Ionic Polyimides: New High Performance Polymers for Additive Manufacturing

PI:

Enrique Jackson, Ph.D. EM22

Collaborator:

Jason Bara, Ph.D. – The University of Alabama – Tuscaloosa

Tim Huff – EM22

Agenda

- Abstract
- Recent Papers on topic
- Introduction
- Experimental Activities
  - Synthesis
  - Thermal Characterizations
    - DSC
    - TG-IR
  - Modeling
- Future Work

Abstract

- There is currently a very limited set of engineering polymers that have been demonstrated as viable for use in 3-D printing
- Additive manufacturing of custom components will require a much larger array of polymers, especially those with physical, thermal, chemical, and mechanical properties that can be tailor-made
- The development of ‘Ionic Polyimides’ offers a solution to this shortage by combining the well understood and widely accepted properties of conventional polyimides, with a new approach to polymer synthesis

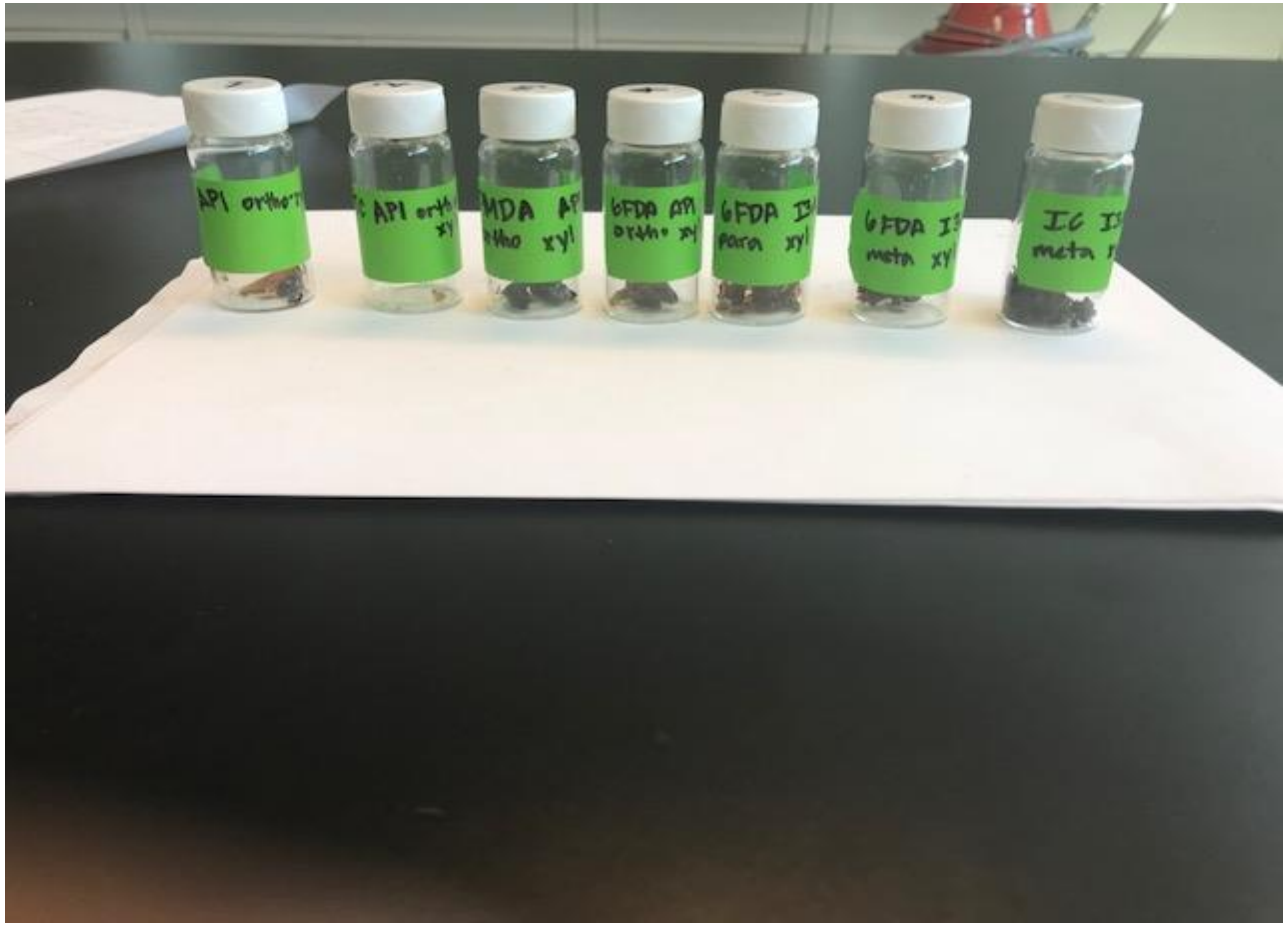
Abstract cont.

- Polyimides and polymeric ionic liquids (poly(ILs)) are at the forefront of advanced polymer materials, each with their own set of advantages and disadvantages
- While it is clear that more types of polymer materials are needed for fused deposition modeling (FDM) additive manufacturing, there is a need to explore these classes of materials
- The synthesis process developed by the Bara Research Group at the University of Alabama allows full control over polymer structure, nanostructure, thermal, electrical, and physical properties making them a prime candidate for use in the additive manufacturing process

Papers

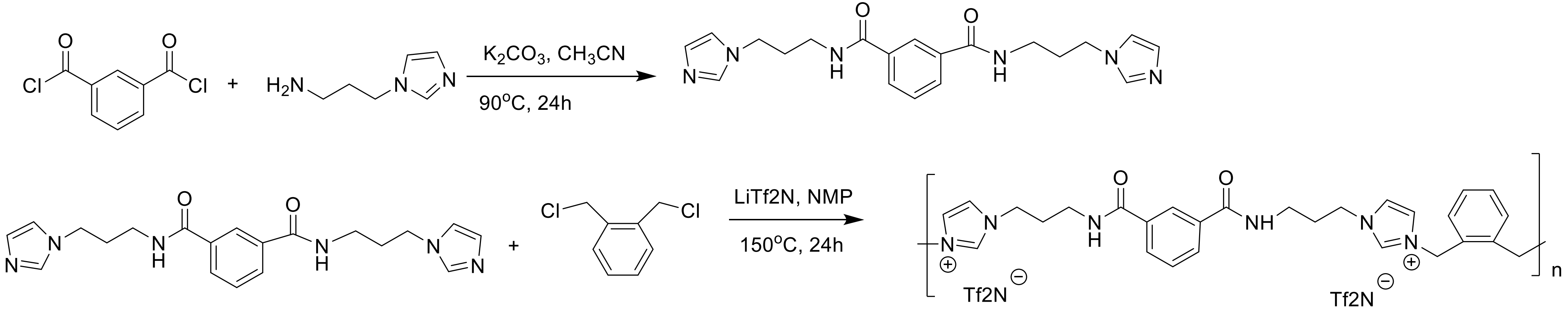
- Kathryn O'Harra, Irshad Kammakakam, Emily M. Devriese, Danielle M. Noll, Jason E. Bara and **Enrique M. Jackson,** "Synthesis and Performance of 6FDA-Based Polyimide-Ionenes and Composites with Ionic Liquids as Gas Separation Membranes," Membranes (2019) 9, 79, **DOI:** 10.3390/membranes9070079
- Kathryn O'Harra, Irshad Kammakakam, Jason E. Bara and **Enrique M. Jackson,** "Understanding the Effects of Backbone Chemistry and Anion Type on the Structure and Thermal Behaviors of Imidazolium Polyimide-Ionenes," Polymer International (2019), **DOI:**10.1002/pi.5825.
- Irshad Kammakakam, Kathryn O'Harra, Grayson Dennis, Jason E. Bara and **Enrique M. Jackson**, "Self-Healing Imidazolium-based Ionene-Polyamide Membranes: An Experimental Study on Physical and Gas Transport Properties," Polymer International (2019), [**https://doi-org.proxy.library.vanderbilt.edu/10.1002/pi.5802**](https://doi-org.proxy.library.vanderbilt.edu/10.1002/pi.5802).
- Irshad Kammakakam, Kathryn O'Harra, Jason E. Bara and **Enrique M. Jackson**, "Design and Synthesis of Imidazolium-Mediated Tröger's Base-Containing Ionene Polymers for Advanced CO_2 Separation Membranes," ACS Omega (2019), 4, 3439-3448, DOI: 10.1021/acsomega.8b03700.
- Jason E. Bara, Kathryn E. O'Harra, Marlow M. Durbin, Grayson P. Dennis, **Enrique M. Jackson**, Brian Thomas & Jamiu A. Odutola, "Synthesis and Characterization of Ionene-Polyamide as Candidates for New Gas Separation Membranes," MRS Advances (2018) DOI 10.1557/adv.2018.376.

Ionic Polyimides



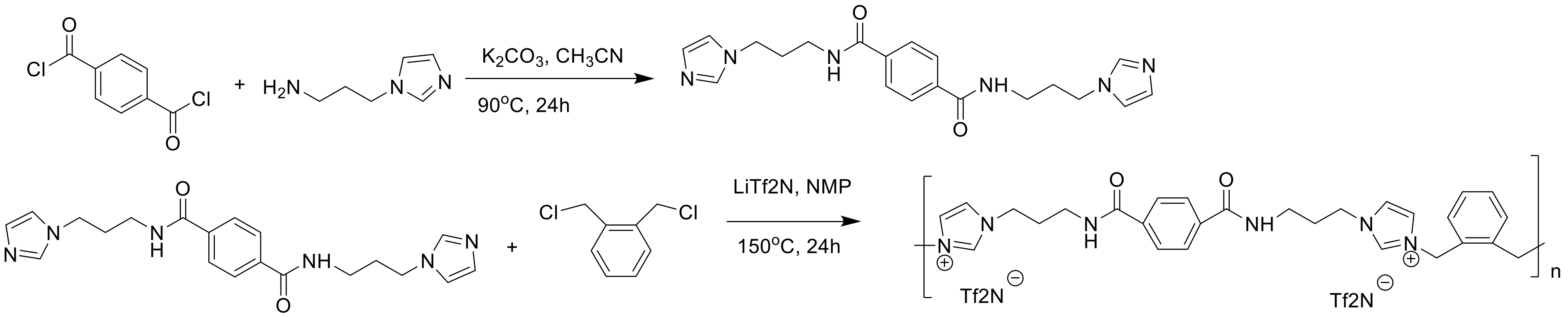
Ionic Polyimide Synthesis

IC API ortho xylene



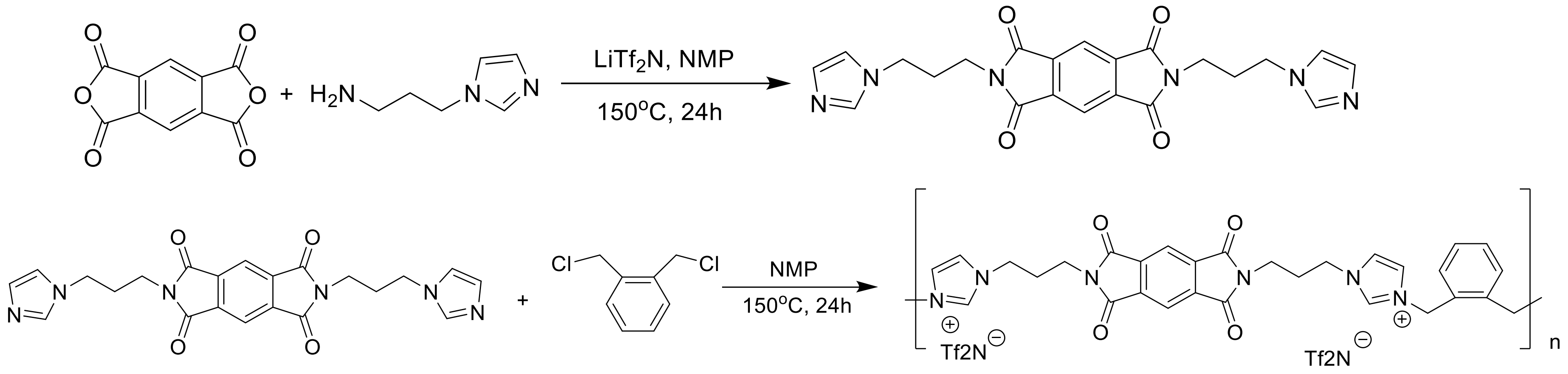
Ionic Polyimide Synthesis

TC API ortho xylene



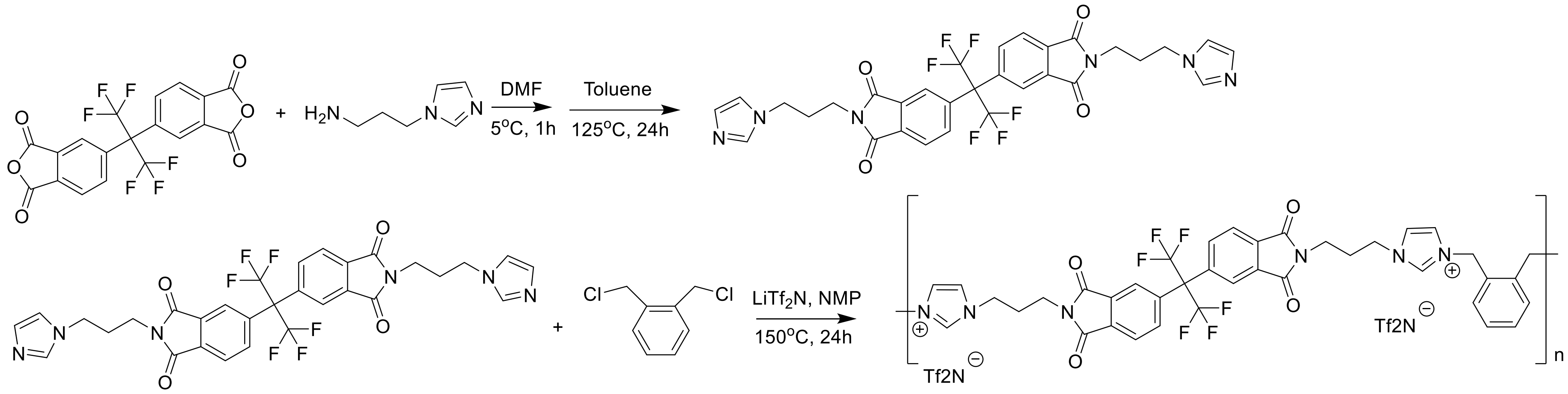
Ionic Polyimide Synthesis

PMDA API ortho xylene



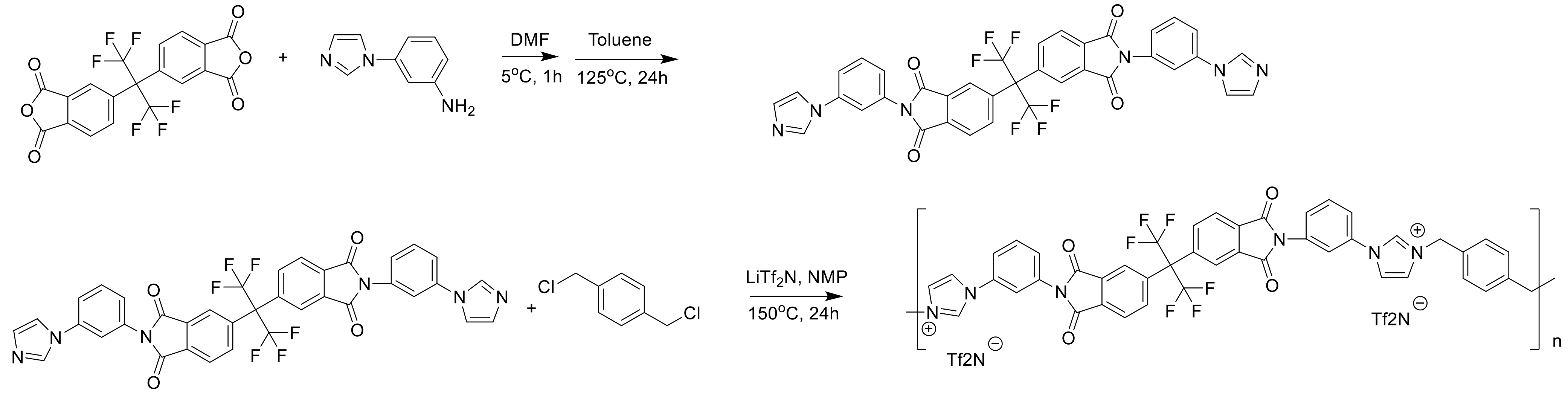
Ionic Polyimide Synthesis

6FDA API ortho xylene



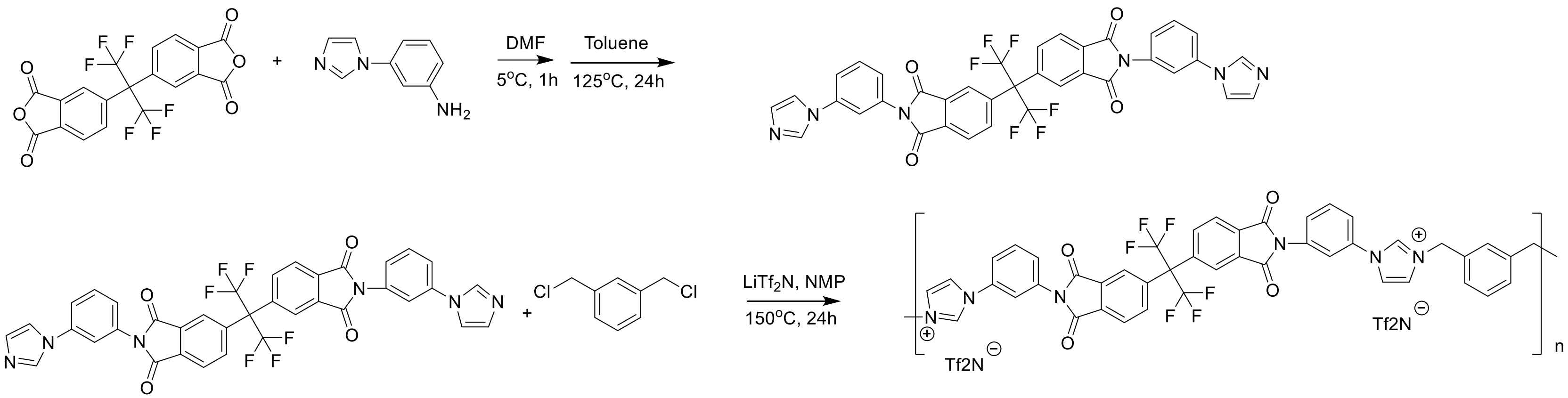
Ionic Polyimide Synthesis

6FDA I3A para xylene



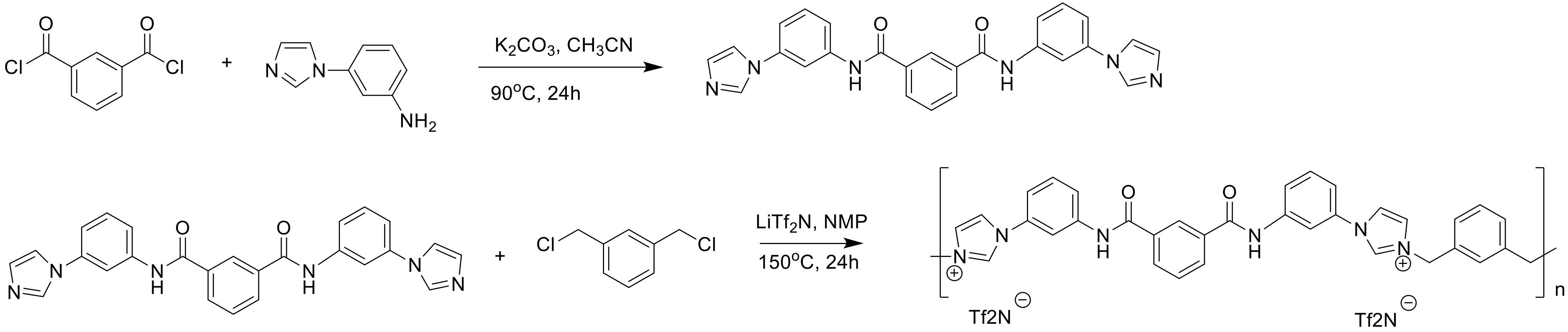
Ionic Polyimide Synthesis

6FDA I3A meta xylene



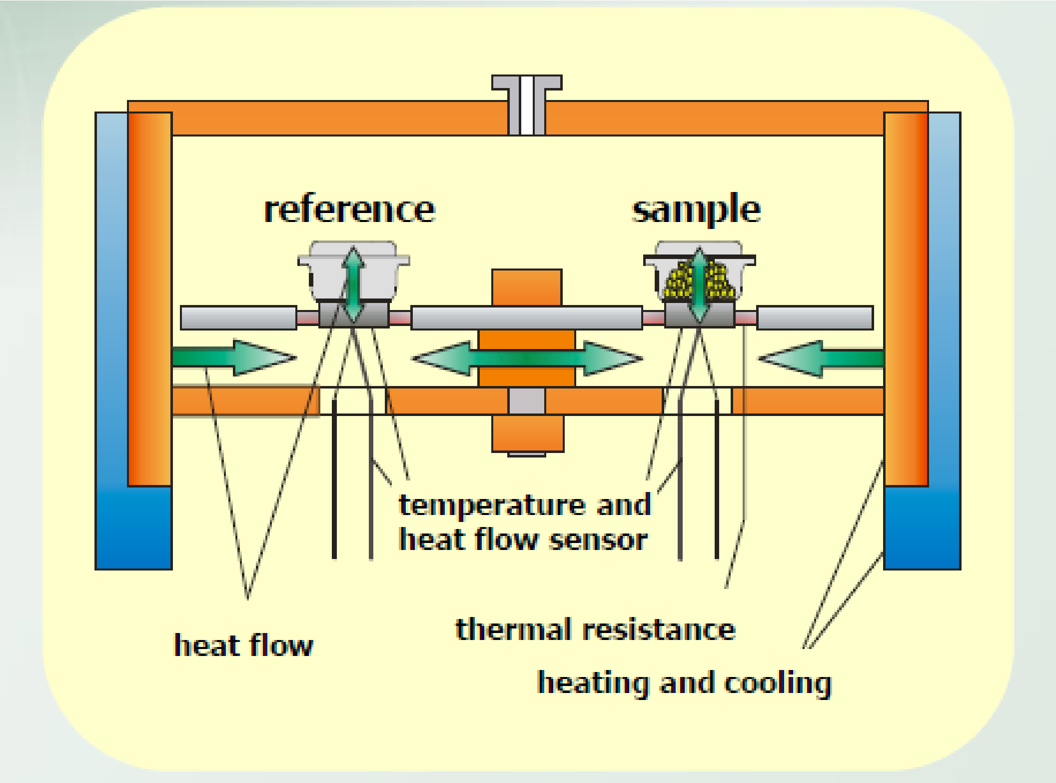
Ionic Polyimide Synthesis

IC I3A meta xylene



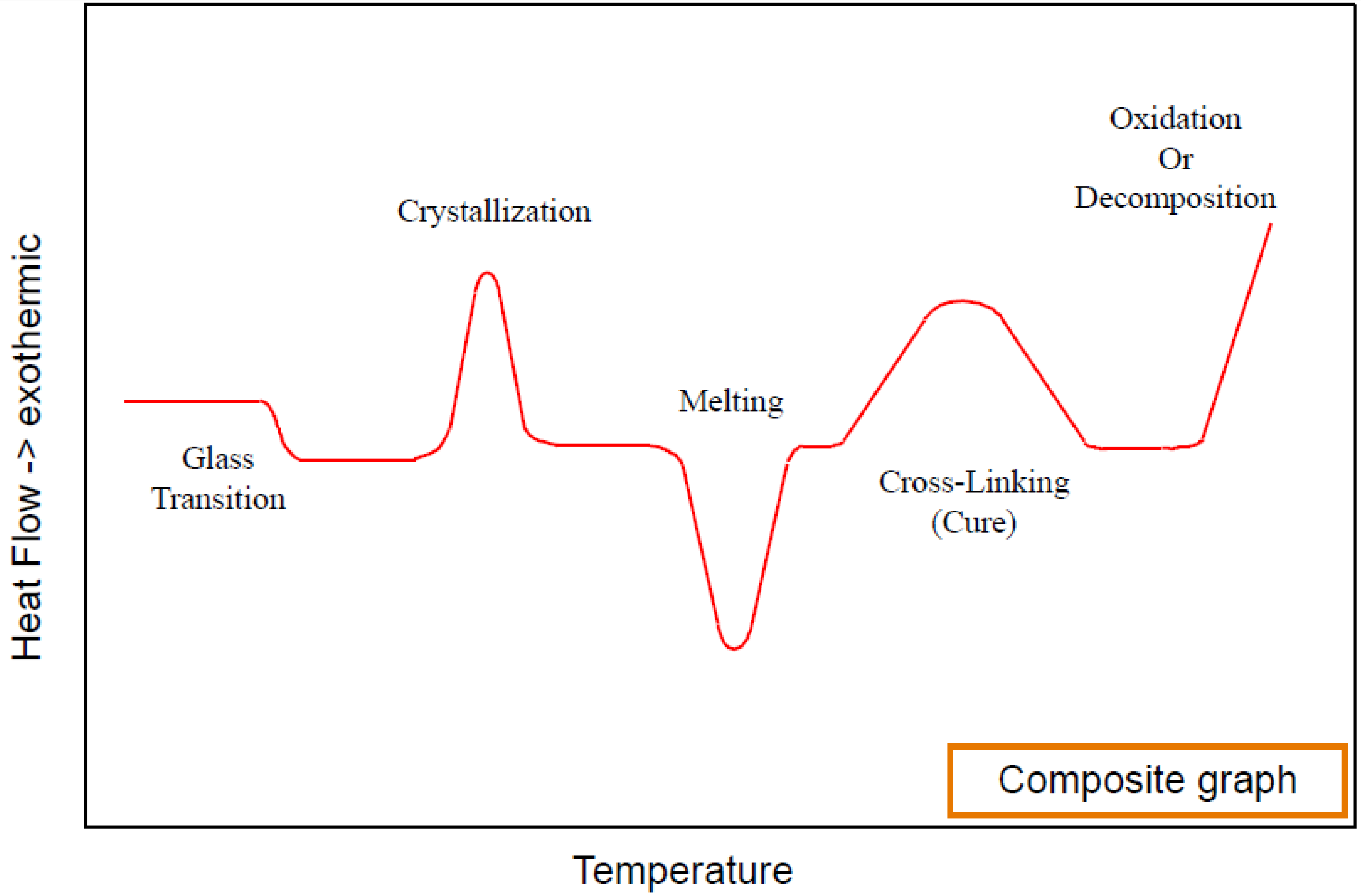
Thermal Characterization Techniques – Differential Scanning Calorimetry (DSC)

DSC is a technique in which the difference in energy inputs into a substance and a reference materials reassured as a function of temperature while the substance and reference is subjected to a controlled-temperature program



Netzsch, Inc. Thermal Analysis – An Introduction 3-7-2005

Typical DSC Transitions

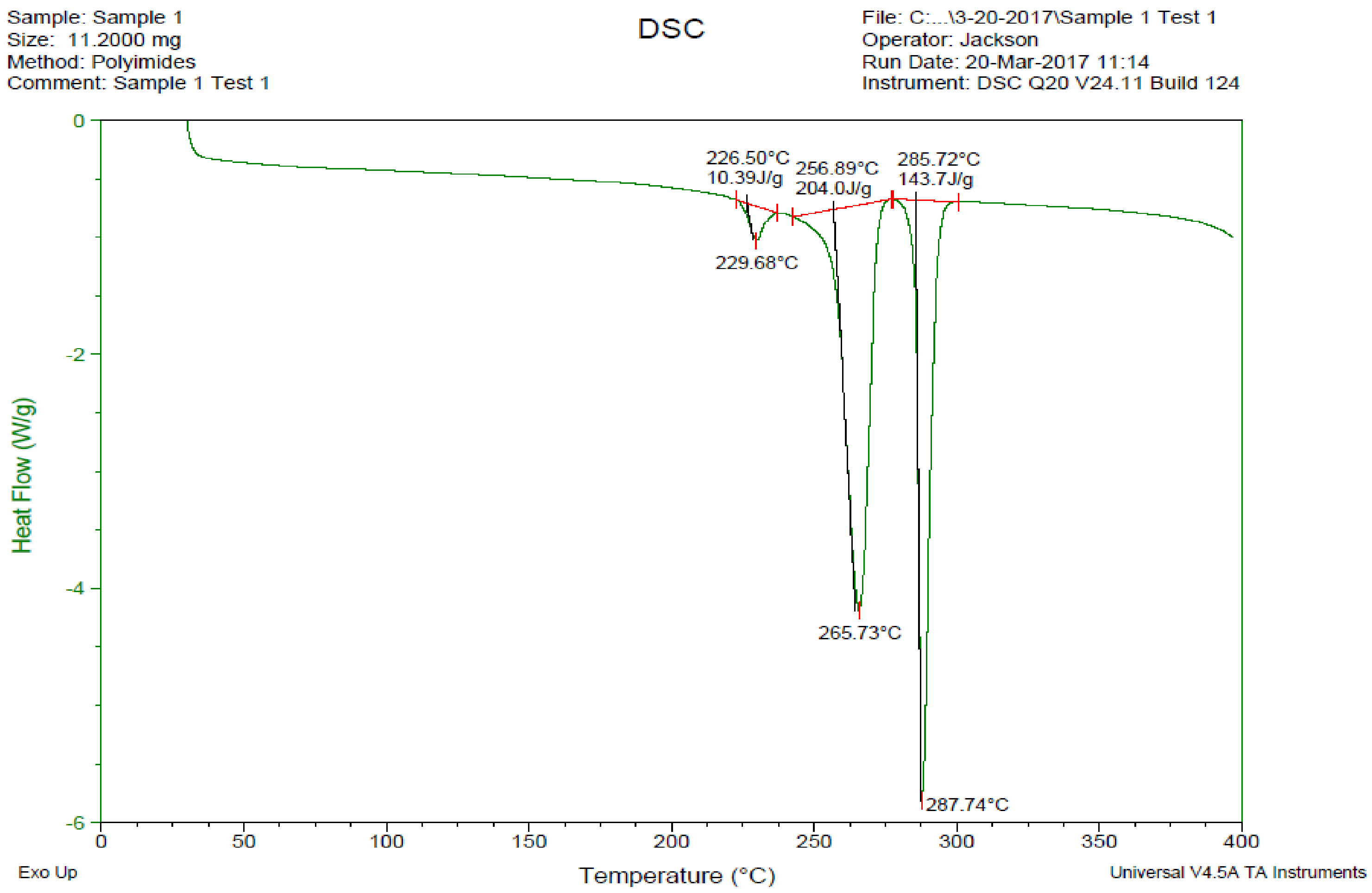


DSC Training – TA Instruments

DSC Results – Starting Materials

Samples	Endothermic Transition 1 (J/g)	Endothermic Transition 2 (J/g)	Endothermic Transition 3 (J/g)	Exothermic Transition (J/g)
Sample 1 **Onset Temperatures (°C)**	10.34 ± 0.08 229.15 ± 0.33	196.45 ± 10.68 265.83 ± 0.13	140.65 ± 4.31 287.85 ± 0.16	
Sample 2 **Onset Temperatures (°C)**	37.59 ± 4.43 229.15 ± 0.33			48.08 ± 0.92 374.22 ± 4.07
Sample 3 **Onset Temperatures (°C)**	356 304.67			
Sample 5 **Onset Temperatures (°C)**	12.65 ± 1.27 74.54 ± 1.02	61.73± 21.45 171.95 ± 0.21		
Sample 6 **Onset Temperatures (°C)**	186.5 ± 1.13 116.79 ± 18.83	153.2 ± 4.80 232.97 ± 16.67		
Sample 7 **Onset Temperatures (°C)**	105.85 ± 1.91 47.75 ± 0.16	218.4 ± 55.58 282.66 ± 4.11		
Sample 8 **Onset Temperatures (°C)**	490.45 ± 232.28 256.81 ± 2.96			
Sample TC **Onset Temperatures (°C)**	9.79 ± 0.26 71.06 ± 0.16	122.65 ± 3.18 85.96 ± 0.41	280.05 ± 0.92 277.37 ± 0.56	
Sample 6FDA **Onset Temperatures (°C)**	110.45 ± 6.71 247.56 ± 0.19			

DSC Results – Starting Materials



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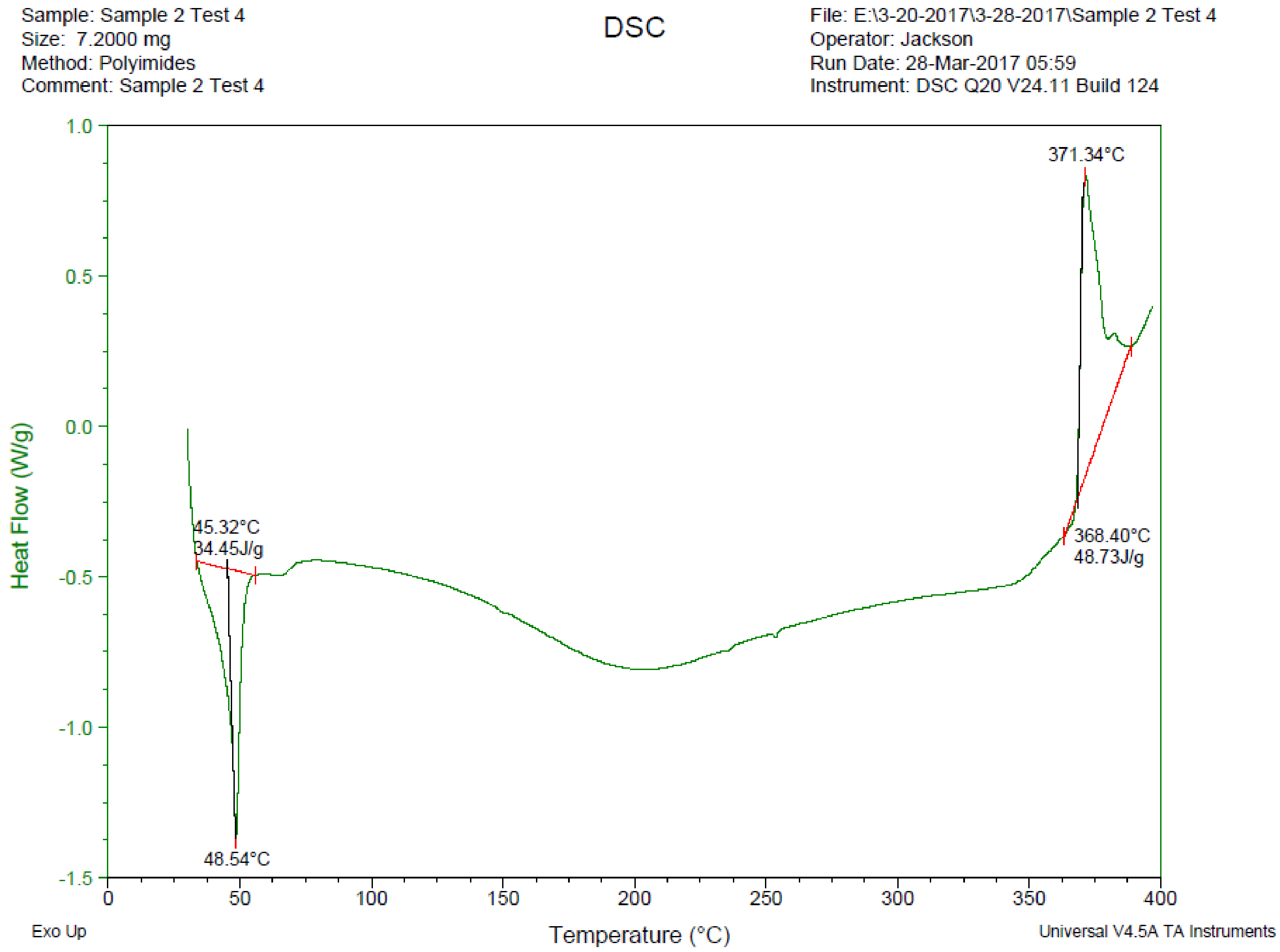

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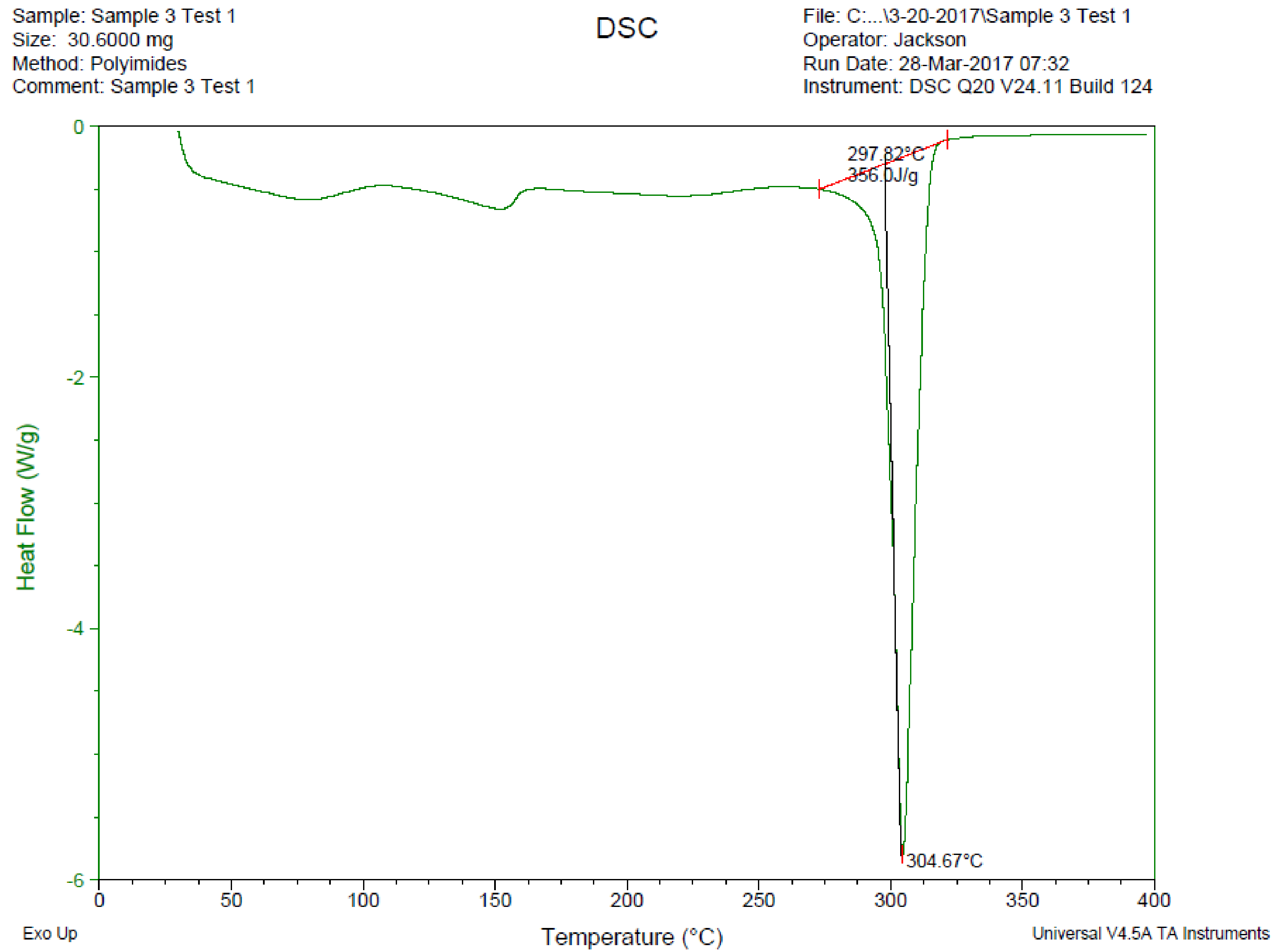

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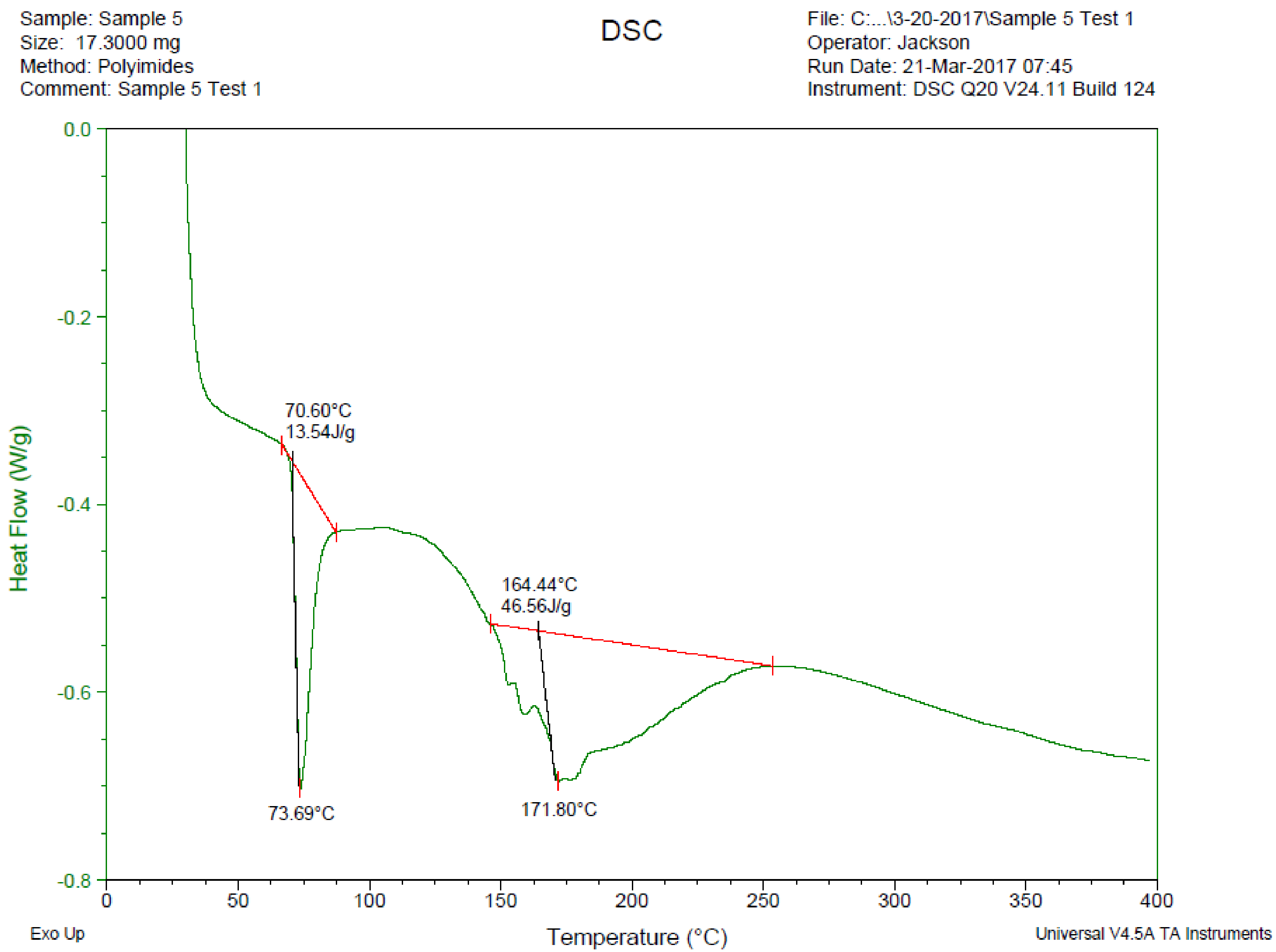

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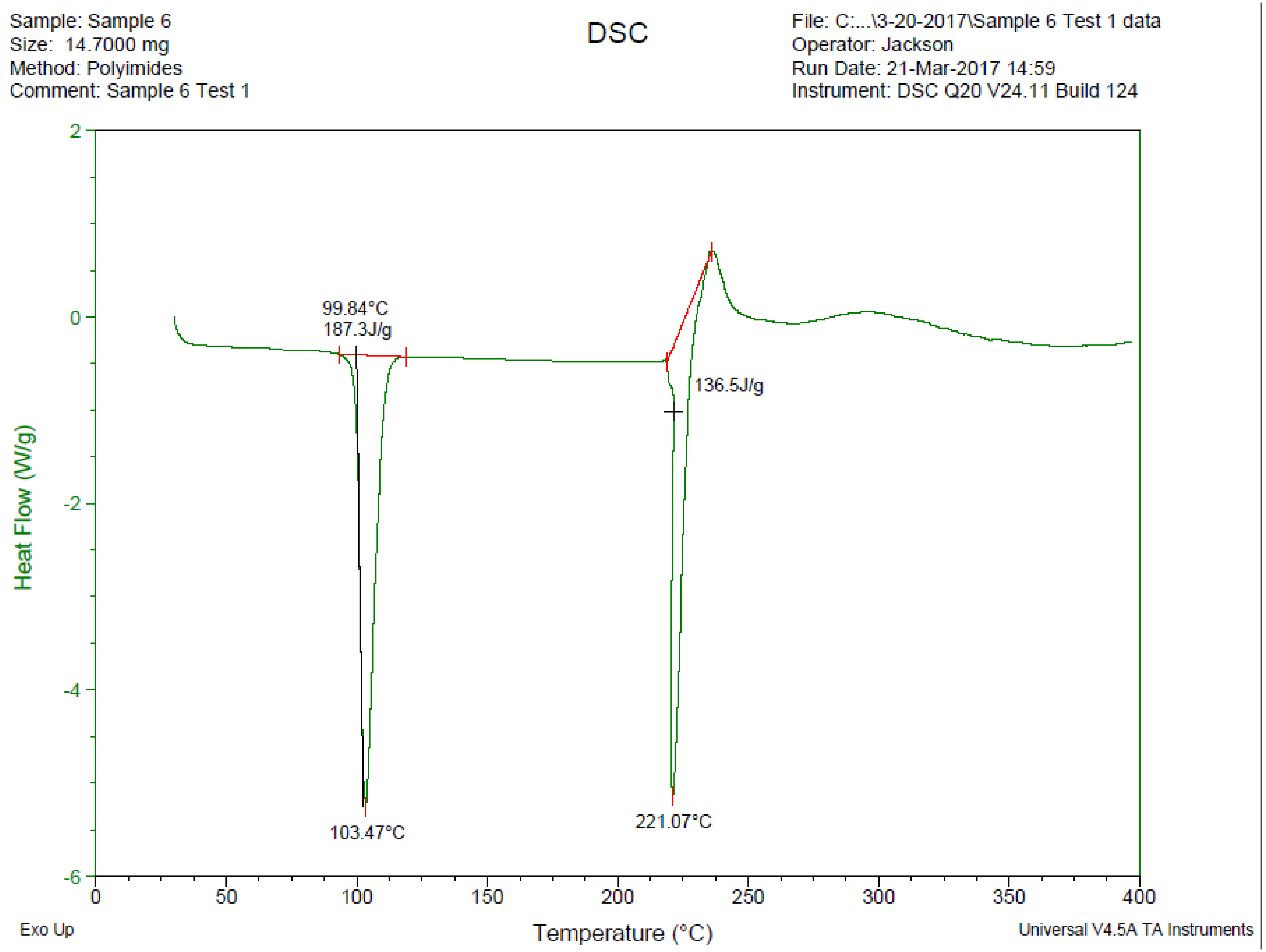

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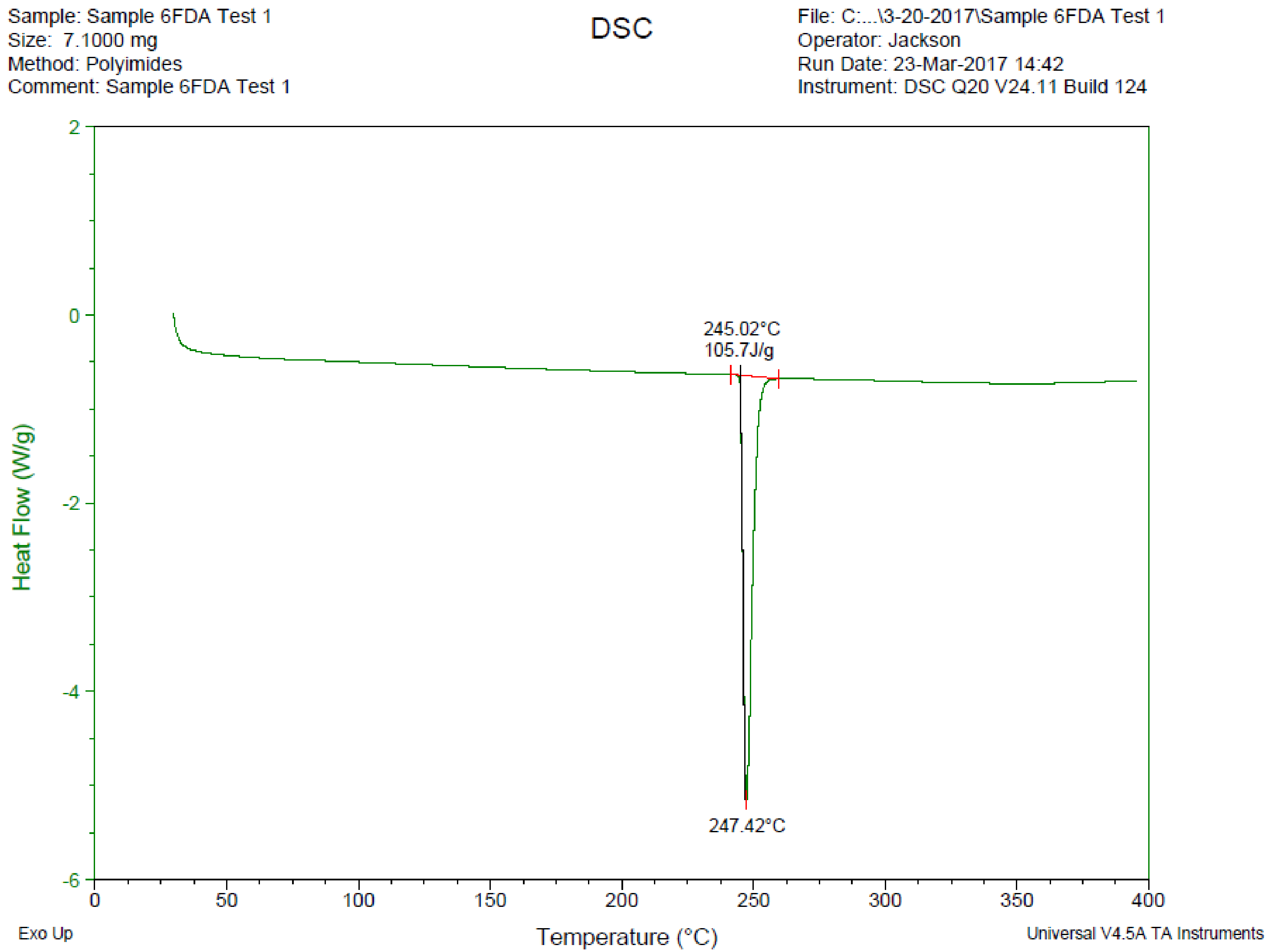

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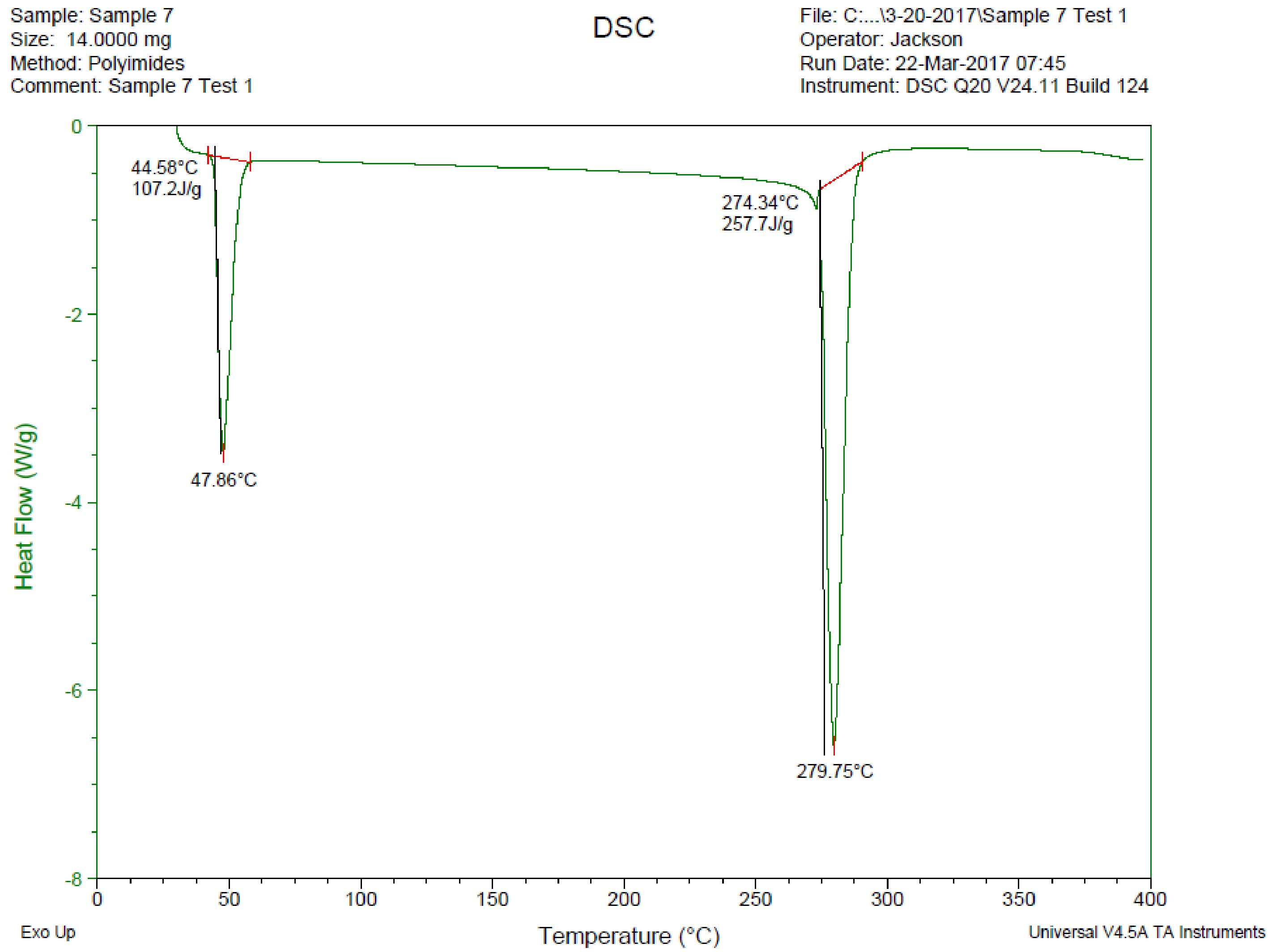

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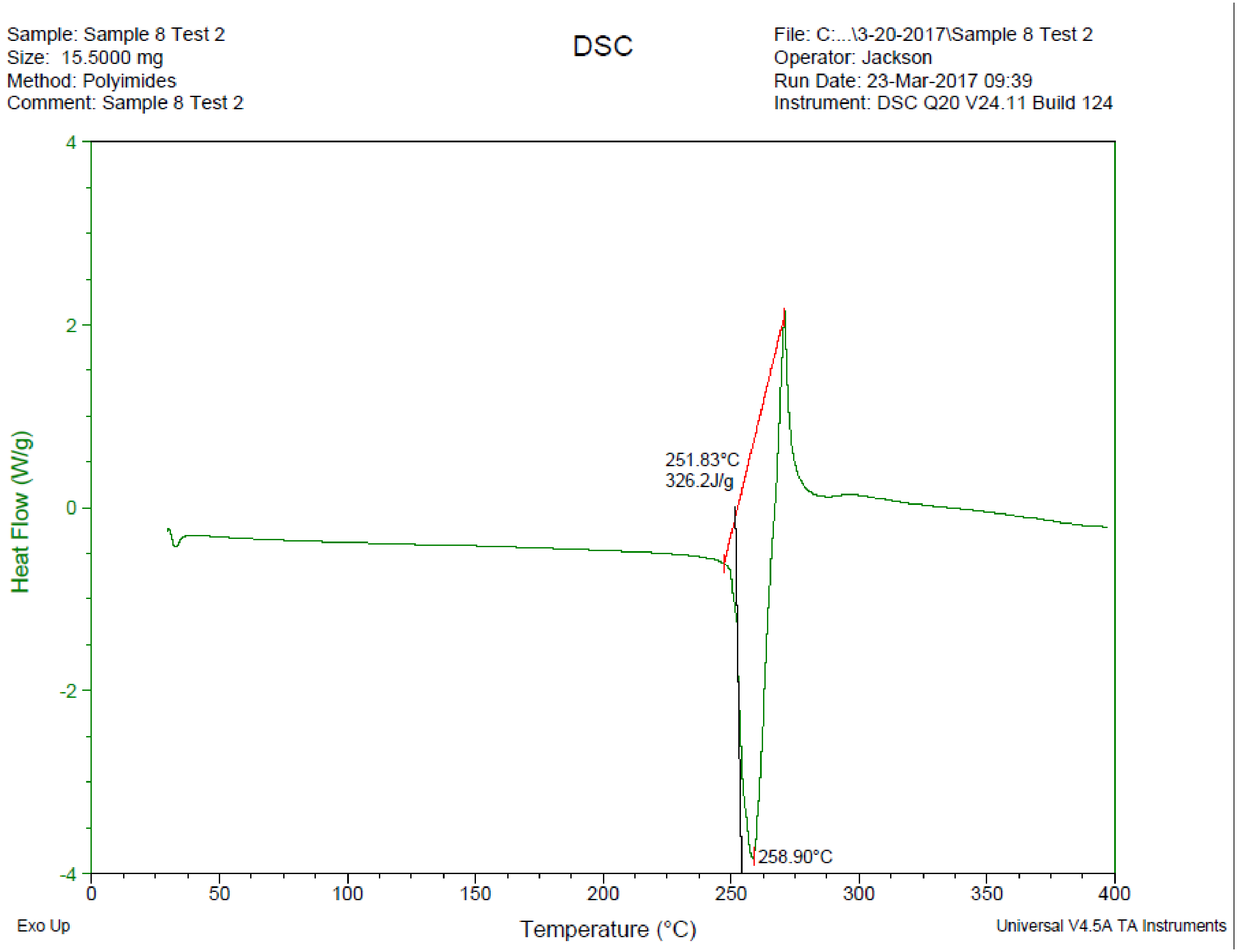

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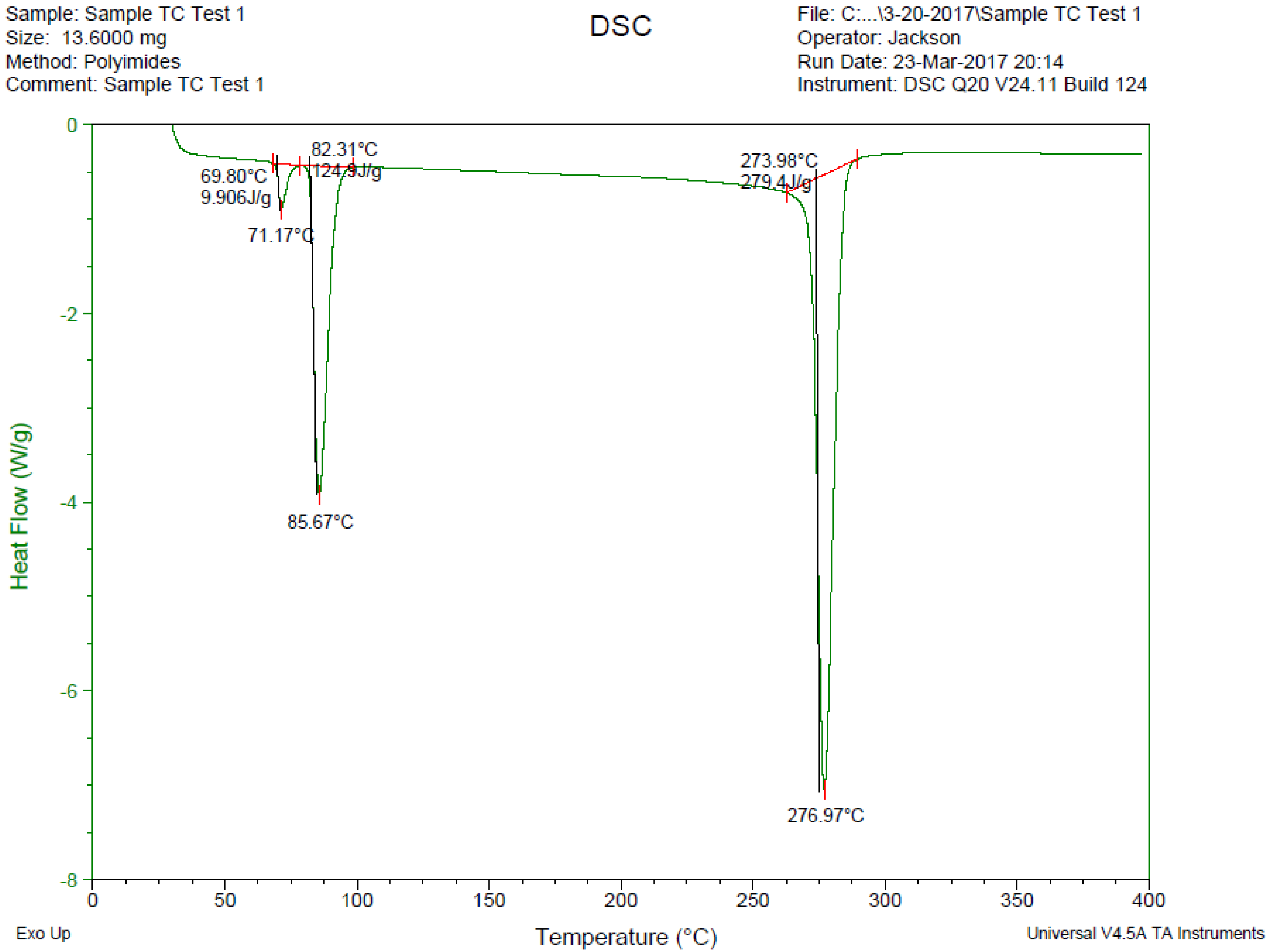
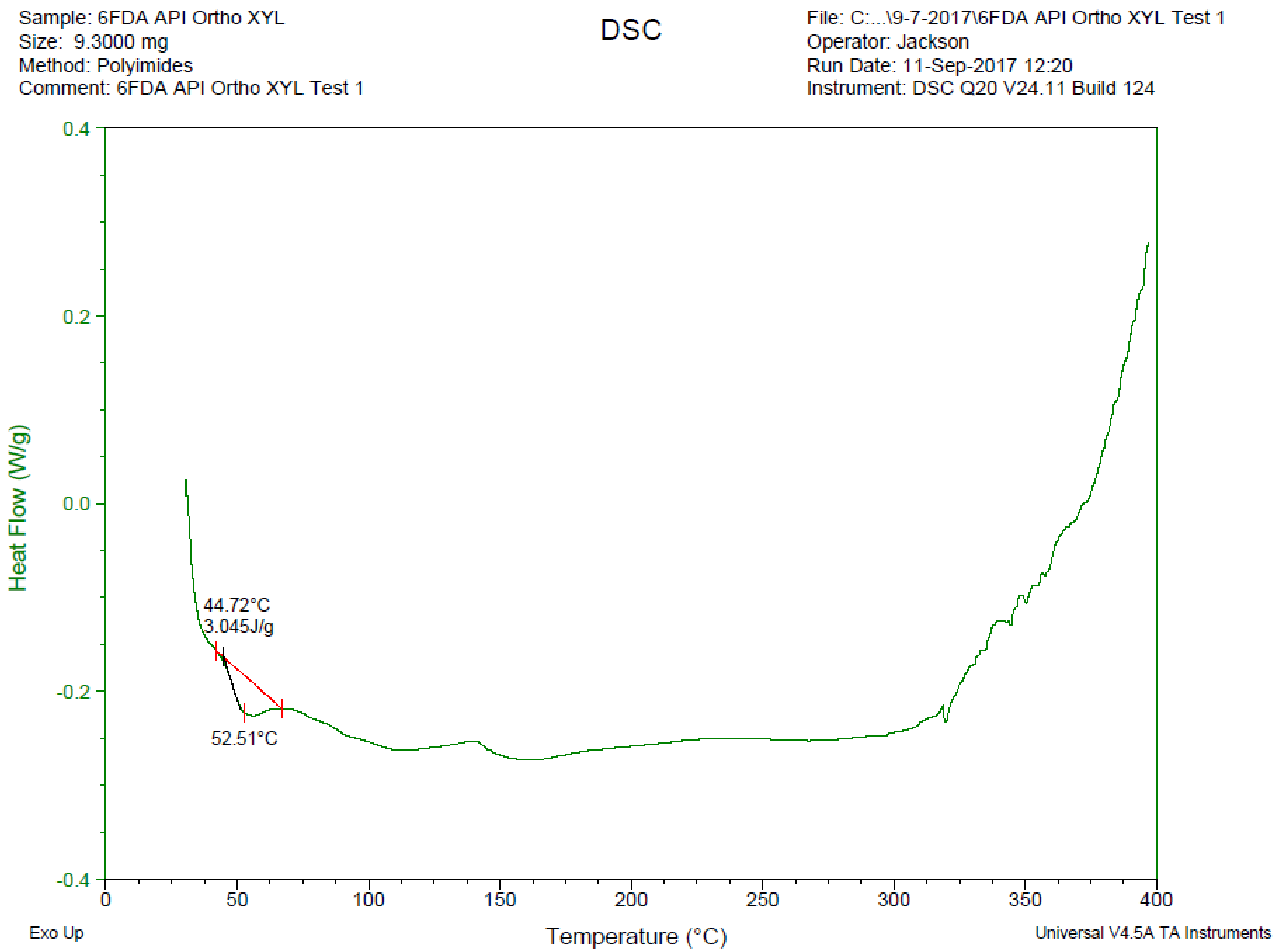


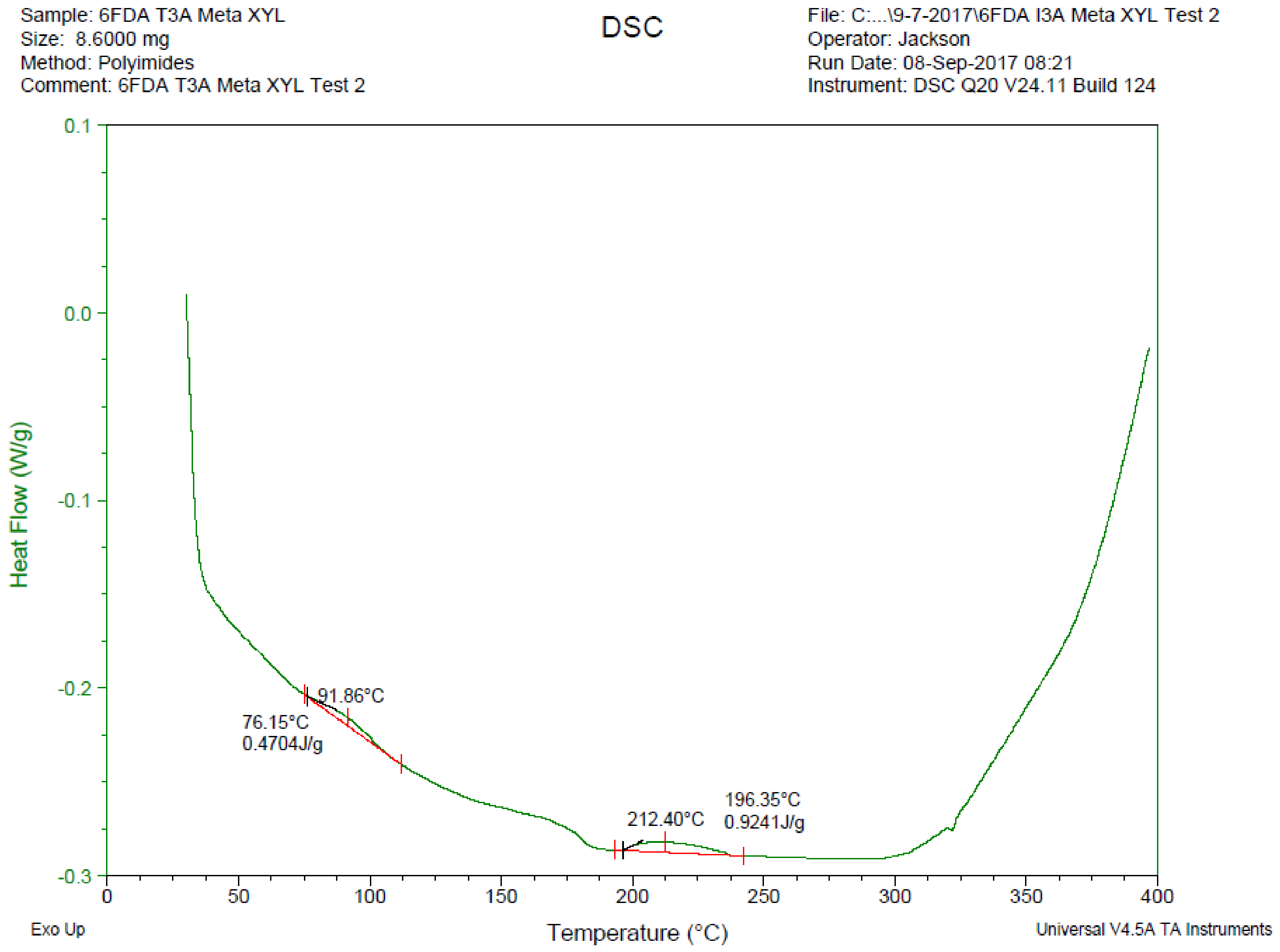
DSC Results – Polymeric Materials

	TC	6FDA	6FDA-Meta	6FDA-Para	PMDA-API-P-XYL	TC-API-M-XYL	6FDA-Starting Mat'L	BPADA-APT-P-XYL
Endotherm #1	67.62 ± 0.36	244.25 ± 0.12	101.21 ± 6.75	80.14 ± 9.98	166.26 ± 8.61	139.16 ± 3.97	244.47 ± 0.05	129.37 ± 5.21
Heat of Fusion #1	9.35 ± 0.63	104.8 ± 4.11	4.90 ± 0.51	50.57 ± 5.12	21.51 ± 0.61	5.86 ± 1.29	98.94 ± 9.80	20.62 ± 8.12
Melting Point #1	69.94 ± 0.77	246.3 ± 0.16	108.62 ± 7.85	132.58 ± 3.80	193.76 ± 1.15	151.07 ± 5.90	246.63 ± 0.21	142.32 ± 5.35
Endotherm #2	81.70 ± 0.38					321.81 ± 2.46		
Heat of Fusion #2	109.27 ± 6.34					0.28 ± 0.24		
Melting Point #2	85.06 ± 1.67					324.17 ± 4.23		
Endotherm #3						340.96 ± 5.92		
Heat of Fusion #3						0.17 ± 0.08		
Melting Point #3						341.48 ± 5.90		

DSC Results – Polymeric Materials



DSC Results – Polymeric Materials



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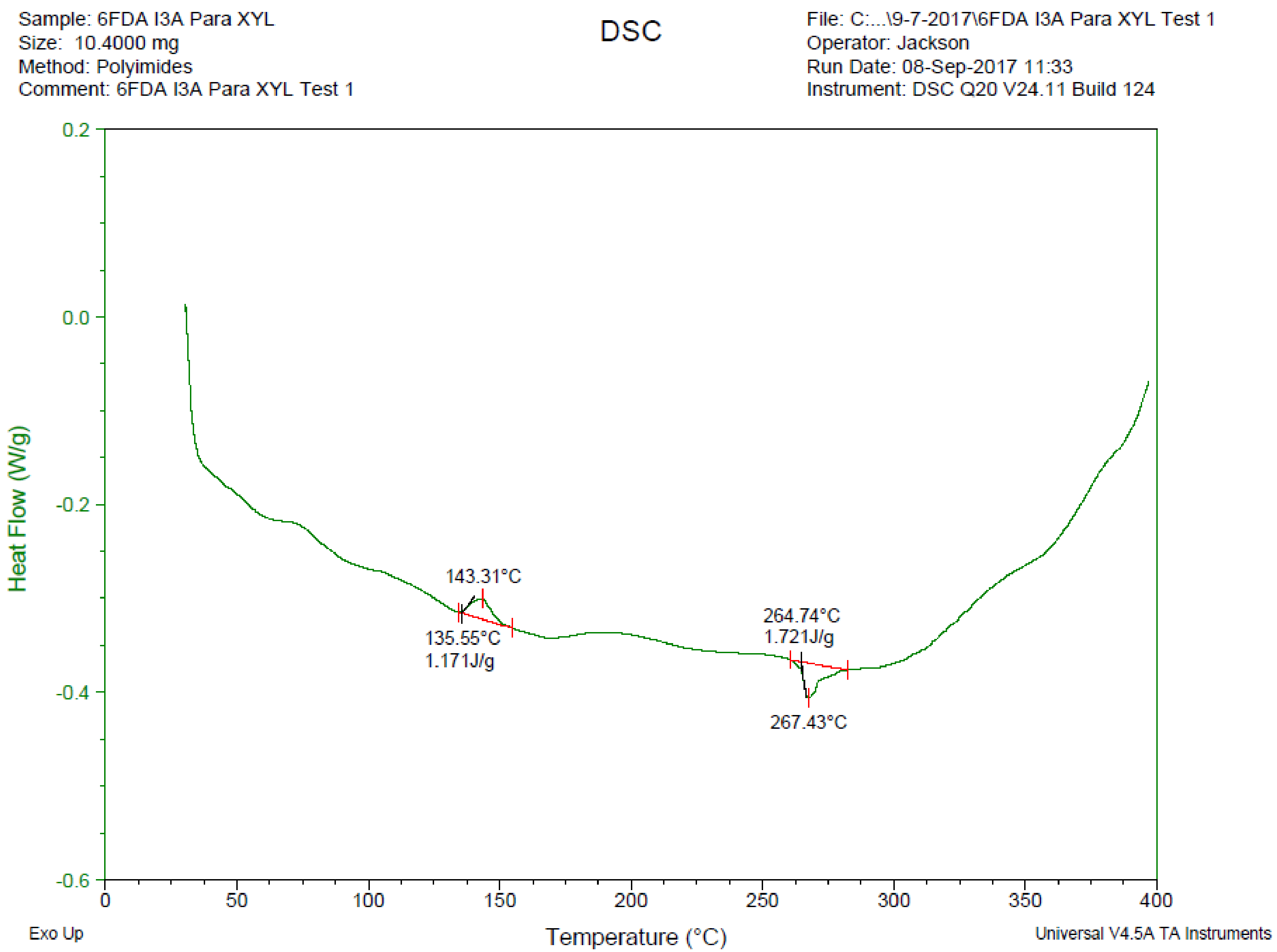

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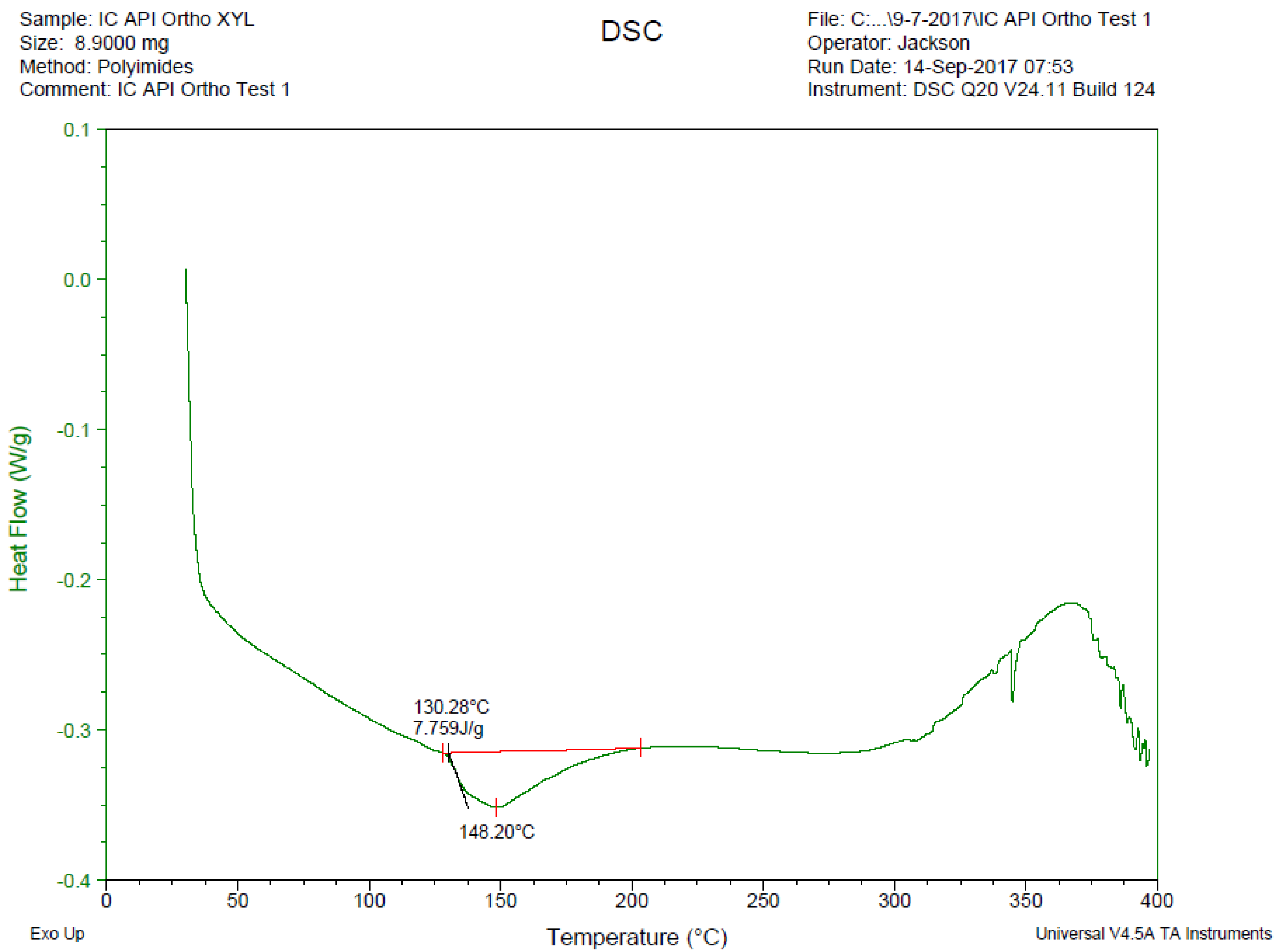

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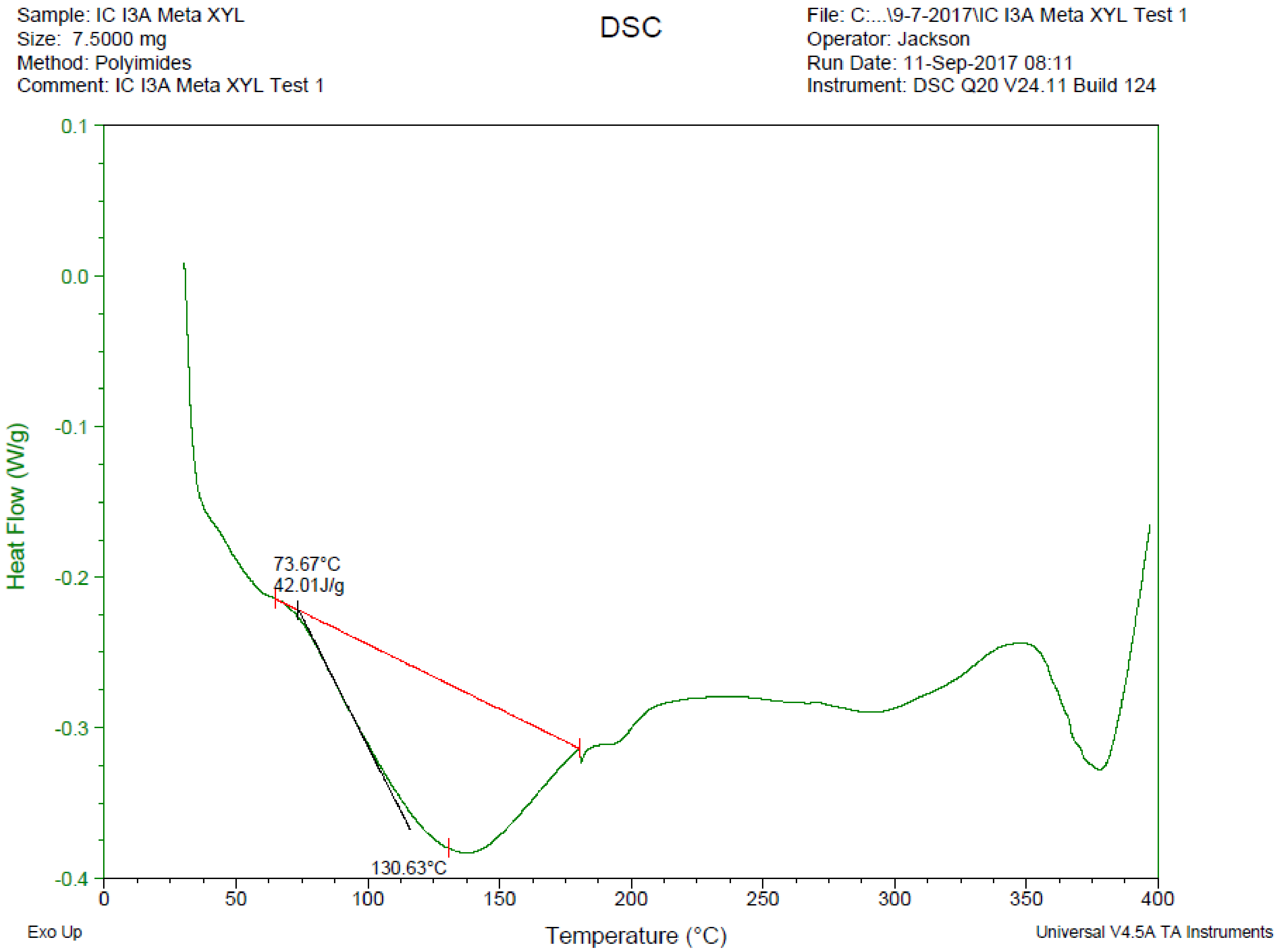

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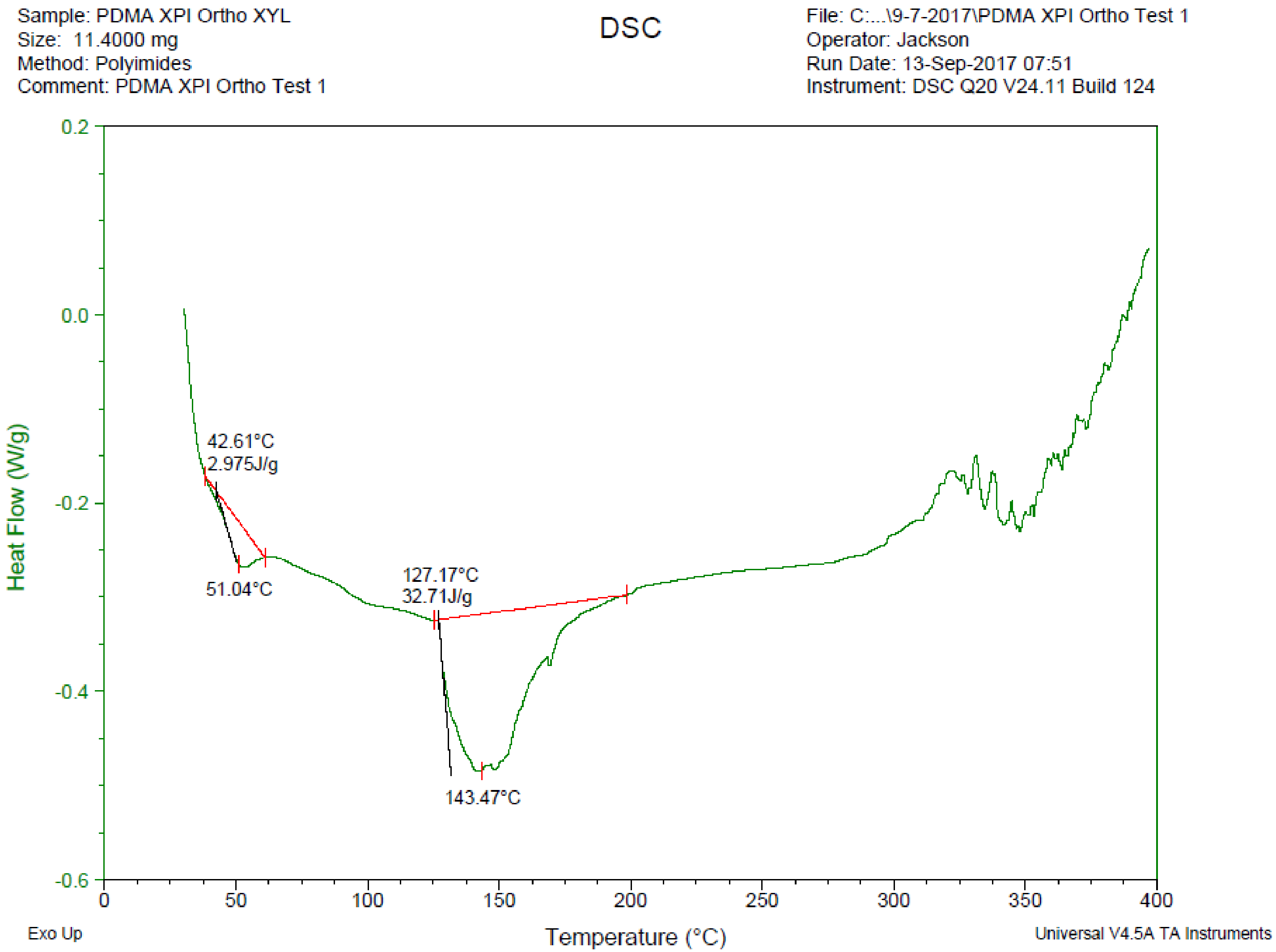

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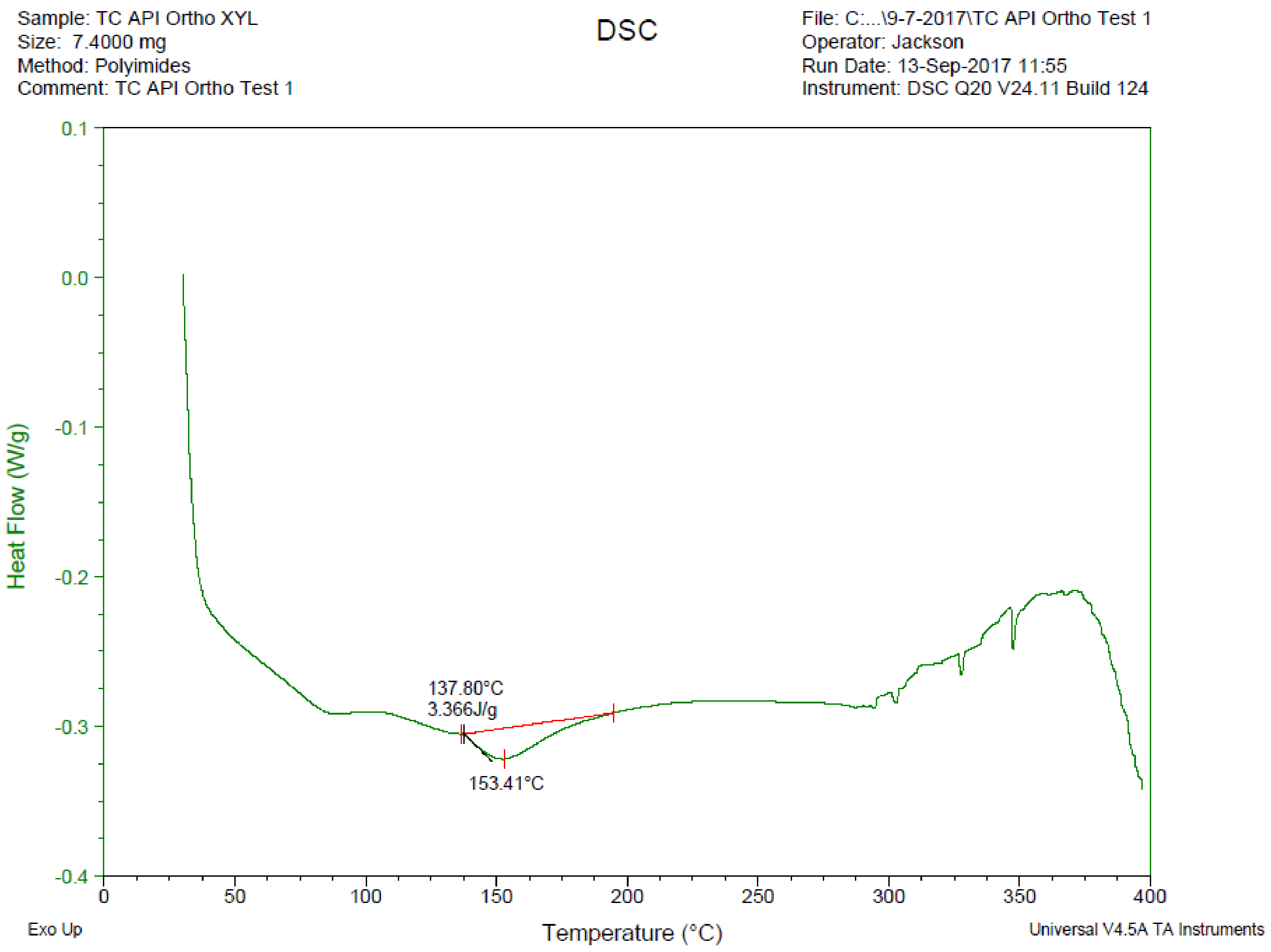


TG-IR

- Thermogravimetric analysis (TG) follows changes in mass of the sample as a function of temperature and/or time.
- TG gives characteristic information about the composition of the measured sample, in particular the amounts of the various components and their thermal behavior.
- In addition, further measurements are possible such as kinetic analysis of thermal decomposition.
- The identification of gases released directly from the sample or during thermal treatment cannot be performed just by thermal analysis, but coupling a spectroscopic method such as Fourier-Transform-Infrared (FTIR) spectroscopy is an excellent solution.

TG-IR cont.

- IR spectroscopy is a classical technique, which depends upon the interaction of infrared radiation with the vibrating dipole moments of molecules.
- It gives, with the exception of homonuclear diatomics and noble gases, a characteristic spectrum for each substance.

- TG-FTIR is useful for a wide range of applications, including:
  - Outgassing of Materials
  - Detection of Residues
  - Analysis of Additives
  - Analysis of Aging Processes
  - Competitive Analysis
  - Characterization of Natural and Raw Materials
  - Desorption Behavior
  - Analysis of Synthesis Processes
  - Analysis of Decomposition Processes

TG-IR Data

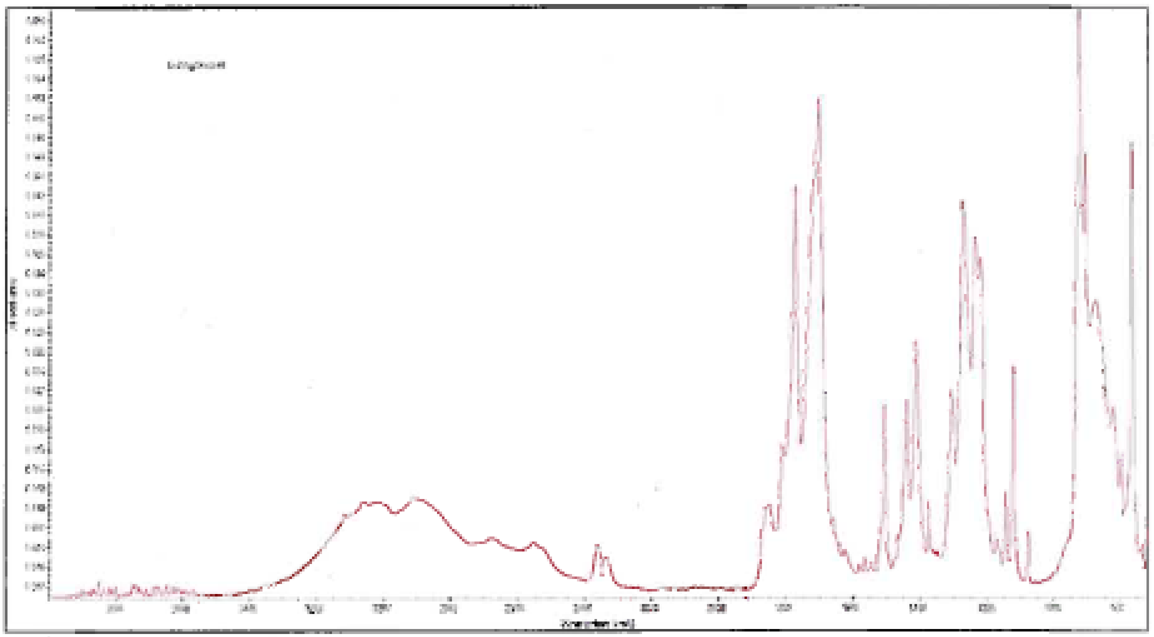


Figure 1. Infrared Spectrum of Building Block #1

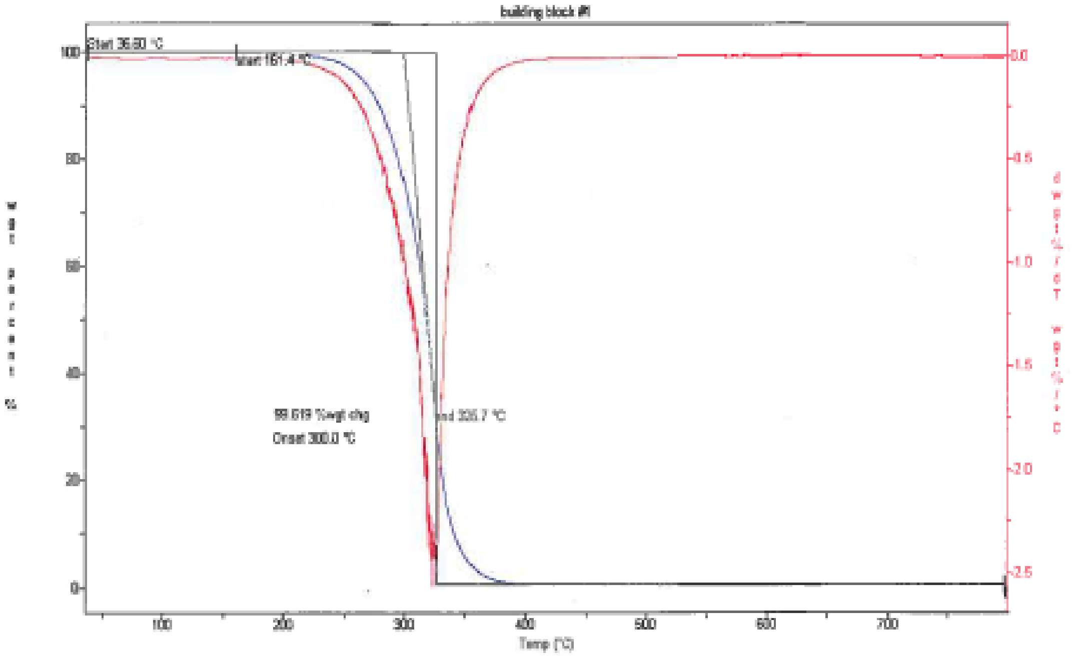


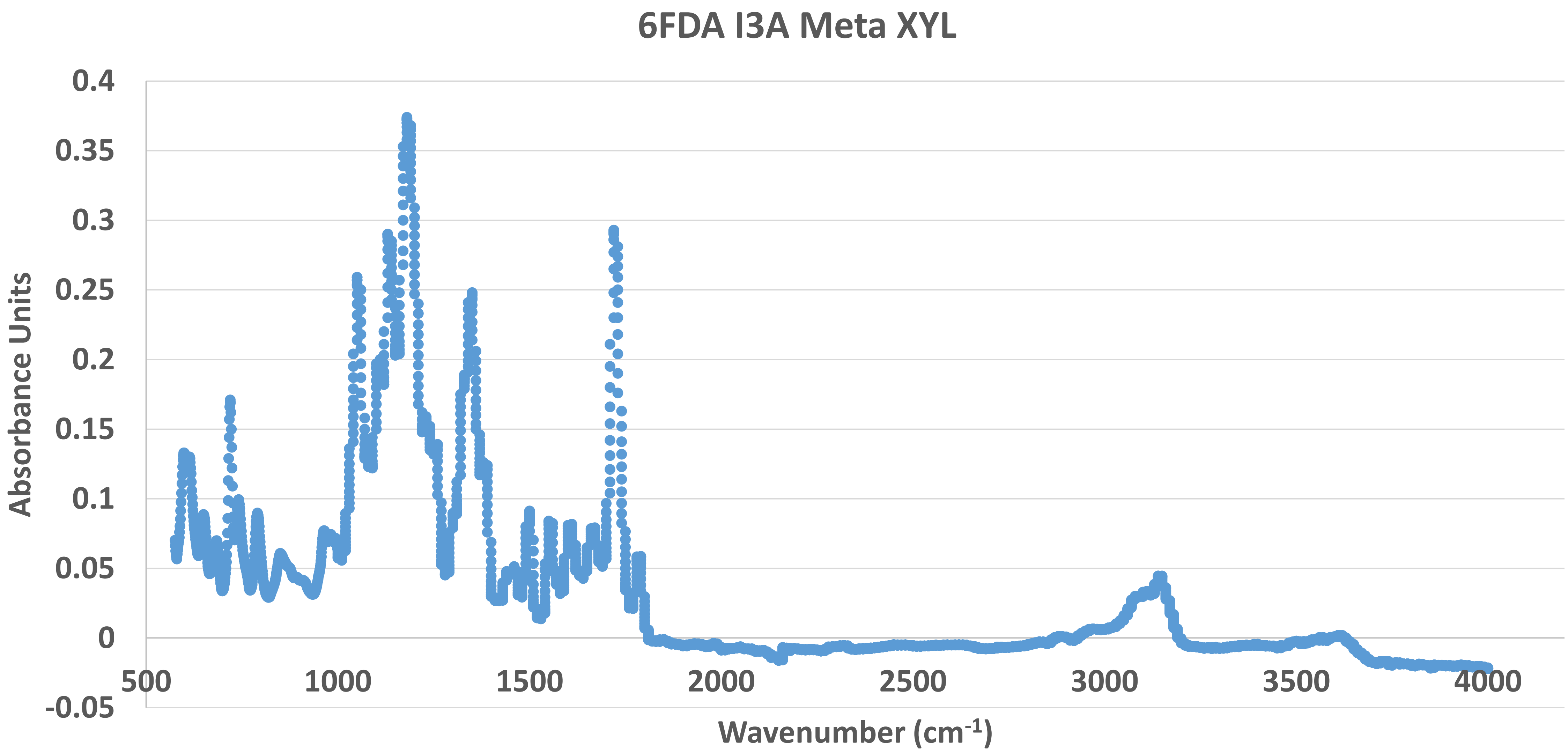
Figure 2. TGA Profile of Building Block #1

FTIR Experimental Method

- ATR module with germanium crystal and pressure device (thunderdome)

  - 64 scans
  - 4 resolution

FTIR Data – Condensed Stage



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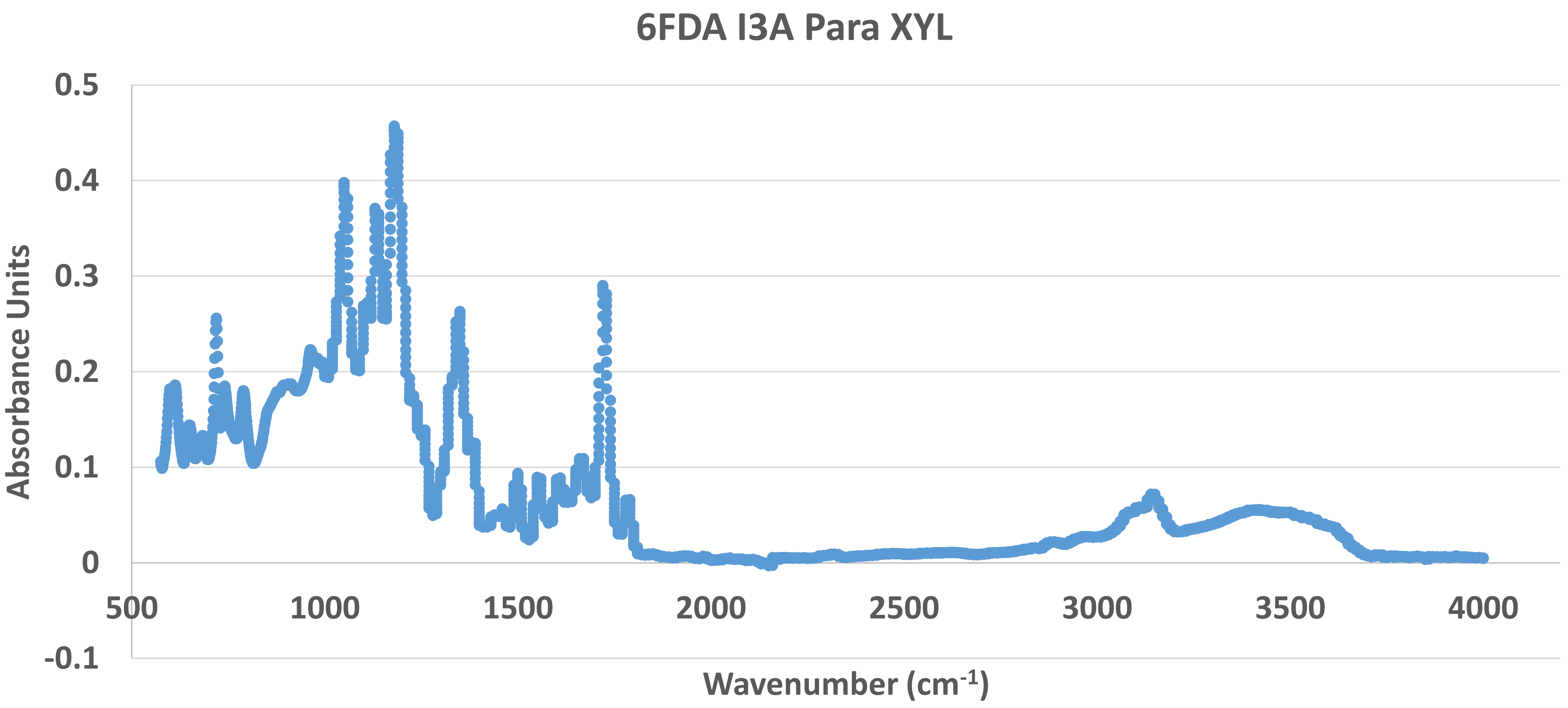

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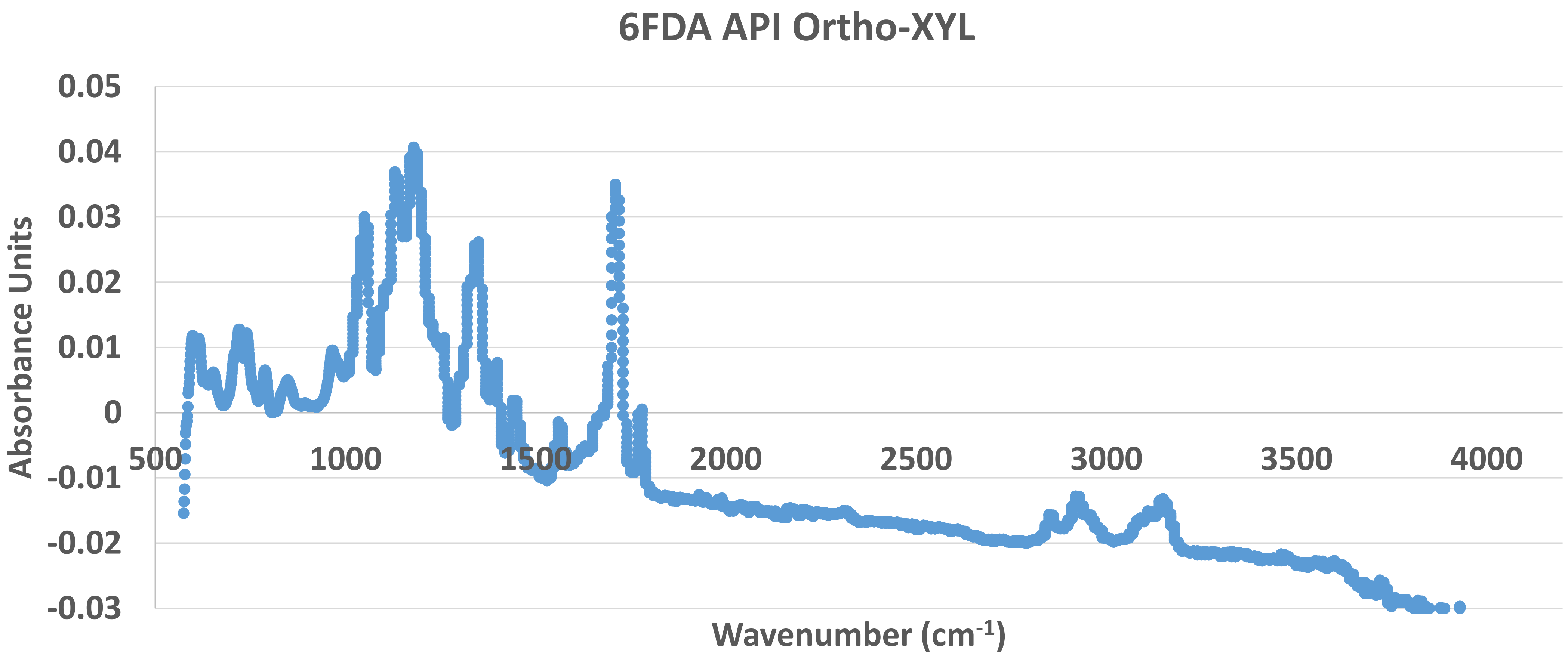

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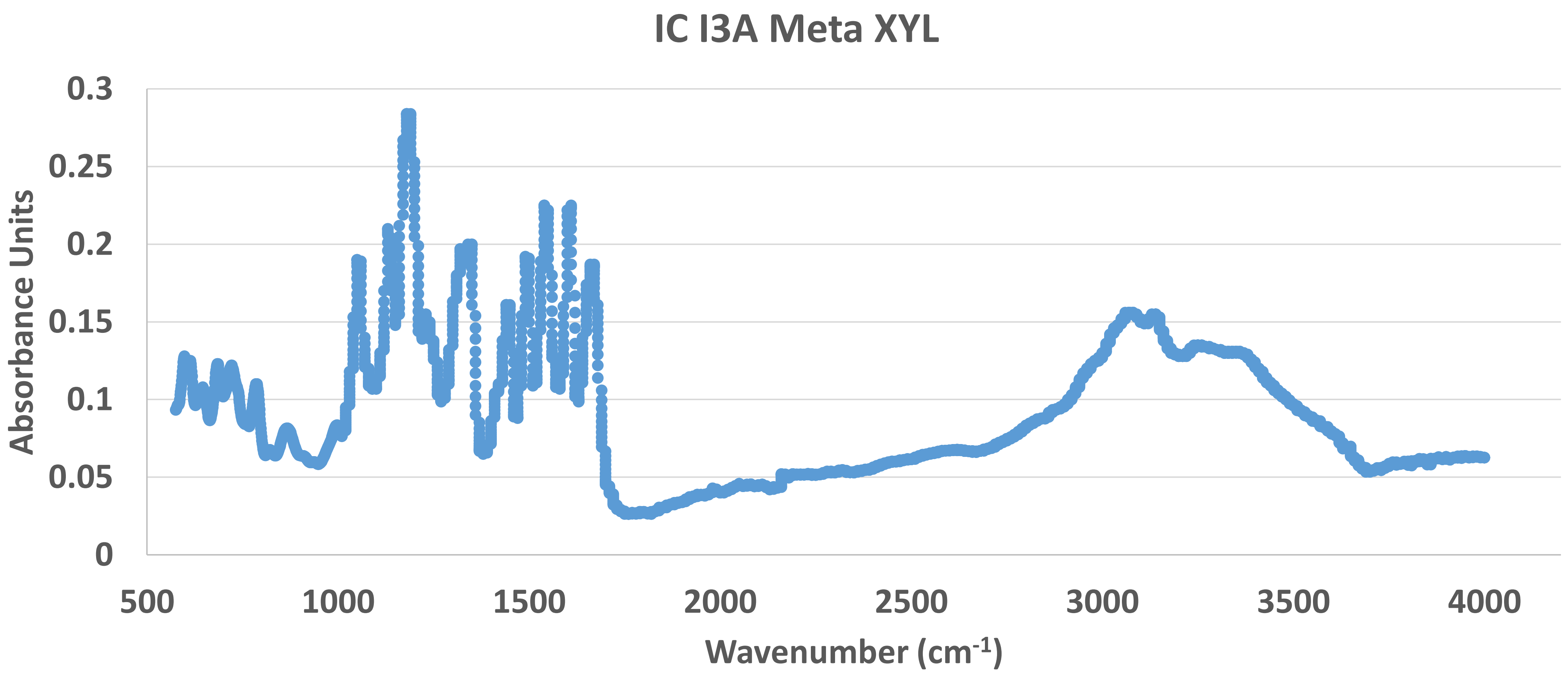
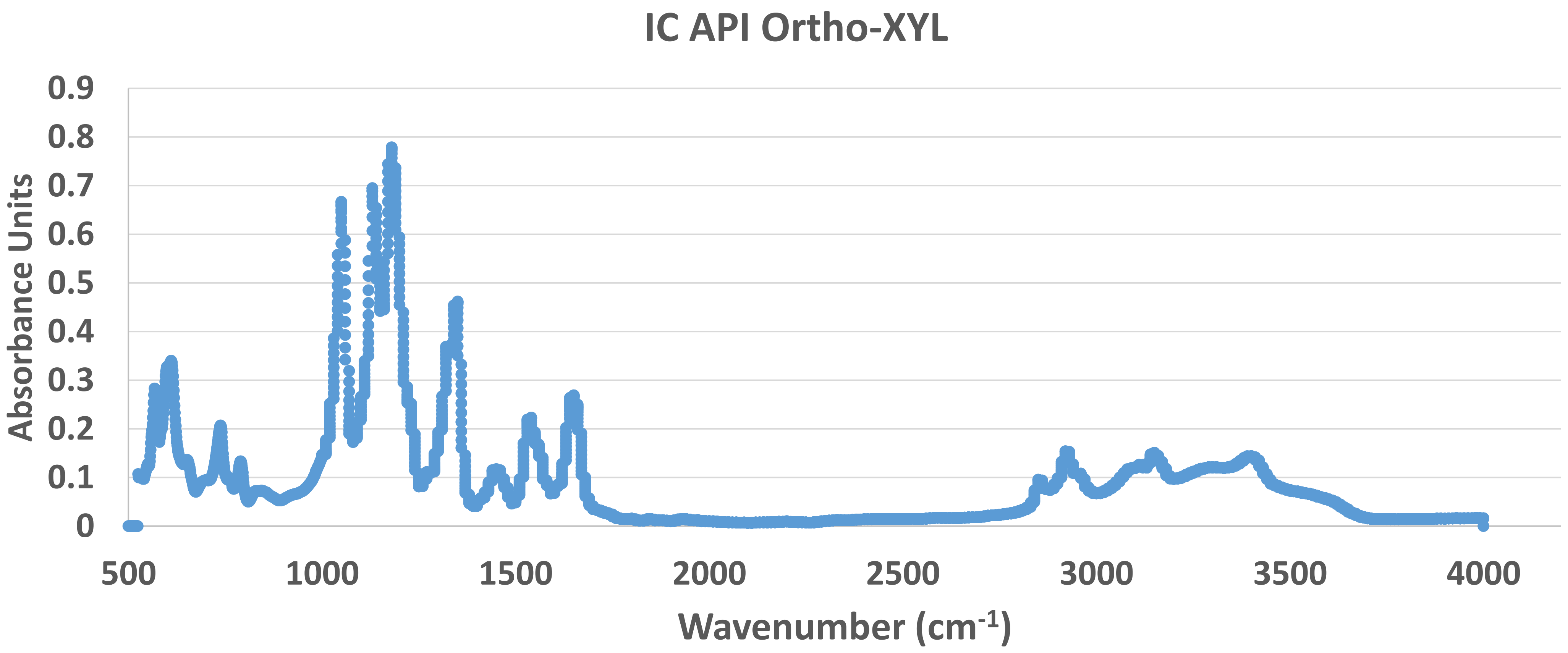


FTIR Data – Condensed Stage



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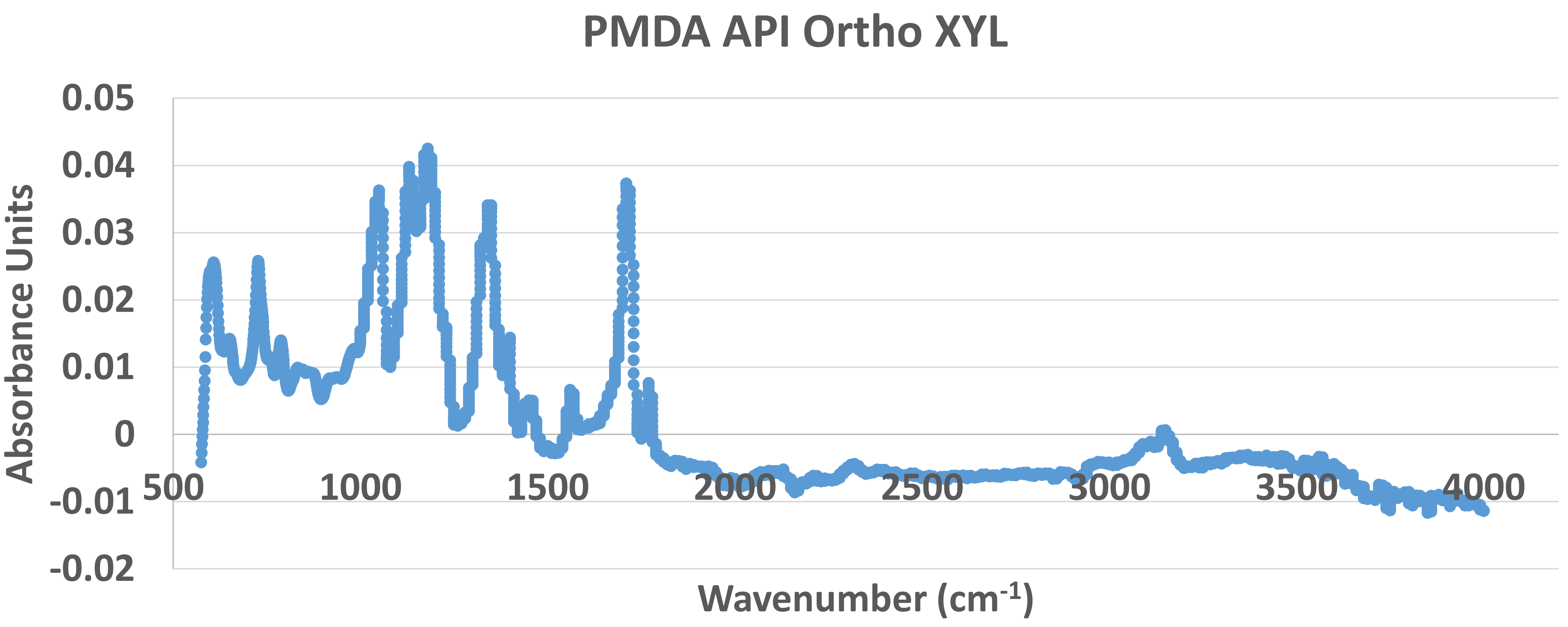

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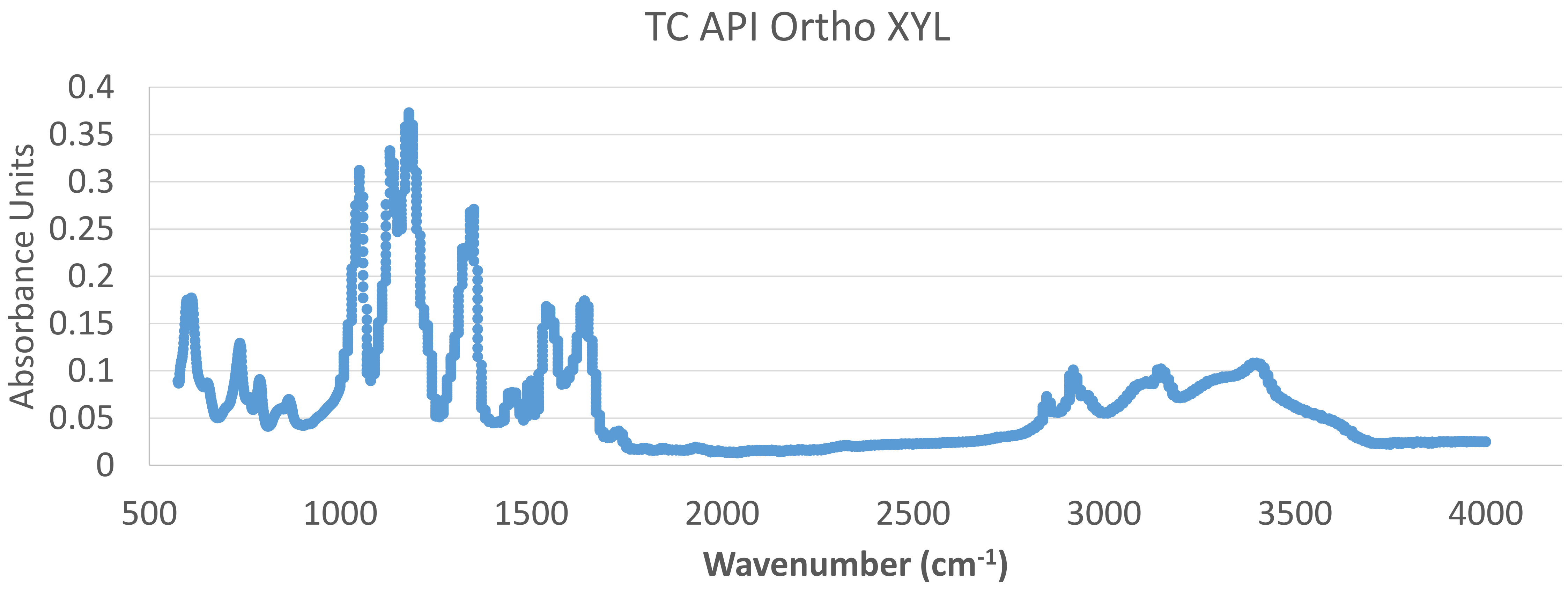


Molecular Modeling

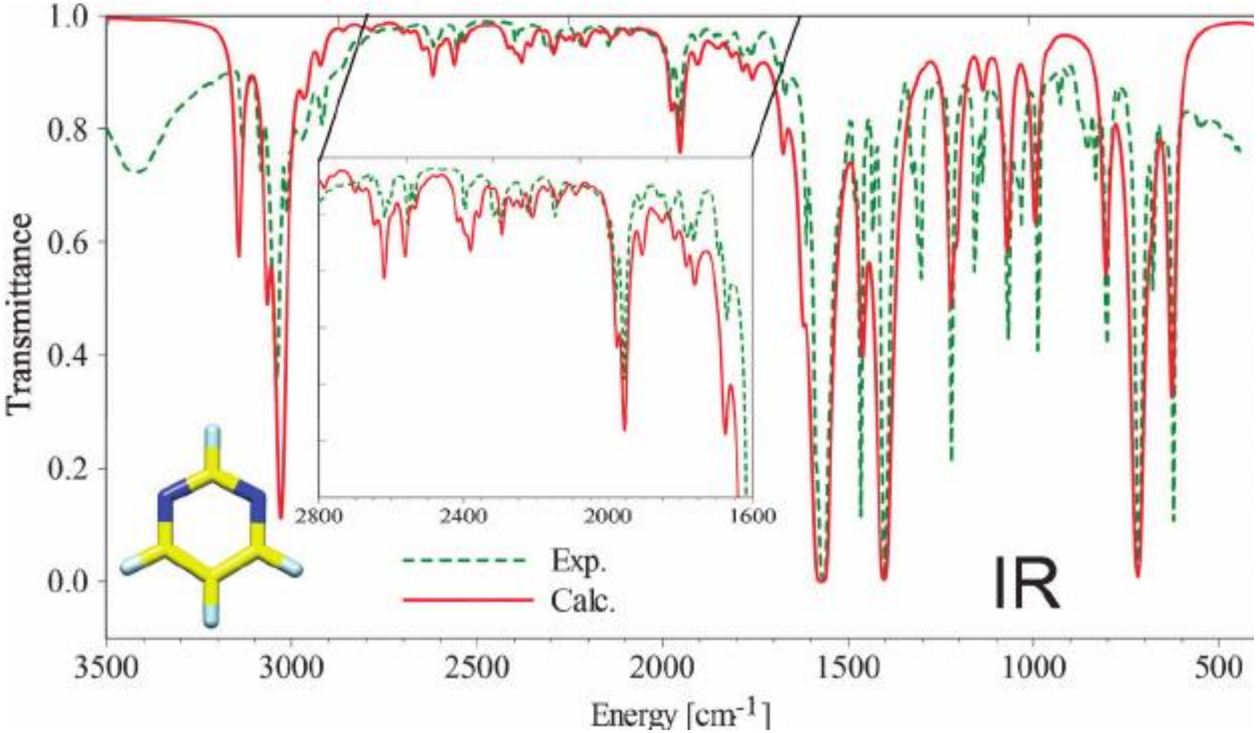
- Properties of ionic polyimides not strictly dependent on bulk structure are calculated using Gaussian ’16:
  - Heats of formation
  - Heats of solvation
  - Heats of reaction (isodesmic series)
  - Infrared and Raman spectra
  - Charge transfer (conductivity)
- Bulk property estimation using molecular dynamics
  - Glass transition temp
  - Others…

Ab Initio Calculations

- Heats of formation are calculated using a Gaussian-3 (G3) formulation, which isolates sources of error in individual methods and derives total energy from the ensemble of energies:
  - Equilibrium structure optimized at HF/6-31G(*d*)
  - Zero-point energy calculated using harmonic frequencies scaled for 6-31G(*d*) basis
  - Geometry optimized at MP2/6-31G(*d*), single-point at MP4/6-31G(*d*); used in subsequent single-point calculations:
    - **Diffuse correction: MP4/6-31+G(*d*)**
    - **Polarization correction: MP4/6-31G(2*df,p*)**
    - **Correlation correction: QCISD(T)/6-31G(*d*)**
    - **Basis correction: "G3Large" basis (3*d* 2*f* 2*df*)++****
    - **Spin-orbit and valence corrections: empirical**
  - Total energy equivalent to QCISD(T)(full)/6-311++G(3*df* 2*df* 2*dp*)

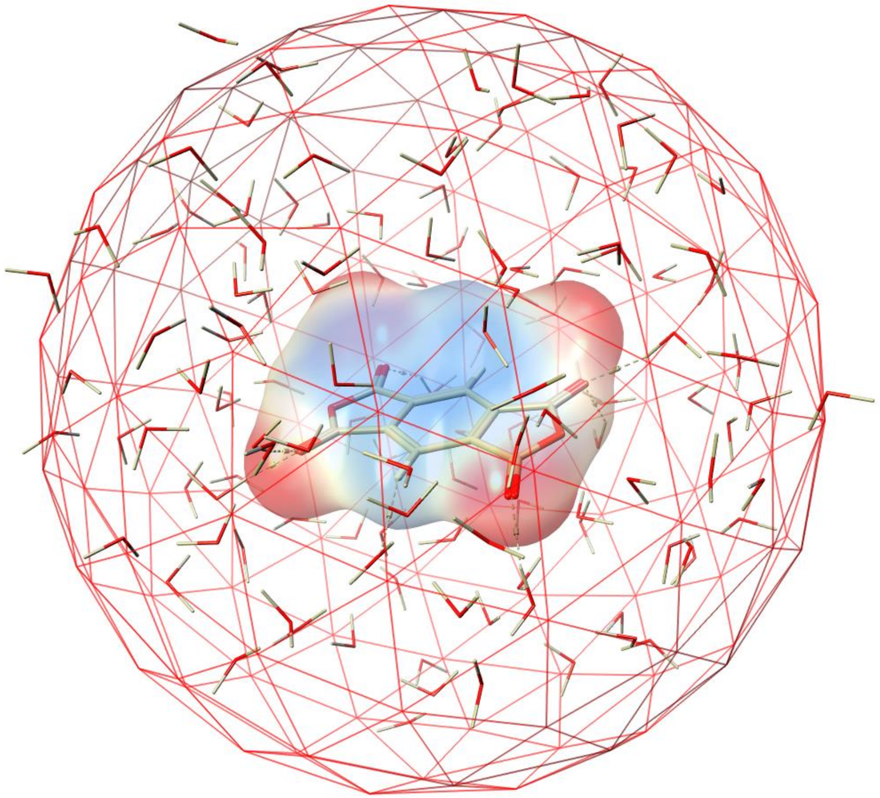
IR & Raman

- Infrared and Raman spectra are calculated from the harmonic vibrational frequencies using medium-range correlation corrected density functional theory:
  - The Minnesota functionals, M*xx*; *e.g.* M06, M06-2X
  - The inclusion of Grimme's correction into other



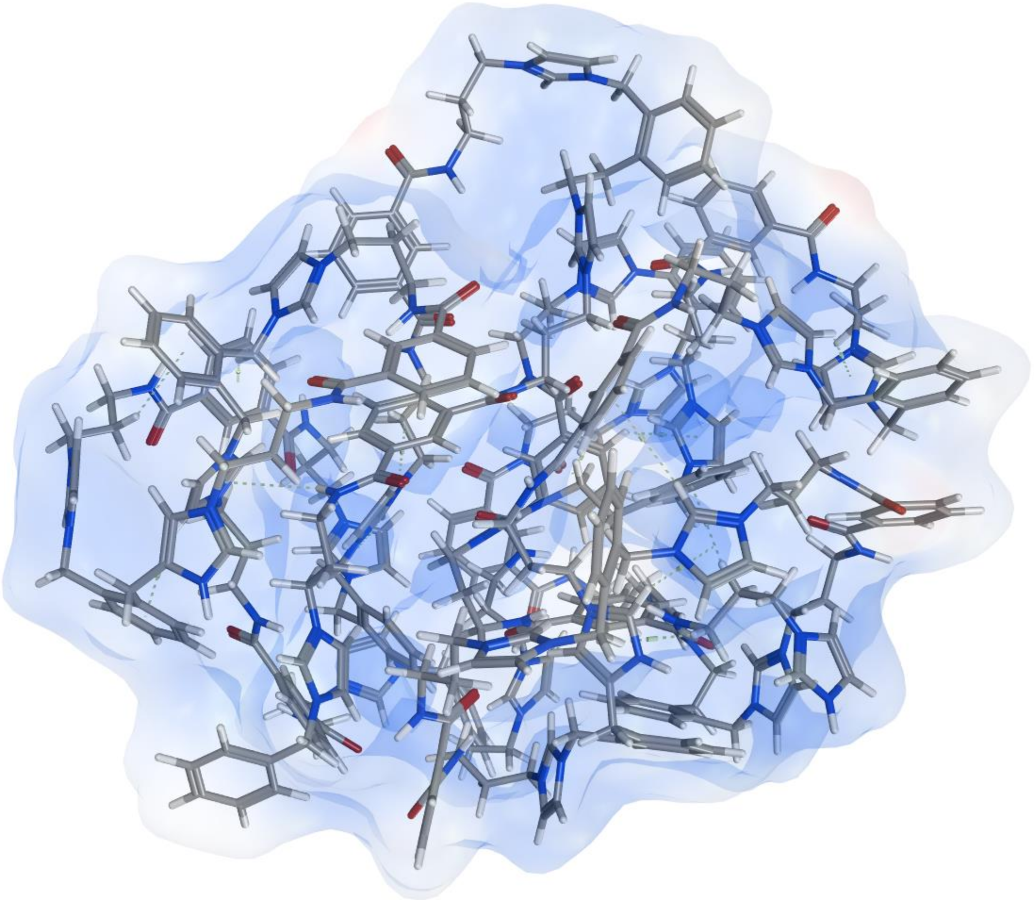
Solvation

- Heats of solvation are determined using self-consistent reaction field calculations with medium-range correlation corrected density functional theory with the SMD method in G16
  - The Minnesota functionals, M*xx*; *e.g.* M06, M06-2X



Charge Transfer

- Conductive/semiconductive properties may be estimated from monomer polarizabilities and from the calculation of charge transfer in local ring systems using Symmetry-Adapted Perturbation Theory



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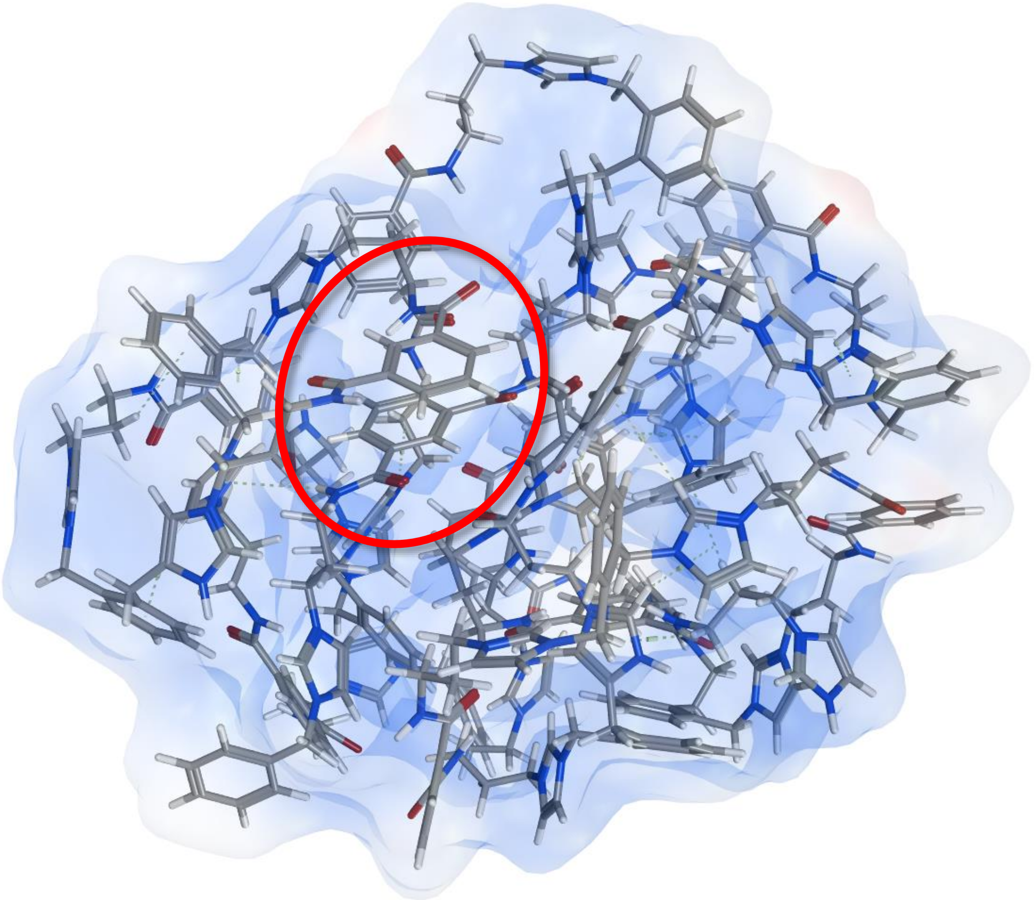

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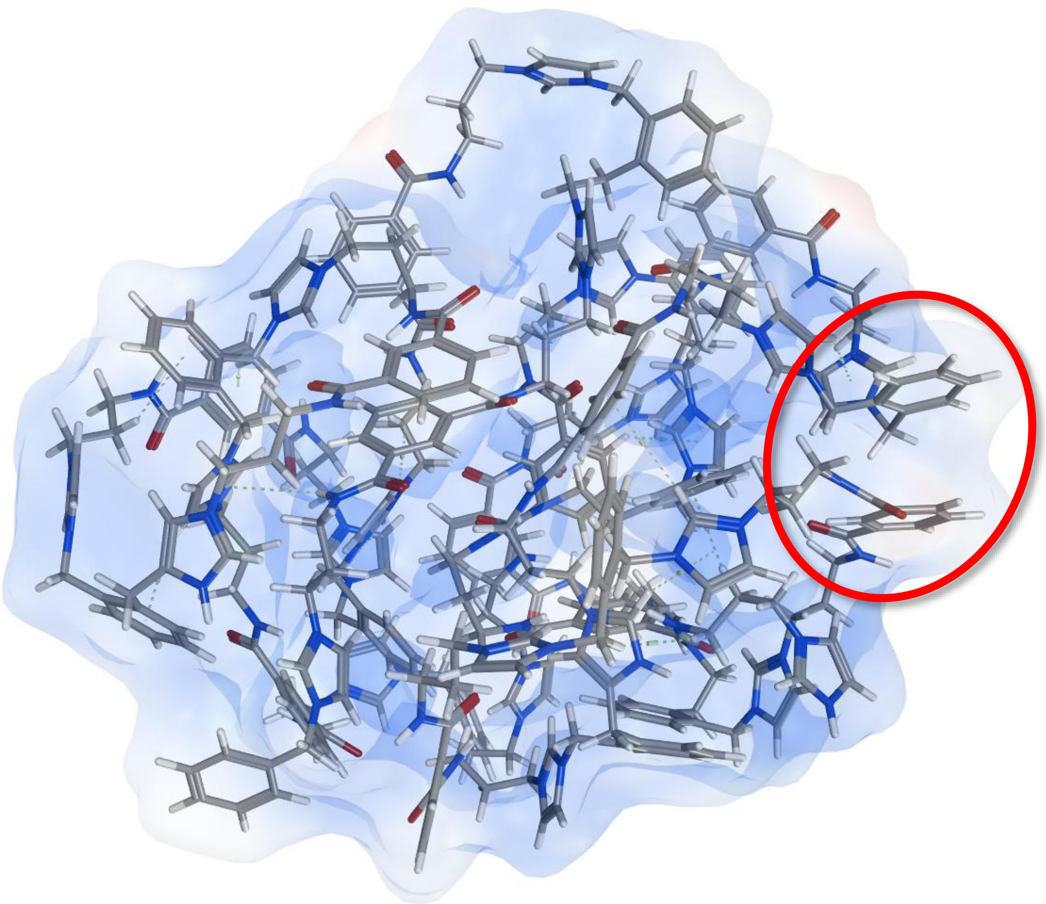

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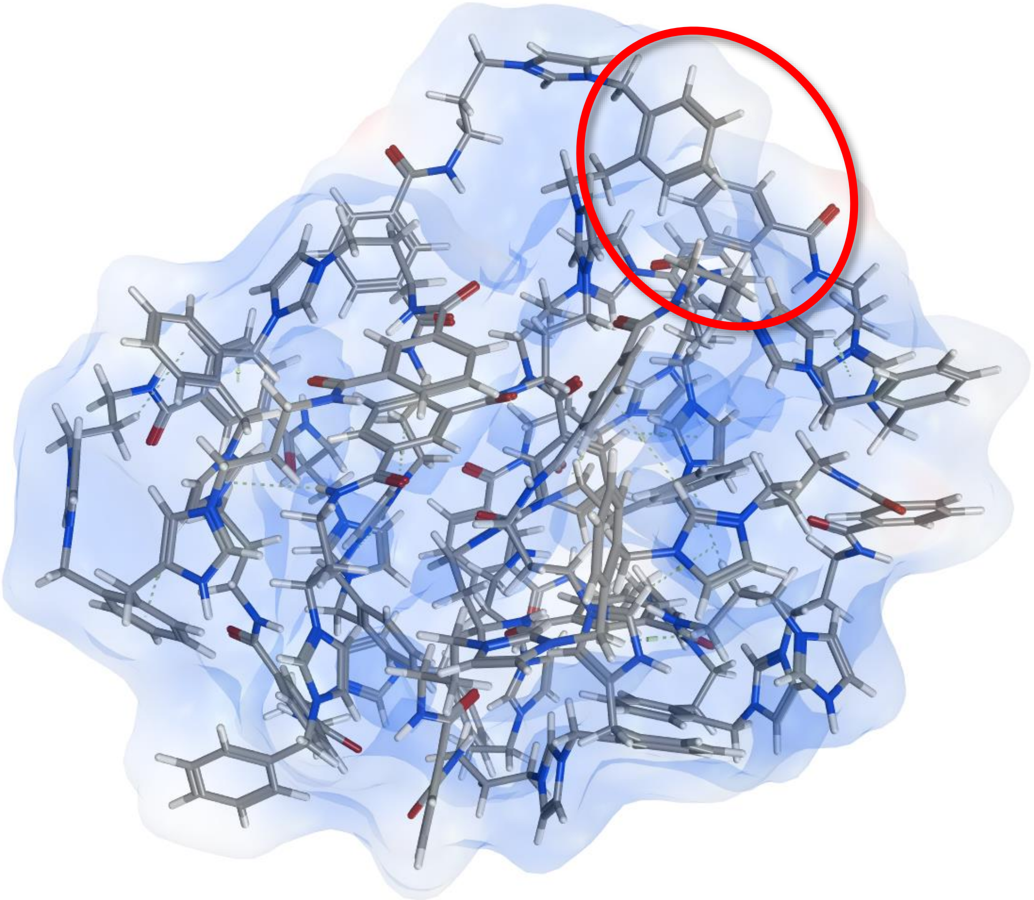

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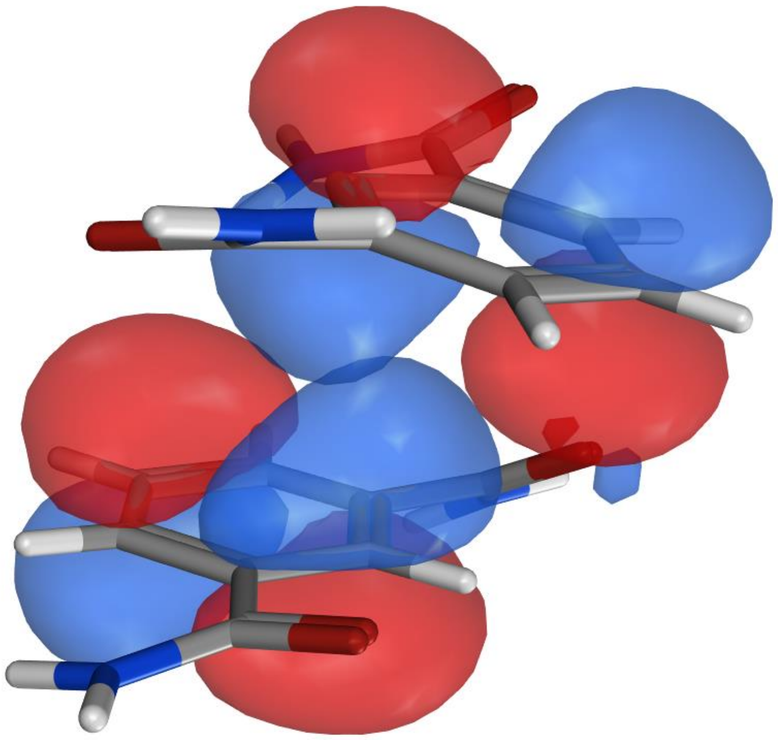

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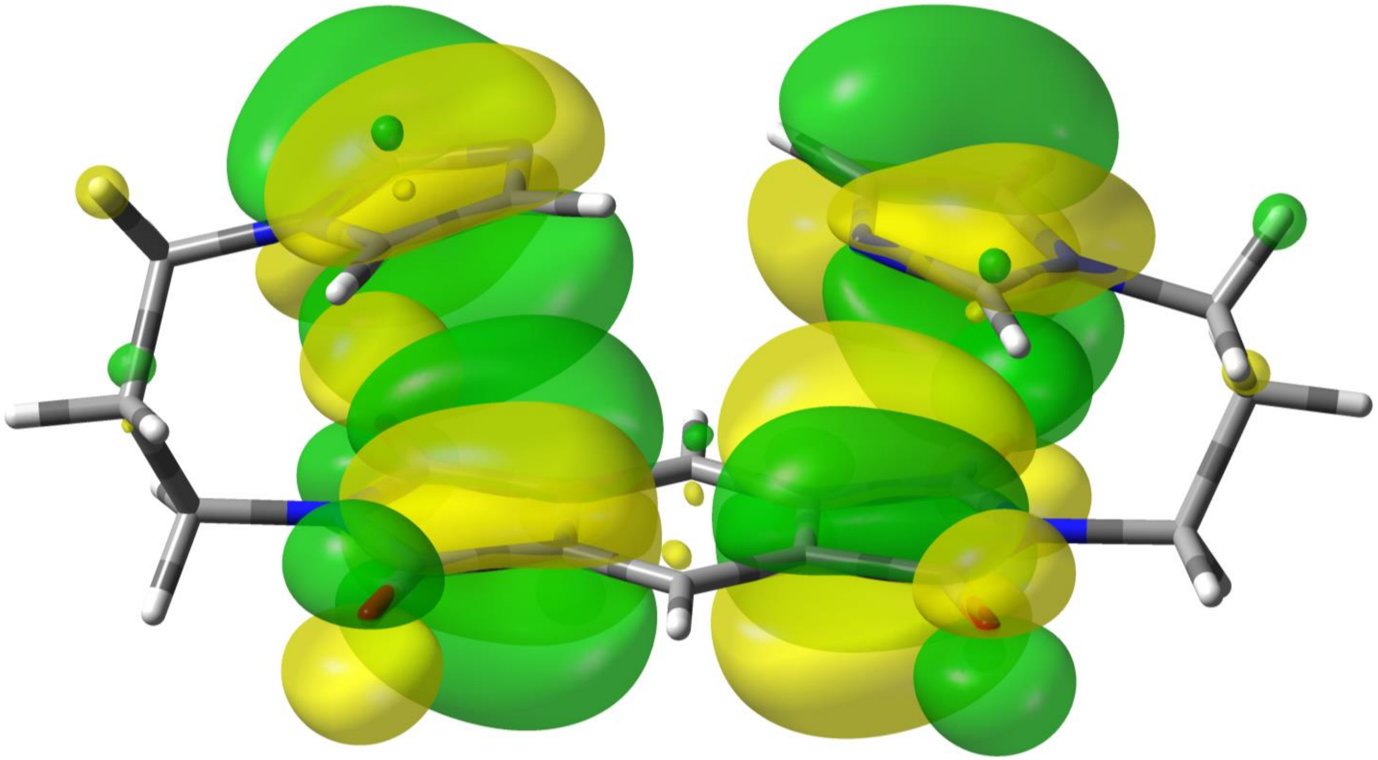

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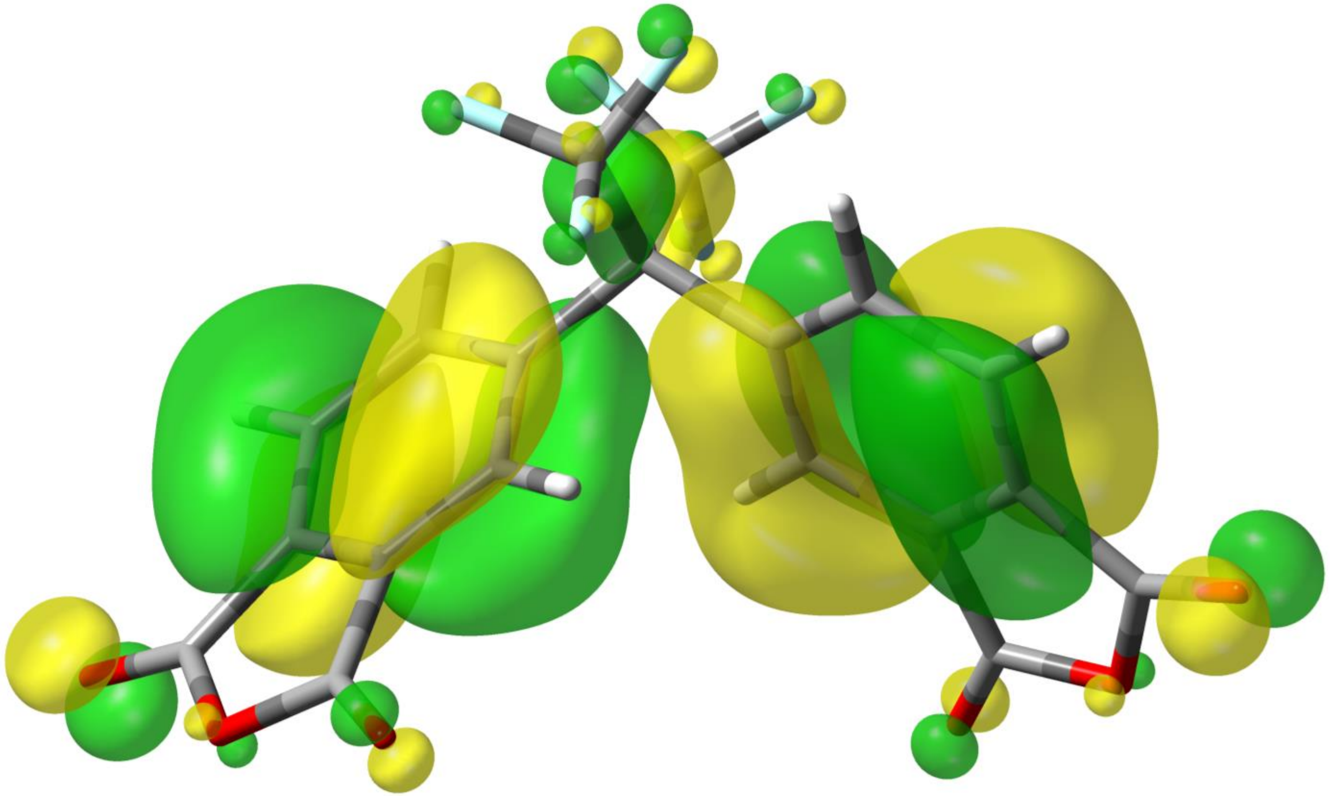


Glass Transition Temperature

- Glass Transition Temperature (T_g) has been estimated with reasonably small errors for OLED polymers from surface polarizabilites of monomers using quantitative structure-property modelling

$$
\begin{aligned}
f(T_g)(\mathbf{r}) = & -0.286 \cdot \sqrt{|V(\mathbf{r})|} - 5.091\times10^{-2} \cdot V(\mathbf{r}) + 9.633\times10^{-3} \cdot \left[|V(\mathbf{r})|\right]^{3/2} \\
& +6.251\times10^{-6} \cdot \left[V(\mathbf{r})\right]^{3} - 3.745\times10^{-3} \cdot EA_L(\mathbf{r}) + 5.833 \cdot \left[\alpha_L(\mathbf{r})\right]^{5/2} \\
& -7.761\times10^{-4} \cdot V(\mathbf{r}) \cdot EA_L(\mathbf{r}) - 2.385\times10^{-2} \cdot \left[|V(\mathbf{r}) \cdot \alpha_L(\mathbf{r})|\right]^{3/2} \\
& -3.135\times10^{-5} \cdot \left[V(\mathbf{r}) \cdot \alpha_L(\mathbf{r})\right]^{3} \\
& +5.192\times10^{-20} \cdot \left[V(\mathbf{r}) \cdot IE_L(\mathbf{r}) \cdot EA_L(\mathbf{r})\right]^{3} \\
& +2.521\times10^{-13} \cdot \left[V(\mathbf{r}) \cdot IE_L(\mathbf{r}) \cdot \alpha_L(\mathbf{r})\right]^{3} \\
& +1.843\times10^{-10} \cdot \left[V(\mathbf{r}) \cdot EA_L(\mathbf{r}) \cdot \alpha_L(\mathbf{r})\right]^{3} + 252.25
\end{aligned}
$$

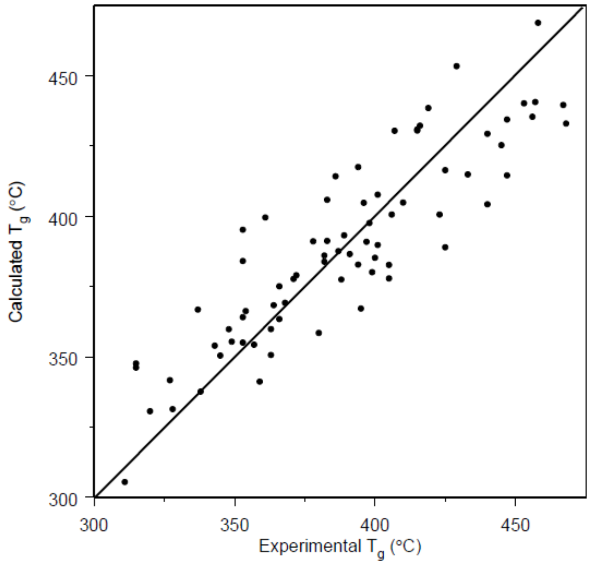
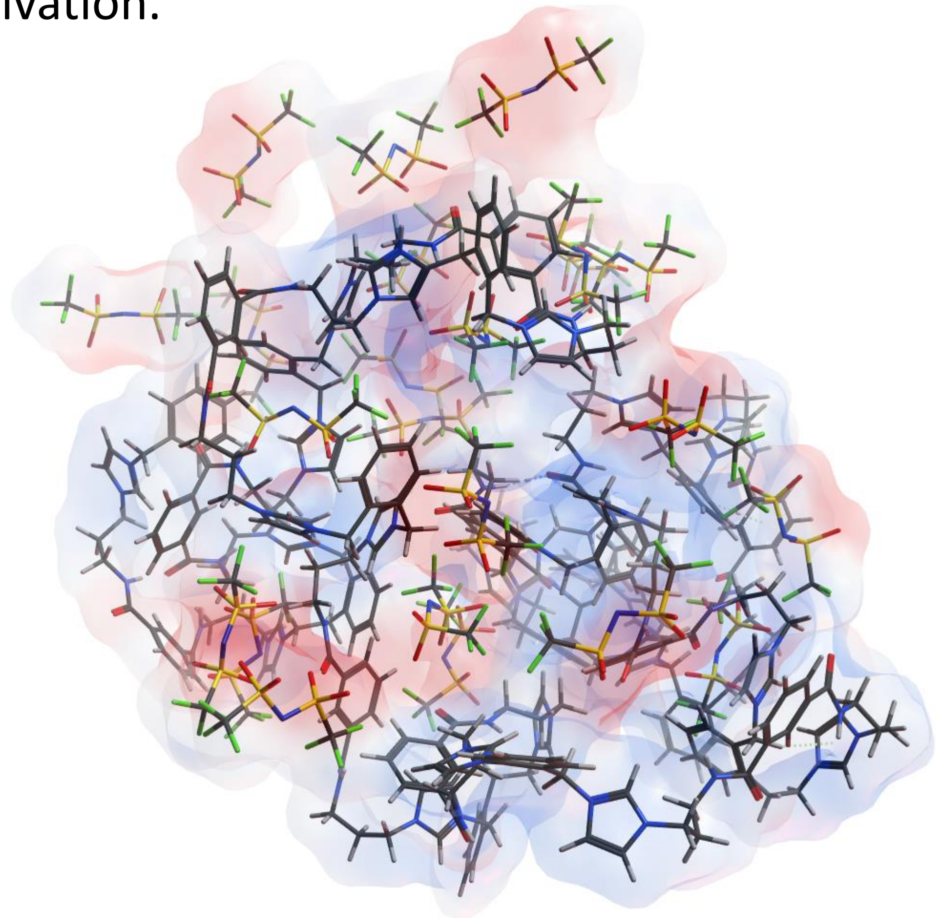


Figure 2.24 Surface-integral model for glass transition temperature using COSMO-optimized structures: MUE= 15.3, RMSD= 18.7, r^2= 0.779, r^2_{cv}=0.491.

Glass Transition Temperature

- A gas solubility study of ionic polyimide oligomers using molecular dynamics (MD) has recently been published. MD may also been used to model bulk properties such a T_g using either explicit solvation or continuum solvation.



Future Work

- Continue synthesizing different variations of these polyimides
- Characterize these polyimides with different thermal characterization techniques
  - DSC
  - TG-IR
  - FTIR
- Model these polyimides via ab-initio calculations
- Develop filament feedstock materials from these ionic liquids to additively manufacture these materials for aerospace applications

Questions?