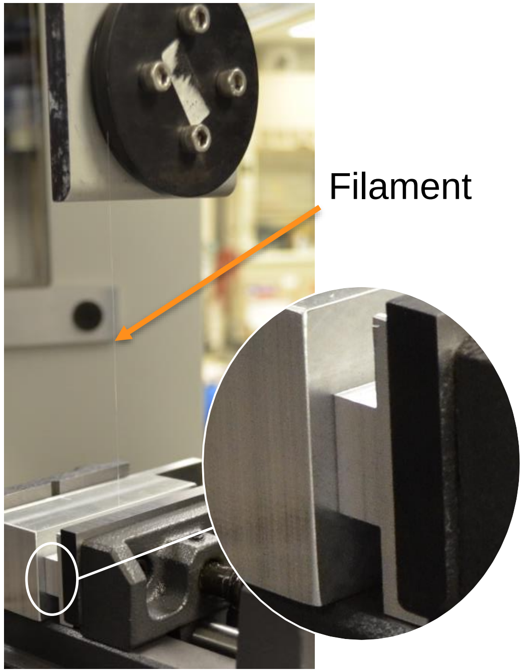
$$T_{load} = T_{hold} \times exp(\mu\varphi)$$

$$\mu = Coefficient\ of\ friction$$
$$\varphi = angle\ of\ contact$$

UHMWPE good for routing but nylon easier to hold without slip

Pinched Tensile Test





Larger diameter filaments and braids are more reliable with crush/pinch

Conclusions

- It is necessary to exceed the melting point of the polymer to reliably cut the filament but it is not necessary to far exceed this temperature.
  - *Incandescent heating of nichrome wire unnecessary*

- Cutting the filament was easier in vacuum and required less power than when air provided convective cooling.

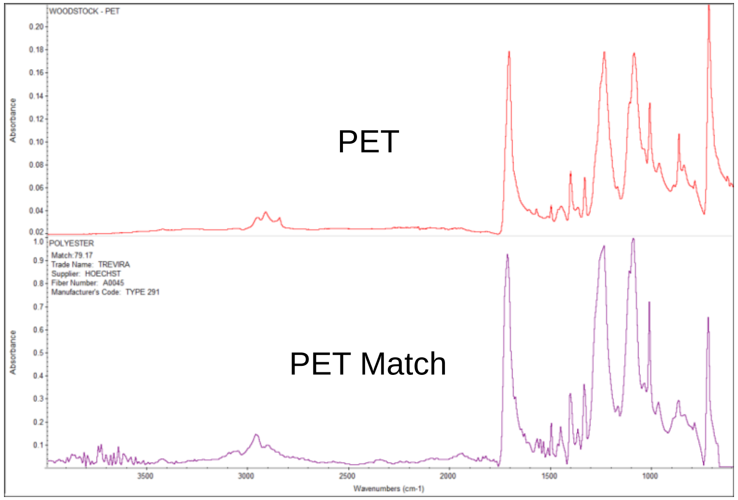
- UHMWPE braids appear to be the most robust filament based on strength, cutting temperature, low friction and pinch resistance; however, unique circumstances could make any of these filaments beneficial.

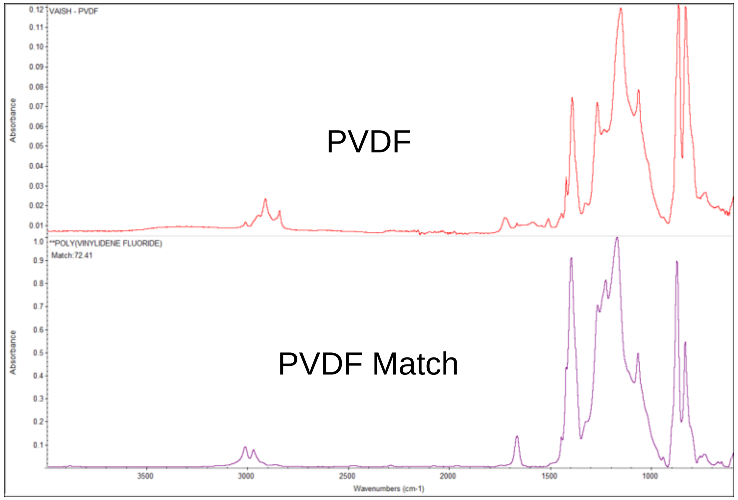
- Work still needed
  - *Creep*
  - *Abrasion*
  - *Knot retention*
  - *Contamination and outgassing*
  - *Space environments / radiation stability*

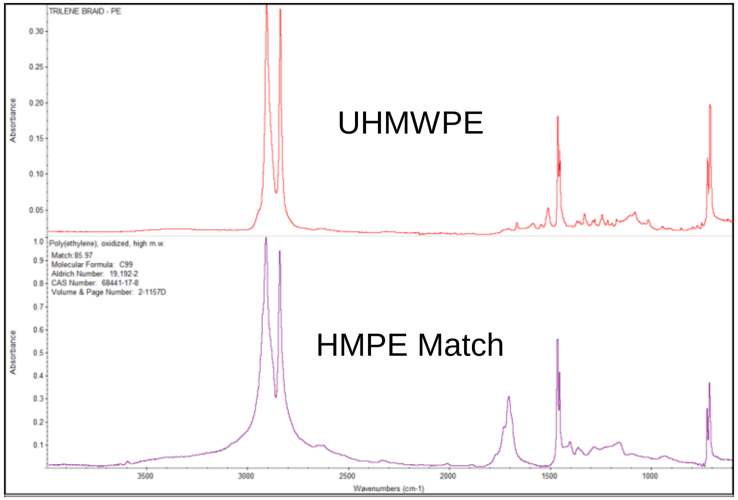
Appendix

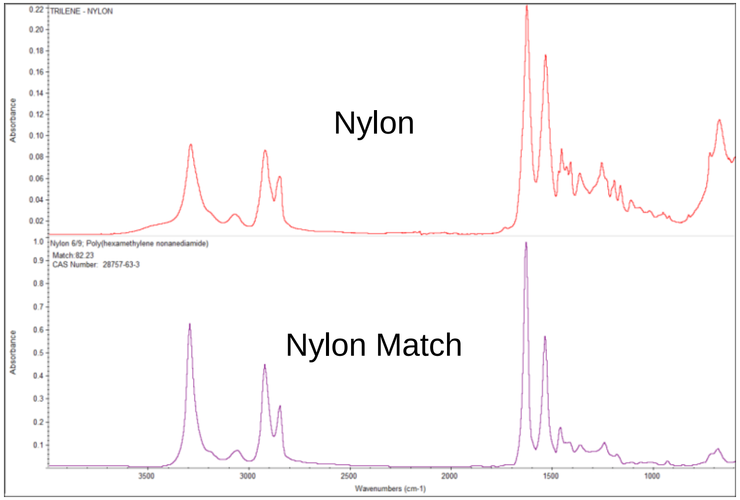
Fourier Transform Infrared Spectroscopy

Verification of filament materials



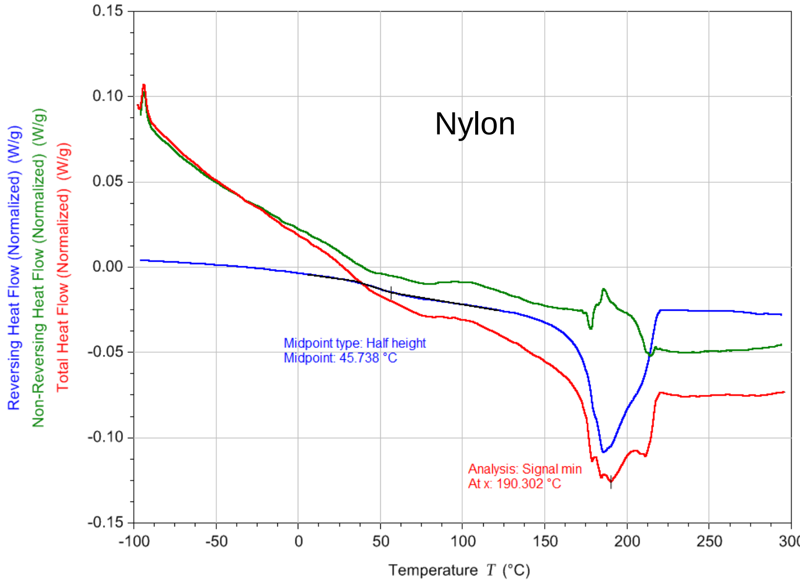


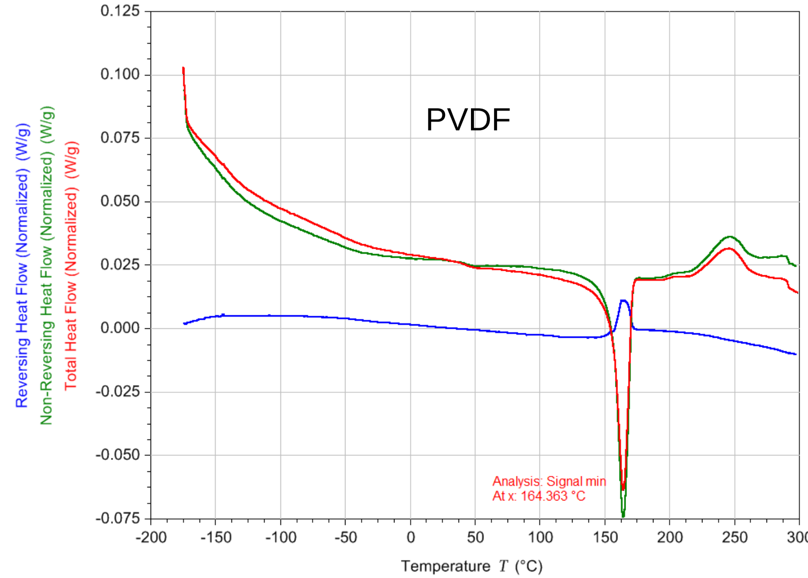


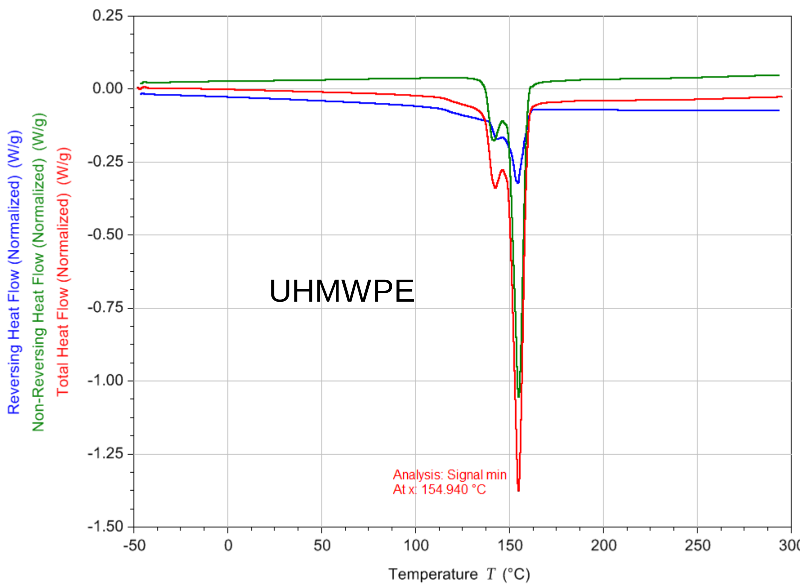


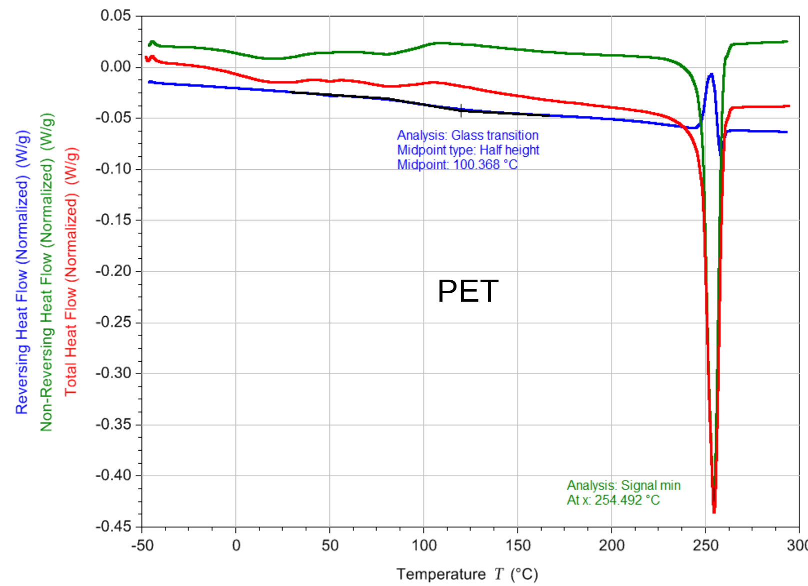
Differential Scanning Calorimetry

Determination of Tg and Melting Point



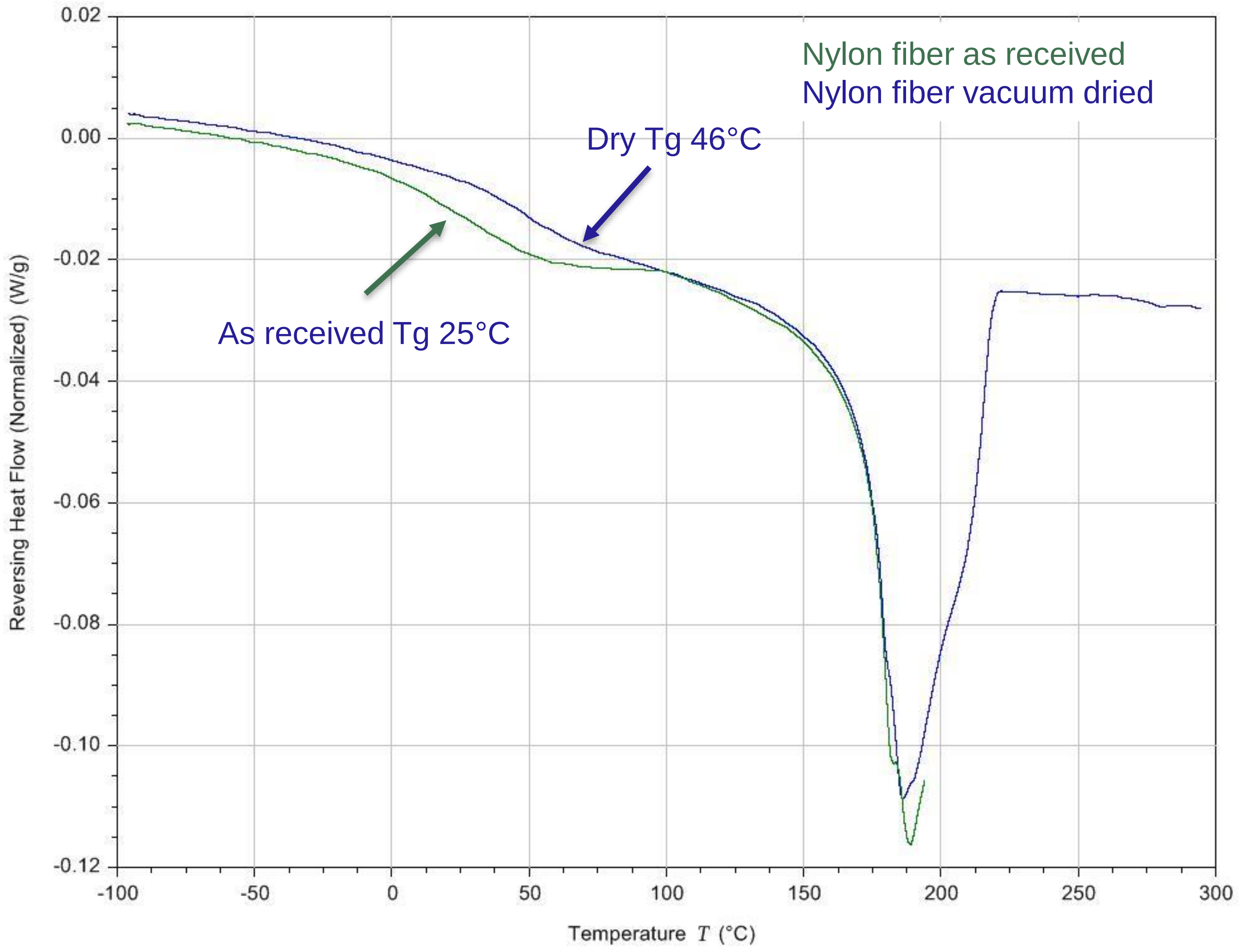






Differential Scanning Calorimetry

Nylon Tg by DSC After Vacuum Drying



Nylon Tg is lower with absorbed moisture from atmosphere