RIGID 10K V. PEEK HEAT GUN EXPERIMENT

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ARCH

BLUF

- 10K material degraded at lower temperatures than PEEK
- PEEK heats faster than 10K for the same geometry indicating higher thermal conductivity for 10K
- 10K could conservatively be maintained above 180°C for 15 seconds and reach around 200°C for short periods of time (a few seconds) with no material degradation
- PEEK can sustain temperatures below 270°C with minimal change to the surface
- Results are geometry dependent

Testing Setup

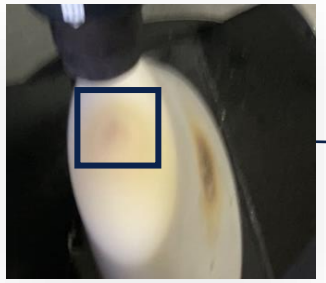
- Model roughly 4 inches from the heat gun
- Steinhel HL1820S heat gun set to its max level (600°C and 13 cfm airflow)
- FLIR X8501sc IR camera
- Shown is the setup of the hemisphere (left), HIFire (middle), and PEEK block (right)

- PEEK model
  - 6-in. x 12-in. x 0.5-in. block
  - Sectioned into 8 squares for up to 8 tests
- 10k models
  - HIFiRE - 1 inch thickness – complex geometry
    - Used different sections for 4 different experiments
  - 4-in. x 4-in. x 0.5-in. block

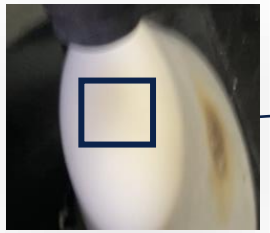
Experiment 1

- 10K and PEEK models were heated for 7 minutes with the heat gun approximately 4 inches from the model
- A synchronized IR camera and traditional camera were used to identify at what temperatures the surface changes occurred
- Surface changes were noticeable in the IR in this test with clearly visible cracking

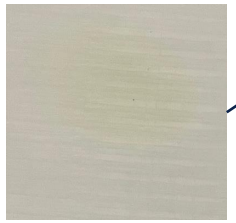
10K Blackening



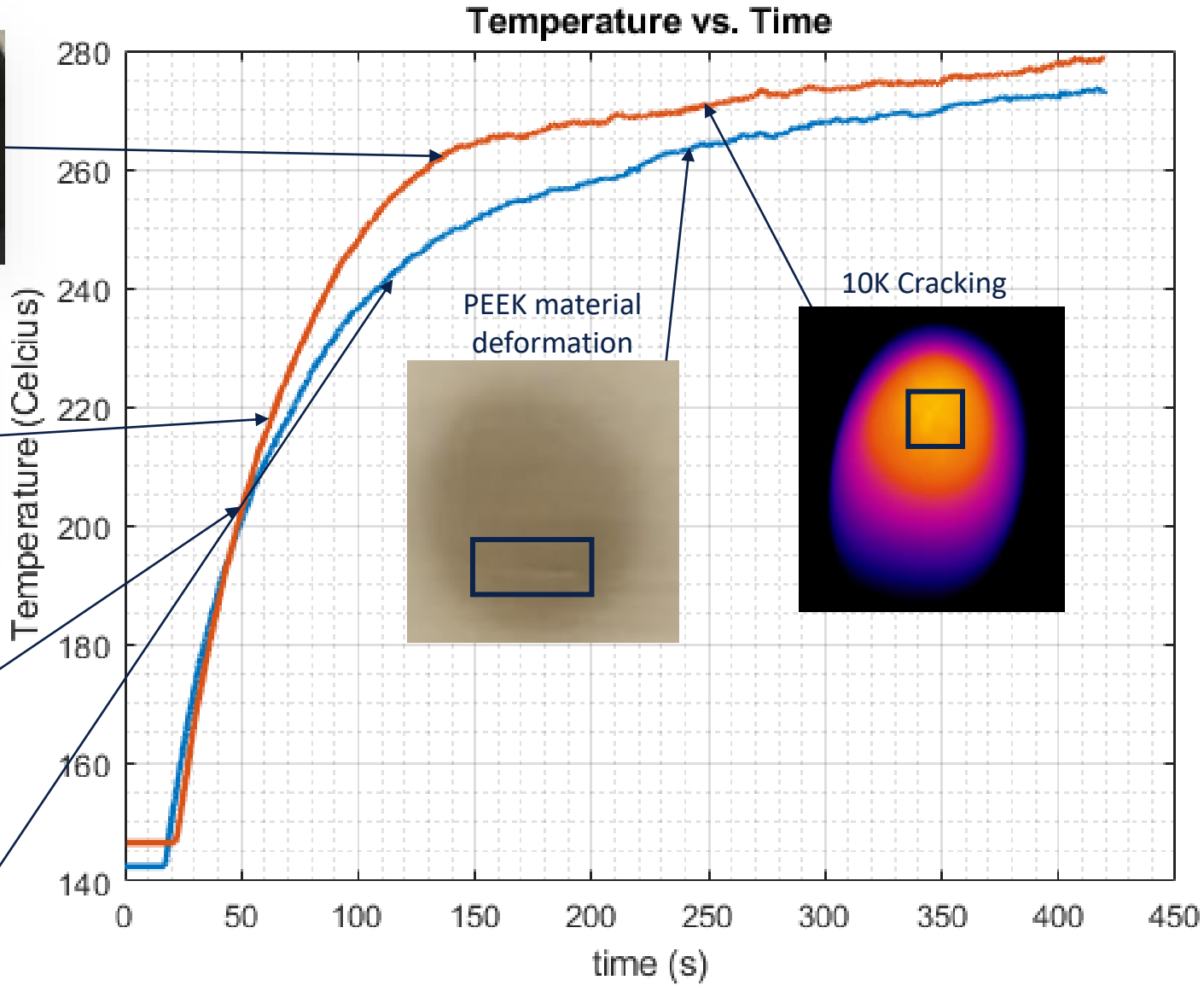
10 K Browning



PEEK yellowing

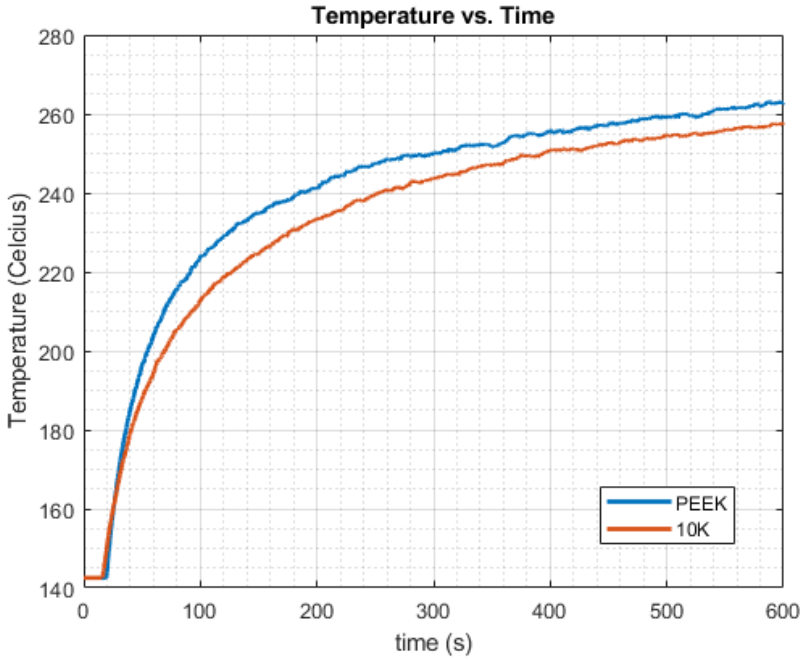


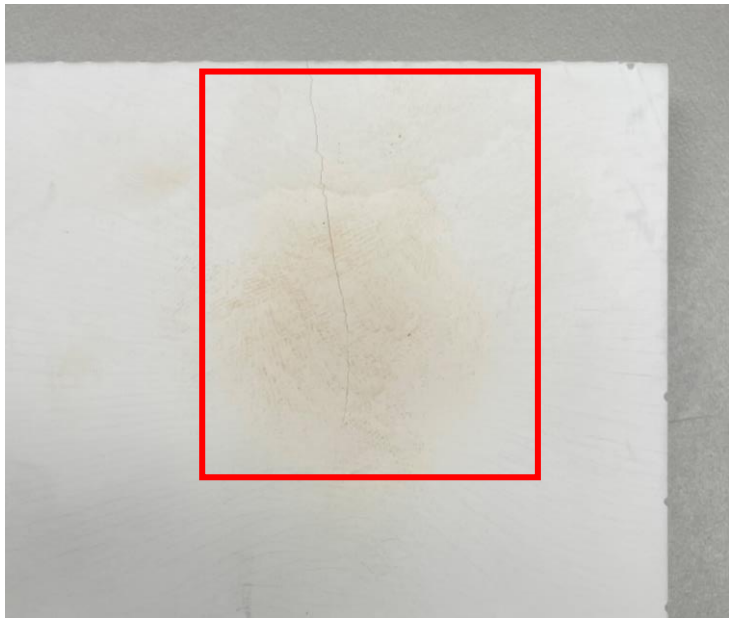
PEEK blackening



Experiment 1 Redo

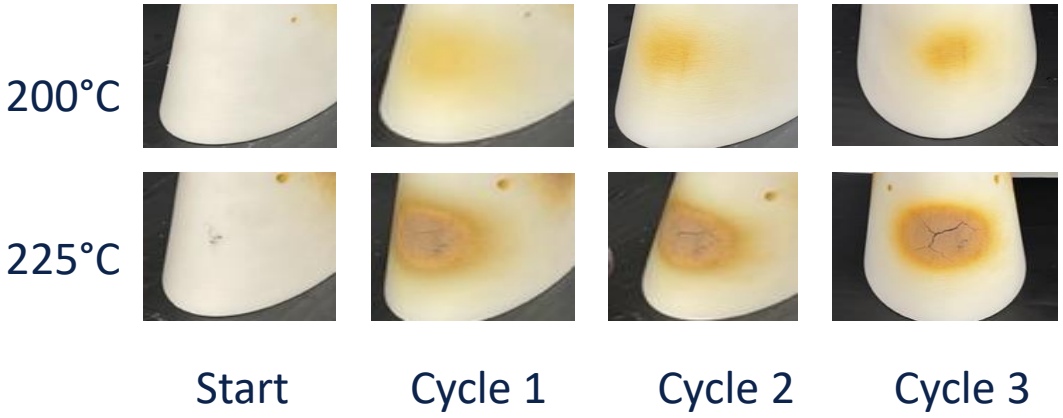
- PEEK heats faster in this experiment, this is reverse of what was observed comparing the first test results
  - Likely due to differences in heat gun distance in first tests and different model geometry
- During these tests the model did not exhibit the same characteristic browning and melting/cracking observed in previous tests
  - 10K did still crack but it was a different cracking not centered around blackened spot
- Two possible reasons models behaved so differently could have been geometry or the curing process on the 10K
  - 4-in. x 4-in. x 0.5-in. block



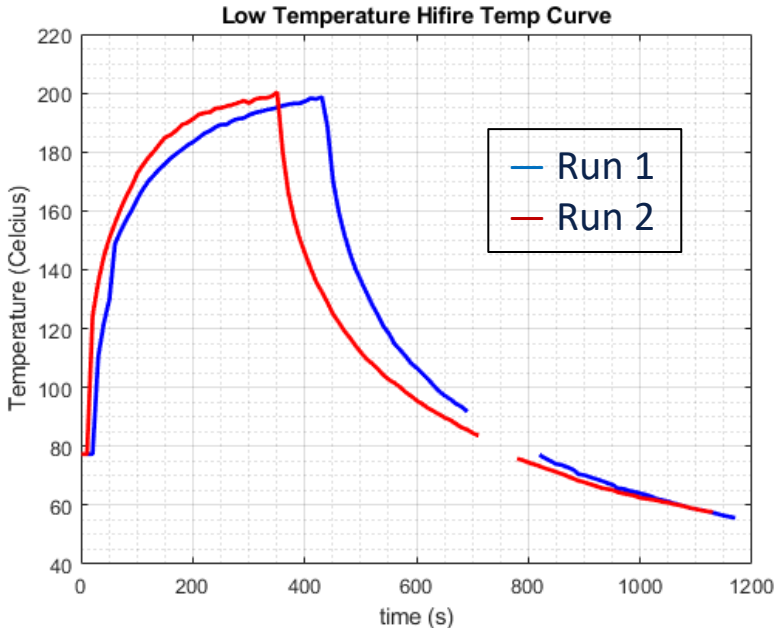


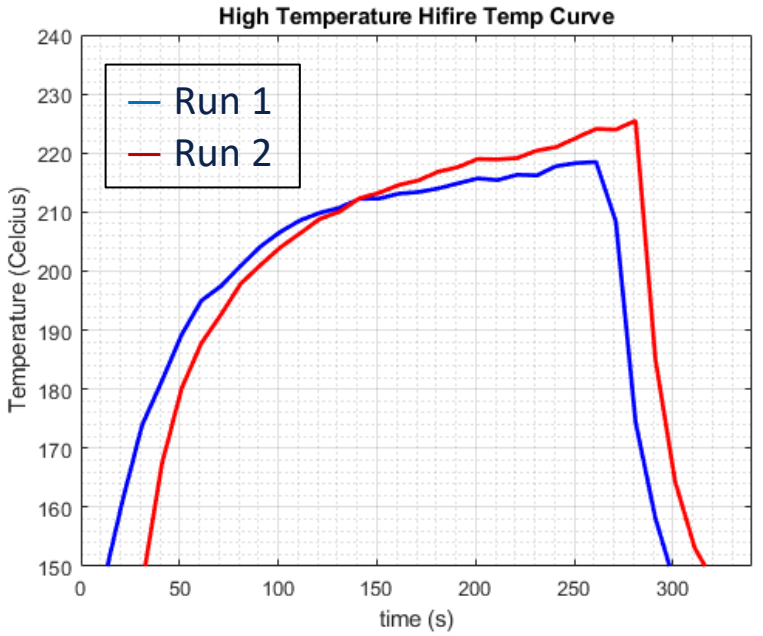
10K Experiment 2

- Models stabilized at 200°C and 225°C and cooled to roughly 75°C — 3 cycles for each temperature
  - Temperatures chosen are just under the browning and blackening stage from experiment 1
- Structural damage occurred after first run for each test – surface roughness for 200°C test and cracking for 225°C test



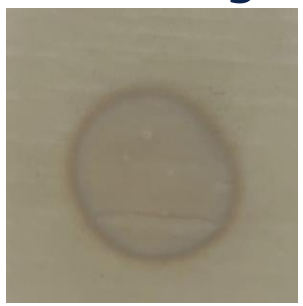
*only two runs shown due to camera difficulties – no valuable data taken from third cycle





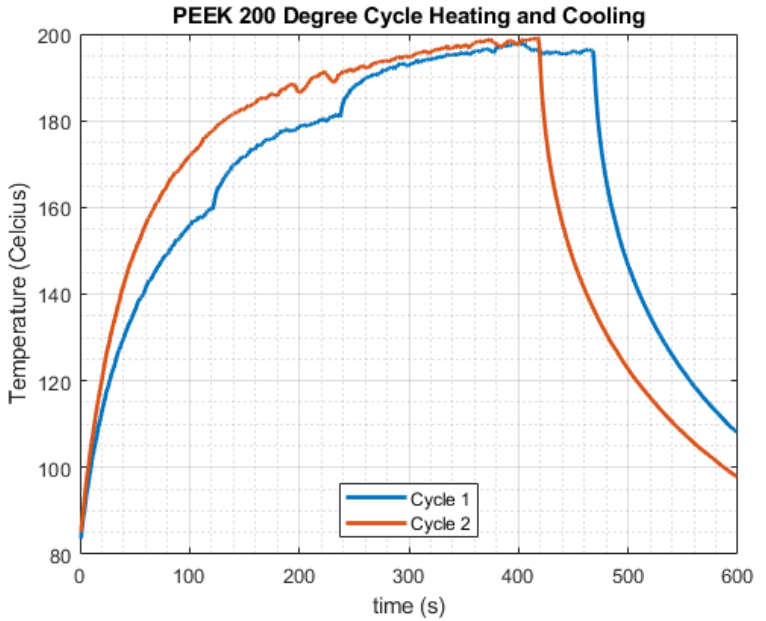
PEEK Experiment 2

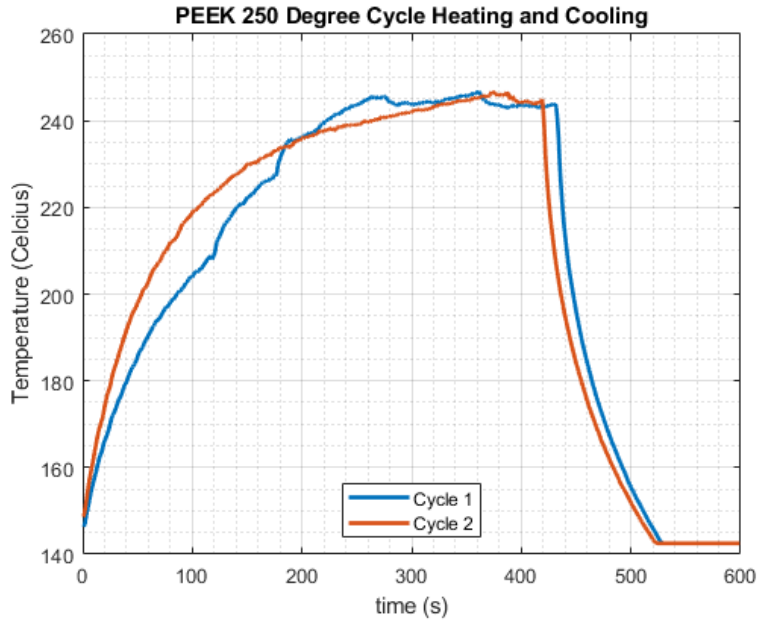
- Gun was placed at a precise distance to make the material reach 200°C, 250°C, and 280°C and stabilize
- Heated for approximately 7 minutes
- 2 cycles performed (except 280°C – melted on first cycle)
- Yellowing occurred for 200°C test but fades once heat is removed
- Browning occurred for 250°C test but fades to faint yellow once heat is removed
- No material degradation
- Model began melting at 270°C



Final result from 280°C test

Final result from 240°C cycling





10K and PEEK Experiment 2

10K Resin

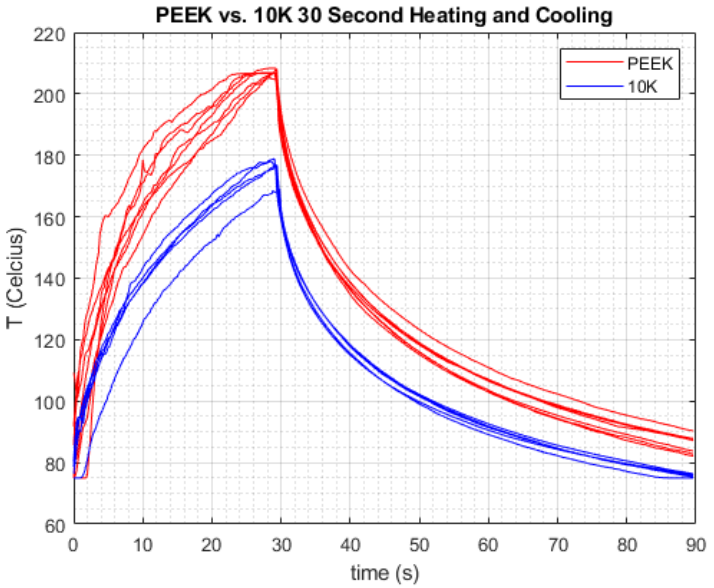
- The material changes were found at lower temperatures than reported in experiment 1
  - Browning was seen at 200°C in experiment 1, but blackening occurred at this temperature in experiment 2
- Material degraded more after each test due to longer exposure to heat
- No material changes at lower temperatures

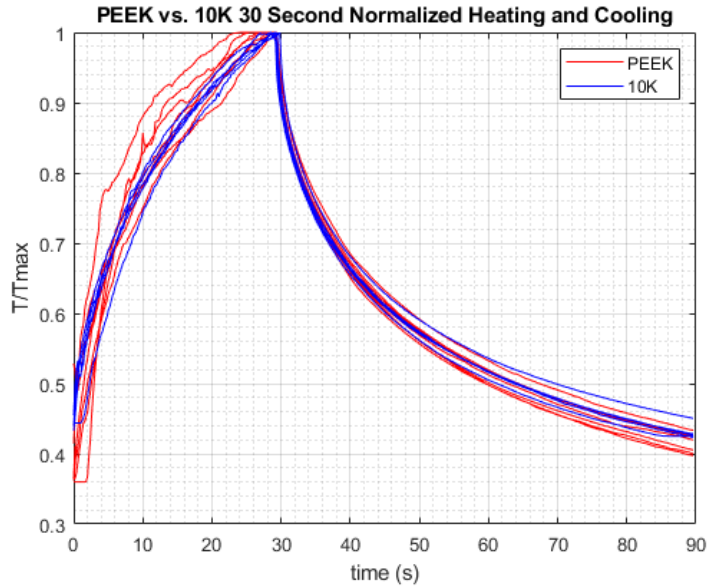
PEEK

- Temperatures for material change found in experiment 1 were consistent in experiment 2
- For 250°C and less, no material degradation

Experiment 3

- Gun was placed about 4 inches from model and was cycled with 30 seconds of heating 7 times
- Cooled to around 30°C between each cycle
- PEEK heats faster
- Surface was unchanged after these 30 second cycles
- After each cycle:
  - Back of PEEK was roughly 41°C ± 2°C one minute after each run
  - Back of 10K was roughly 53°C ± 2°C one minute after each run





Experiment Summary

- Experiment 1: What happens when the model is heated?
  - 10K and PEEK found to have color change and material degradation in a range of similar temperatures
- Experiment 2: What happens when notable temperatures are maintained for a duration of time?
  - 10K showed that the damage becomes worse compared to experiment 1 at notable temperatures
  - PEEK showed that no further effects were observed at the notable temperatures from experiment 1
- Experiment 3: Does cycling damage the model?
  - For both 10K and PEEK, prolonged heat exposure is likely more of a problem than cycling at a temperature

Comparison of PEEK and 10K

PEEK

- Began changing color at just over 200°C
- Began blackening at around 250°C
- Material Degradation at 270°C
- Unlike 10K, prolonged heat exposure has no worsening effects
- Cycling found to have no effects other than minor color change between cycles, which could be due to prolonged heat exposer rather than a change in material properties
- Overall, PEEK found to withstand more heating before it begins to degrade compared to 10K

10K

- Short term exposure to heat (around 30 seconds or less at 200°C or less) will cause no material degradation
- Slight material degradation (surface roughness) at 200°C for prolonged heat exposure
- Cracking and other material degradation at 225°C for prolonged heat exposure
- Cycling found that heating and reheating caused the material to degrade more with each run if it was degraded during the first cycle (again, could be prolonged exposure to heat rather than change in material properties)

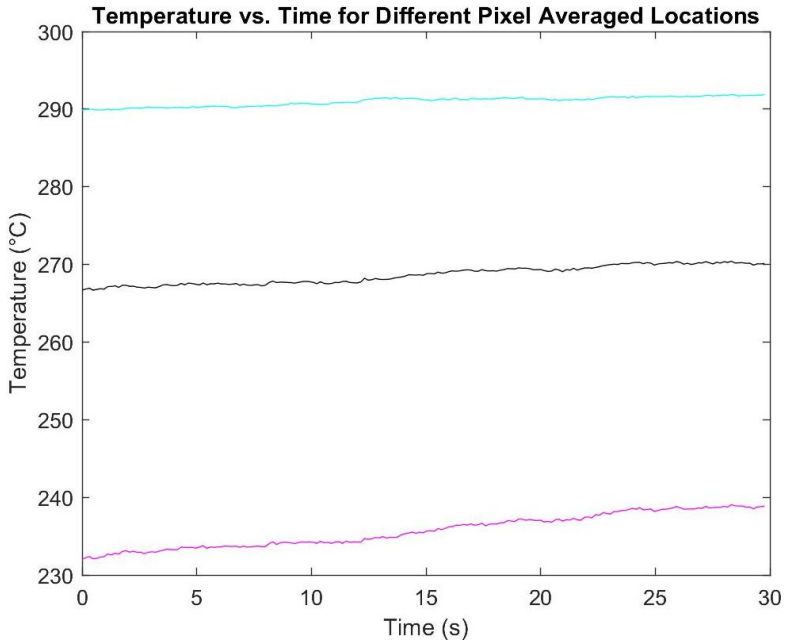
Summary

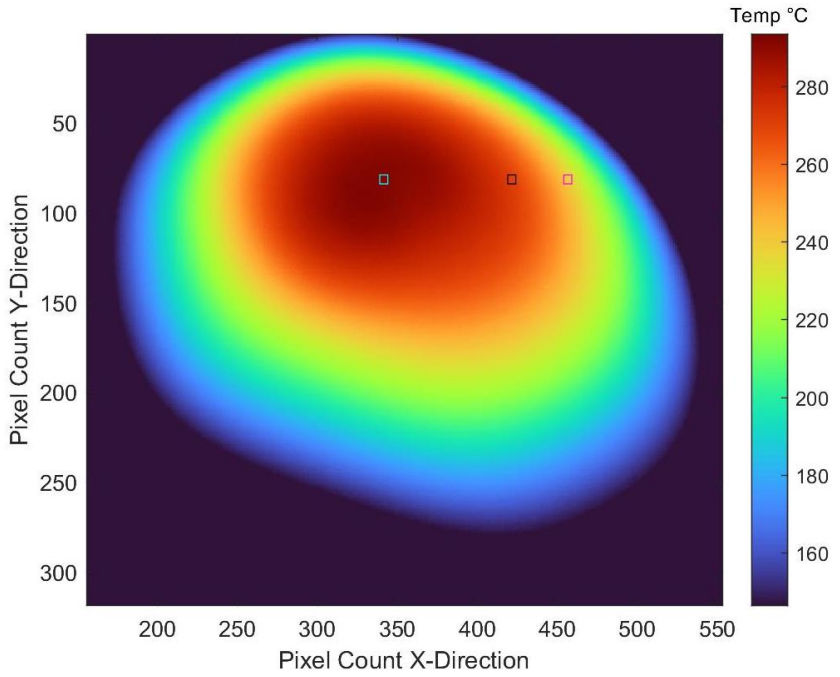
- PEEK performed better than 10K under higher temperatures
- 10K material degraded at lower temperatures than PEEK
- Cycling likely did not change the material properties of either material – reheating just prolonged heating exposure and continued the effects of that temperature
- PEEK heats faster than 10K for the same geometry, this and the increased back temperature of the model indicates higher thermal conductivity for 10K
- Both materials performed well for the 30 second cycles where there was a slight color change during the run, but went away once the heat was removed
- 10K material behaved differently between geometry's, due to either the geometry or curing process
- 10K could conservatively maintain above 180°C for 15 seconds and reach around 200°C for short periods of time (a few seconds) with no material degradation
- PEEK can sustain temperatures below 270 °C with minimal change to the surface

Appendix

Initial 10K Testing

- The model was heated to 293.69°C as measured by the IR Camera
- After the heating, the surface appeared burned and had cracks in it
- Surface changes were not noticeable in the IR Images

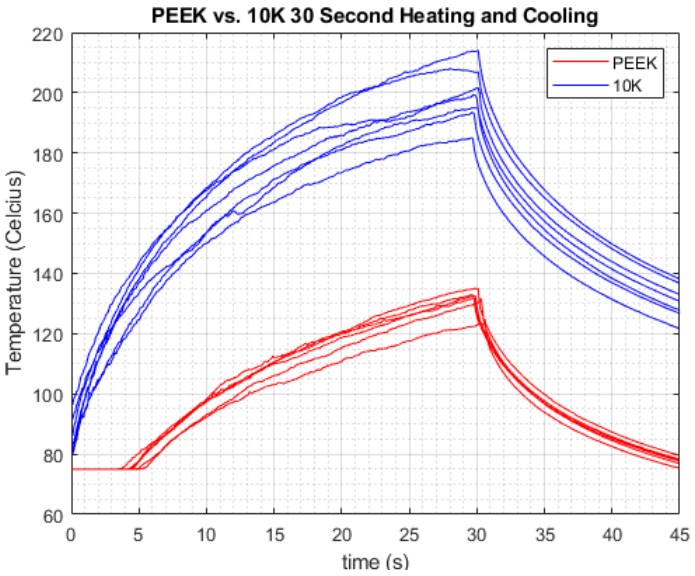


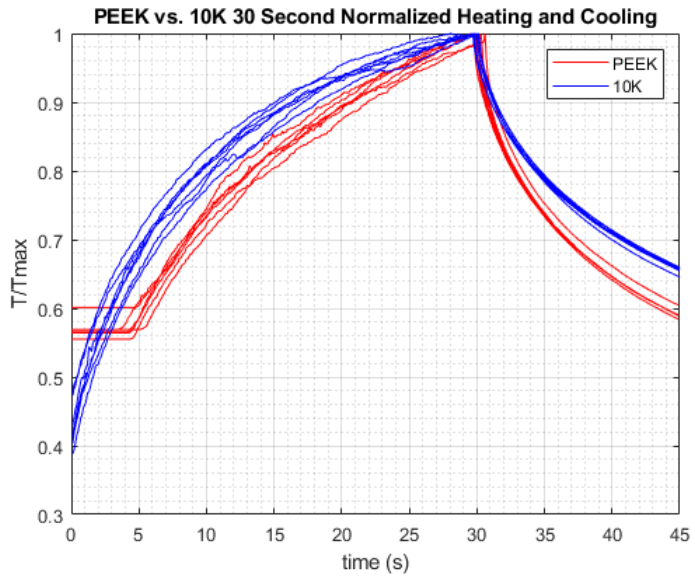


- Temperatures averaged across 5x5 pixel grid. Colored lines in plot (left) correspond to boxed areas in figure (middle). Final product of model after experiment (right).

Experiment 3

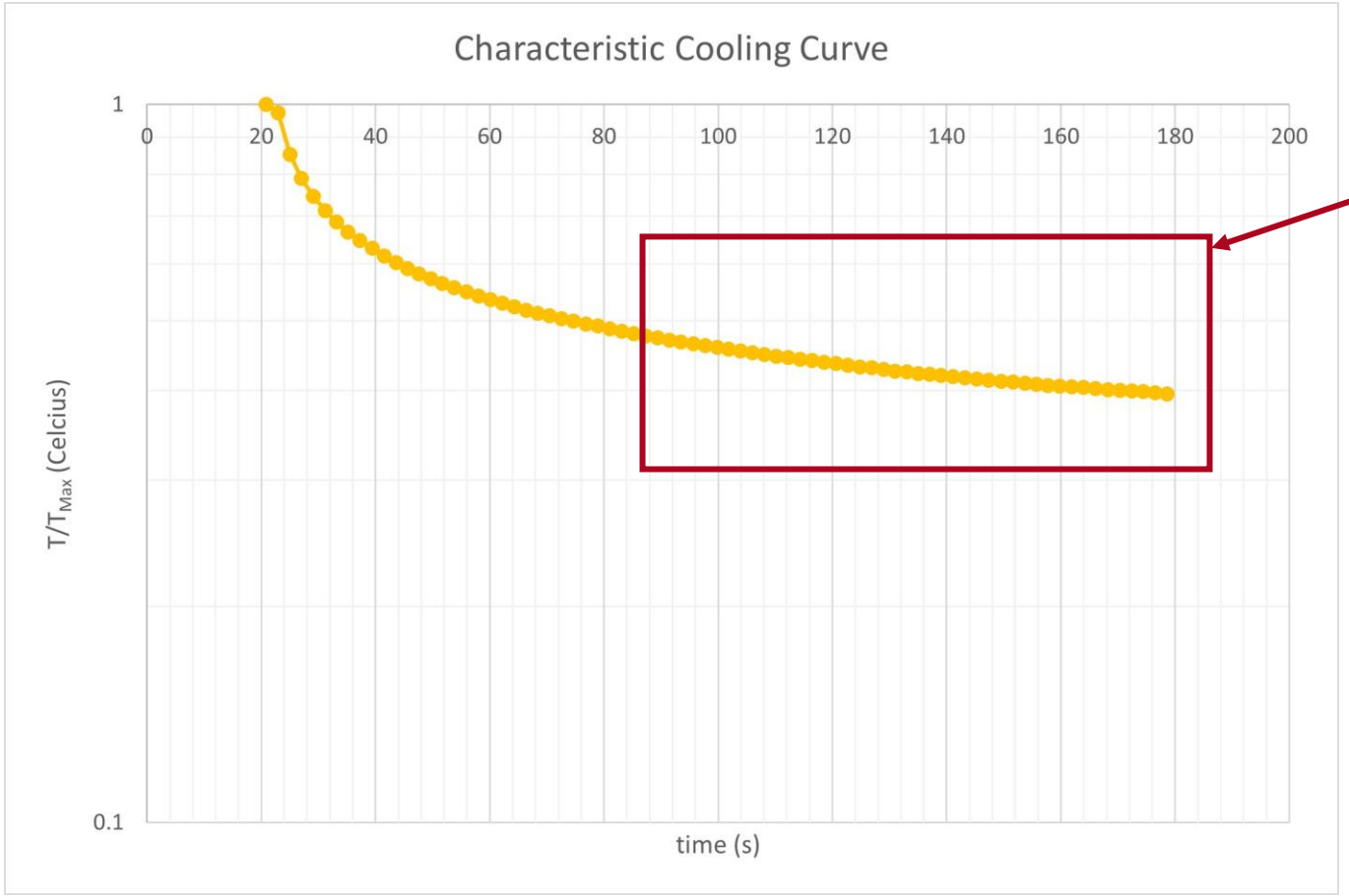
- Gun was placed about 4 inches from model and was cycled with 30 seconds of heating 7 times
- Cooled to around 30°C between each cycle
- "Line" on PEEK curves are due to limited range of the camera, but model was heated from same starting temperature as 10K
- 10K reached over 200C and saw no material degradation for these short runs
- PEEK took much longer to heat up resulting in lower peak temperatures
  - Could be due to slight difference in heat gun distance from model
- Both models yellowed slightly during test but returned to normal once heat was removed





Time Constant Calculations

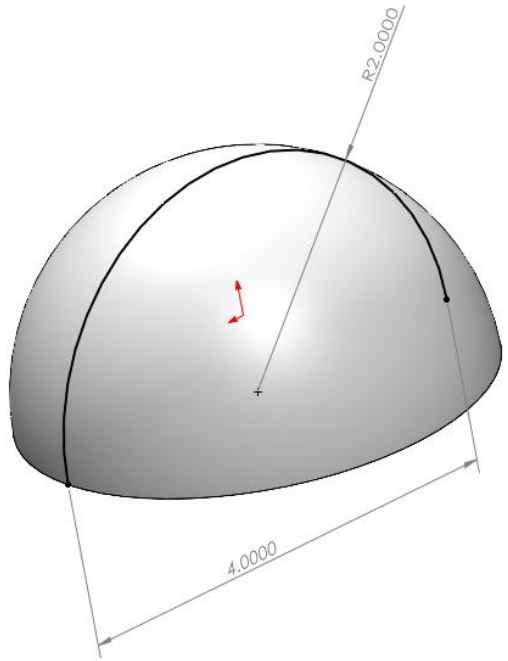
- Cooling time constant calculated using $\frac{T-T_\infty}{T_i-T_\infty} = e^{-\frac{t}{\tau}}$
- Data did not follow Newton's Law of cooling (exponential decay), so we plotted the data on a log scale to see where it was liner and used two points from that part of the data



Hemisphere fabrication

The model was built, cured and processed the same way as the hemisphere sent to NASA. Dimensions were identical as well.

- Printed on Formlabs Form3 printer in Rigid 10k resin
- Layer thickness .05mm
- Standard cure at 70°C for 60min + additional thermal cure at 90°C for 125min
- sanded and polished to achieve a smooth surface



MATERIAL PROPERTIES DATA

Rigid 10K Resin METRIC

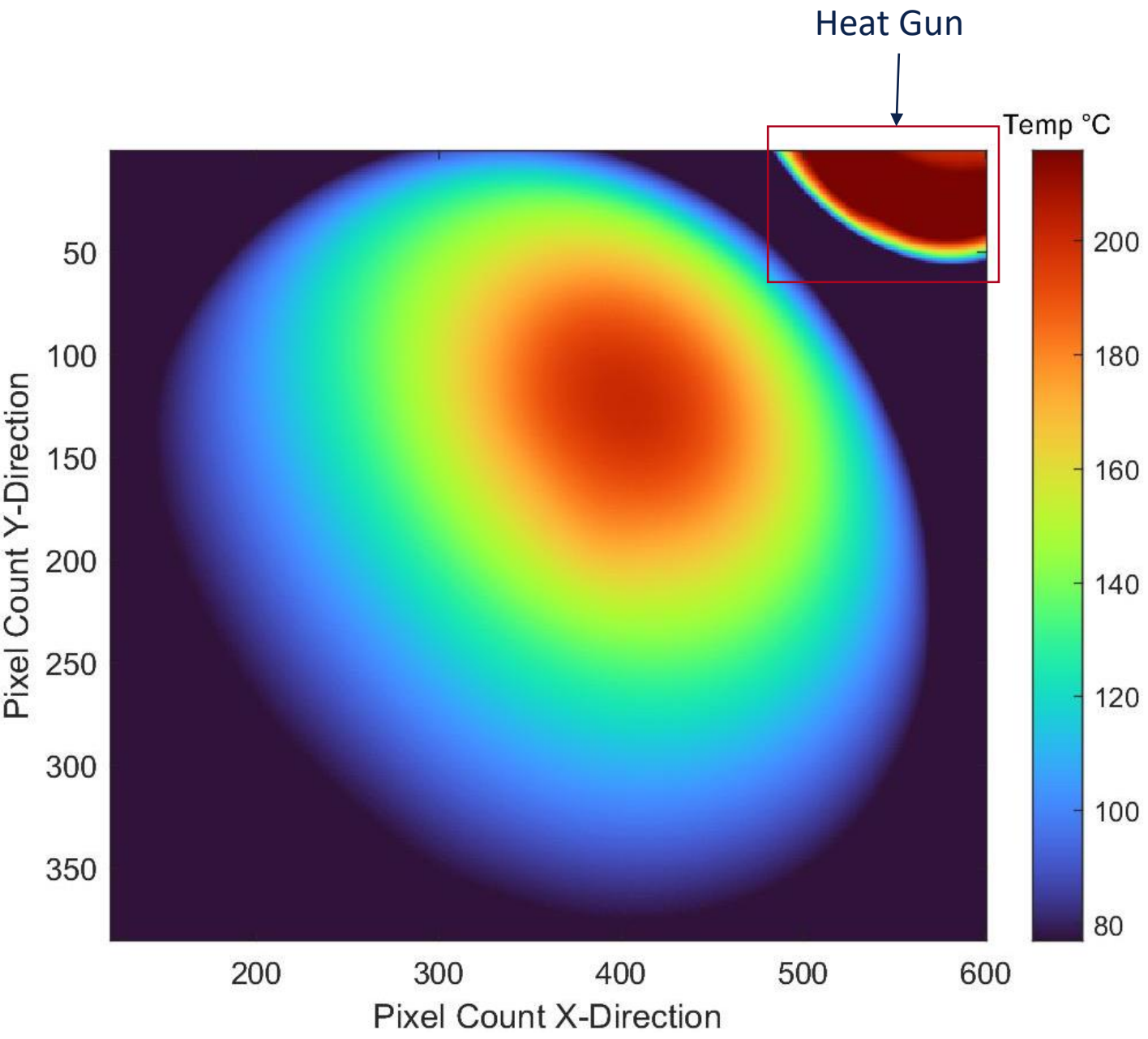
	Green	UV Post-cured [1]	UV + Thermal [2]
Tensile Properties			
Ultimate Tensile Strength	55 MPa	65 MPa	53 MPa
Tensile Modulus	7.5 GPa	10 GPa	10 GPa
Elongation at Break	2%	1%	1%
Flexural Properties			
Flexural Strength	84 MPa	126 MPa	103 MPa
Flexural Modulus	6 GPa	9 GPa	10 GPa
Impact Properties			
Notched IZOD	16 J/m	16 J/m	18 J/m
Unnotched IZOD	41 J/m	47 J/m	41 J/m
Thermal Properties			
Heat Deflection Temp. @ 1.8 MPa	56 °C	82 °C	110 °C
Heat Deflection Temp. @ 0.45 MPa	65 °C	163 °C	218 °C
Thermal Expansion, 0-150 °C	48 µm/m/°C	47 µm/m/°C	46 µm/m/°C

Setup

- Heat gun mounted ~3.5” from hemisphere surface
- Steinhel HL1820S heat gun set to its max level (600 °C and 13 cfm airflow)

- FLIR X8501sc IR camera
  - 30 seconds of video and model heating at a time
  - 25 Hz, 750 frames, 512 x 640 resolution

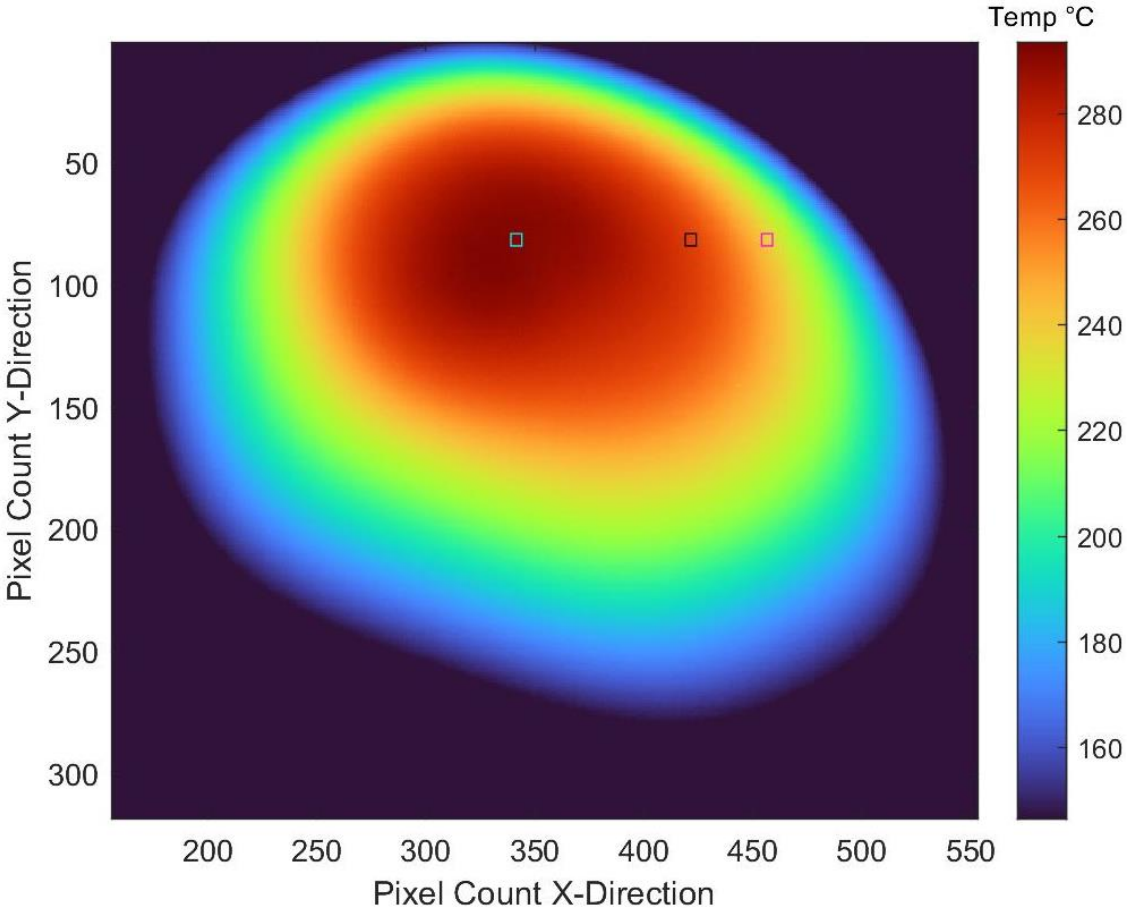
Results: Low End of Range

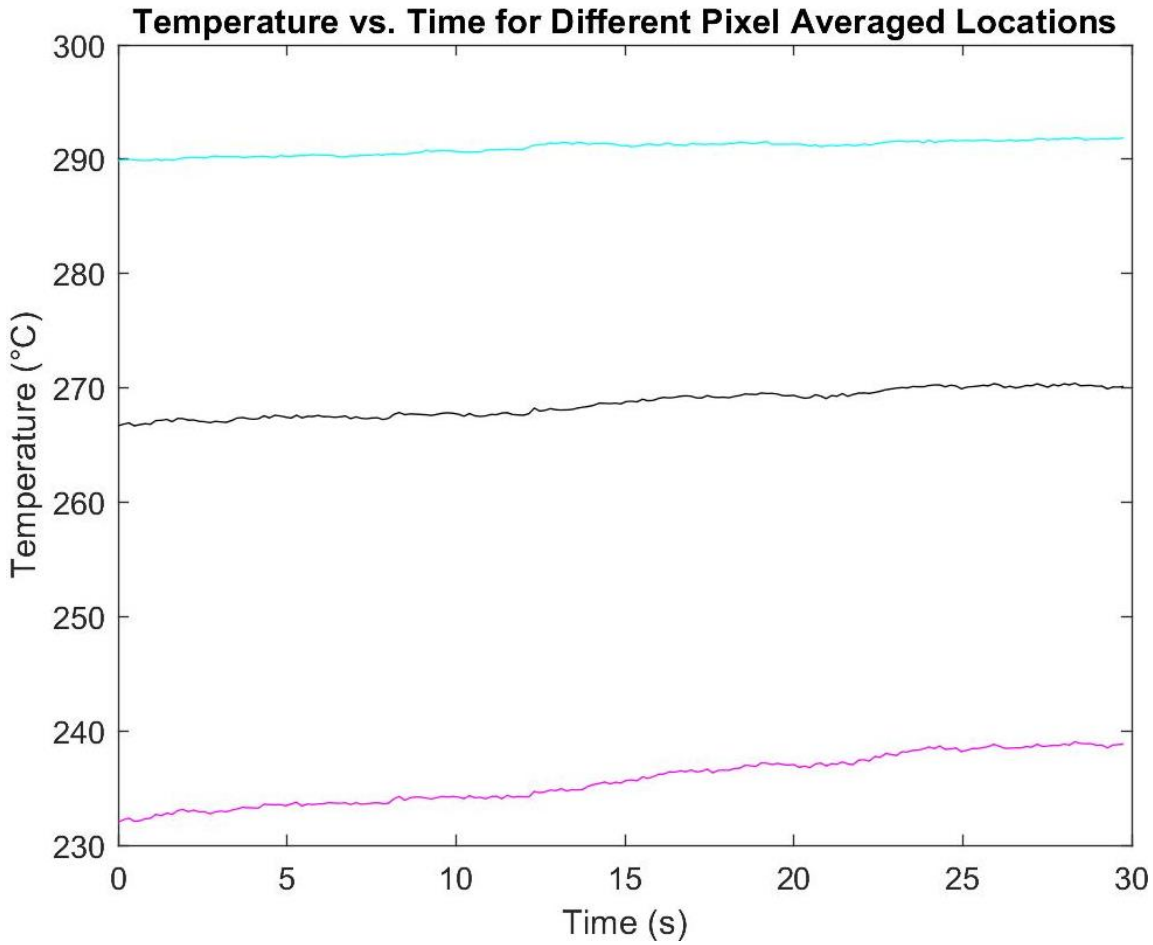


- Last image of 30 second IR video
- Max temp on the surface is 200.98 °C
- After heating, hemisphere was discolored where heat gun jet was concentrated
- Slight crackling effect that appeared to be subsurface

Results: Mid/Upper Range

- To achieve hotter surface temperatures, the heat gun was left on for several minutes before placing hemisphere underneath
- Last frame of 30 second IR video
- Max surface temperature is 293.69 °C





- Temperatures averaged across 5x5 pixel grid. Colored lines in plot (right) correspond to boxed areas in figure (left)

Final Hemisphere Condition

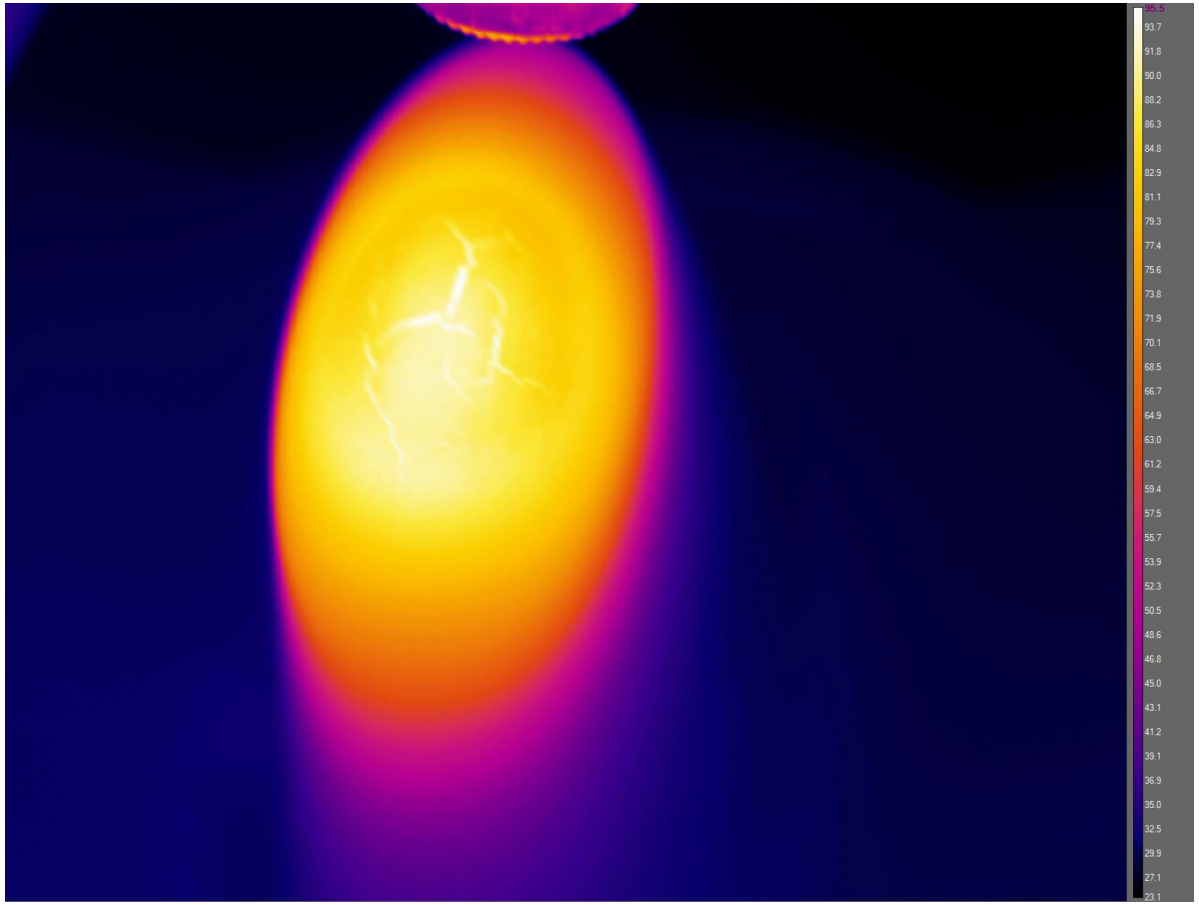
- Much larger surface cracks along with network of smaller cracks
- Additional discoloration following the 3D print pattern
- Changes to hemisphere are not apparent in the IR. Surface temperatures look smooth throughout the video

Heating Videos

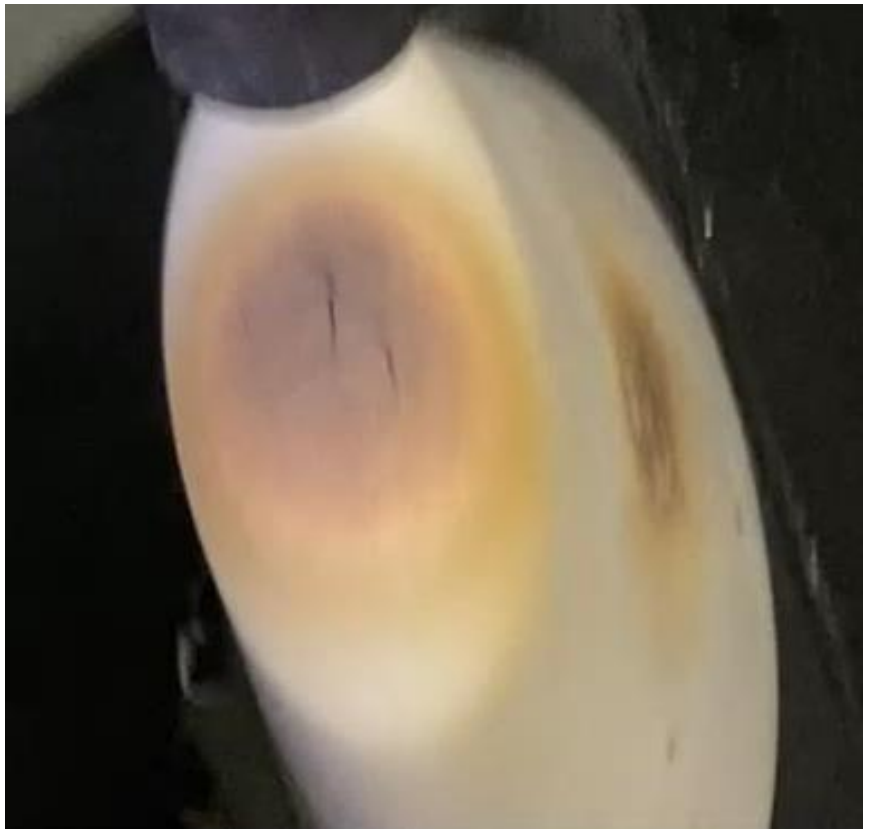
Temperatures On Right are in ˚C

*Video appears wobbly due to the hot air rising from the surface

Heating Videos Continued



Temperatures On Right are in ˚C



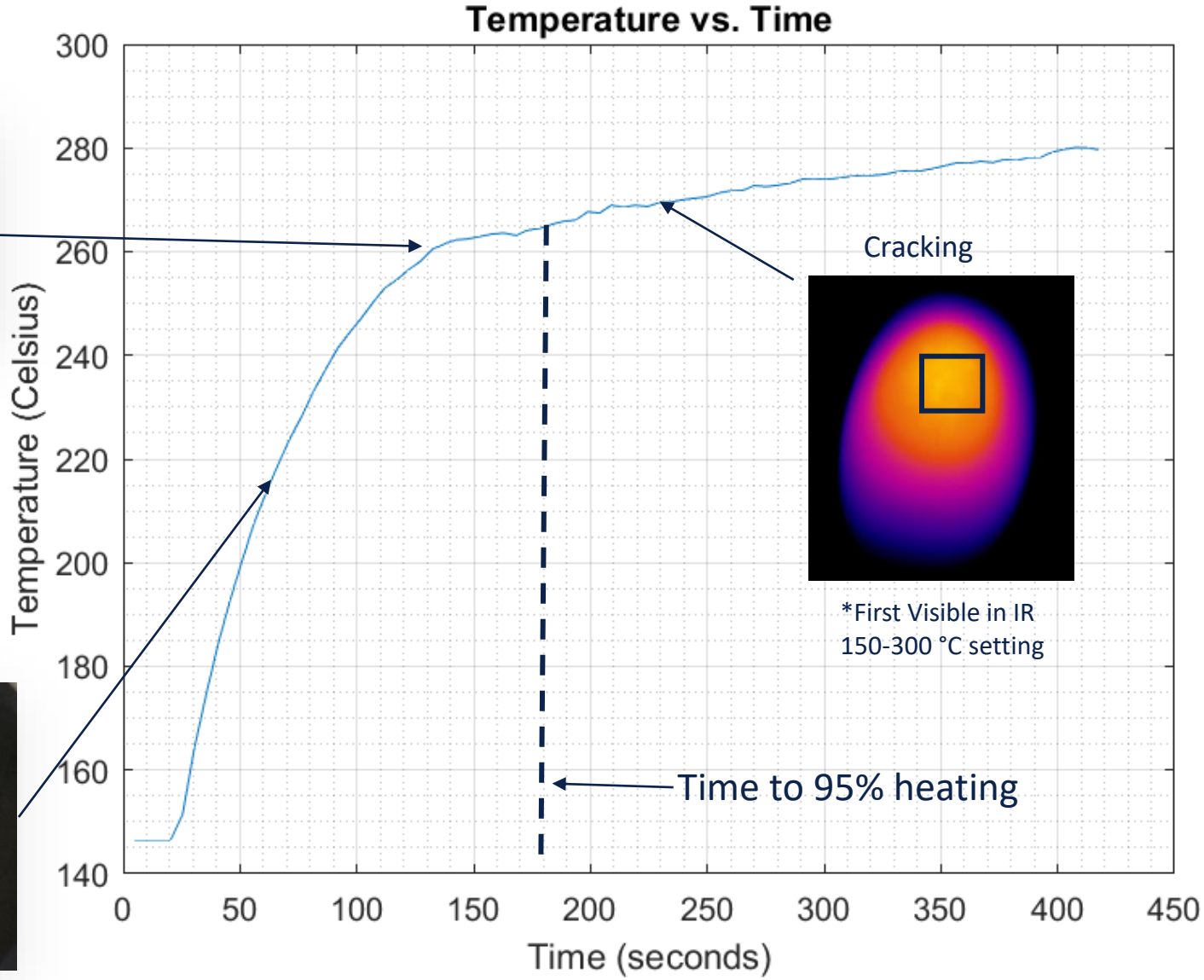
*Video appears wobbly due to the hot air rising from the surface

Experiment 1

- 10K and PEEK models were heated for 7 minutes with the heat gun approximately 4 inches from the model
- A synchronized IR camera and traditional camera were used to identify at what temperatures the surface changes occurred
- Surface changes were noticeable in the IR in this test with clearly visible cracking

Blackening

Browning

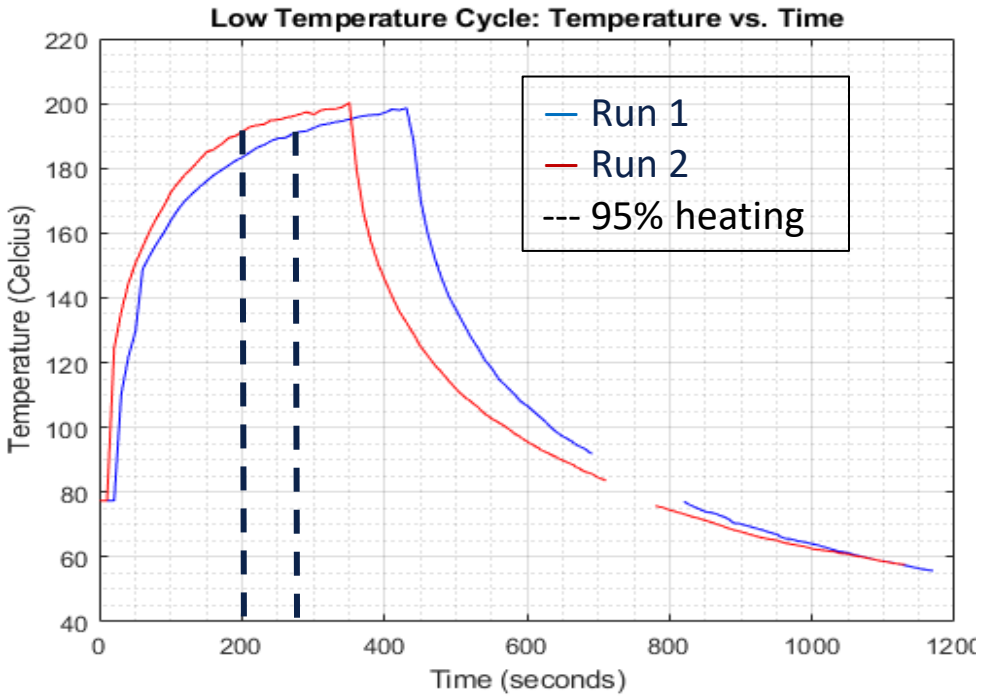


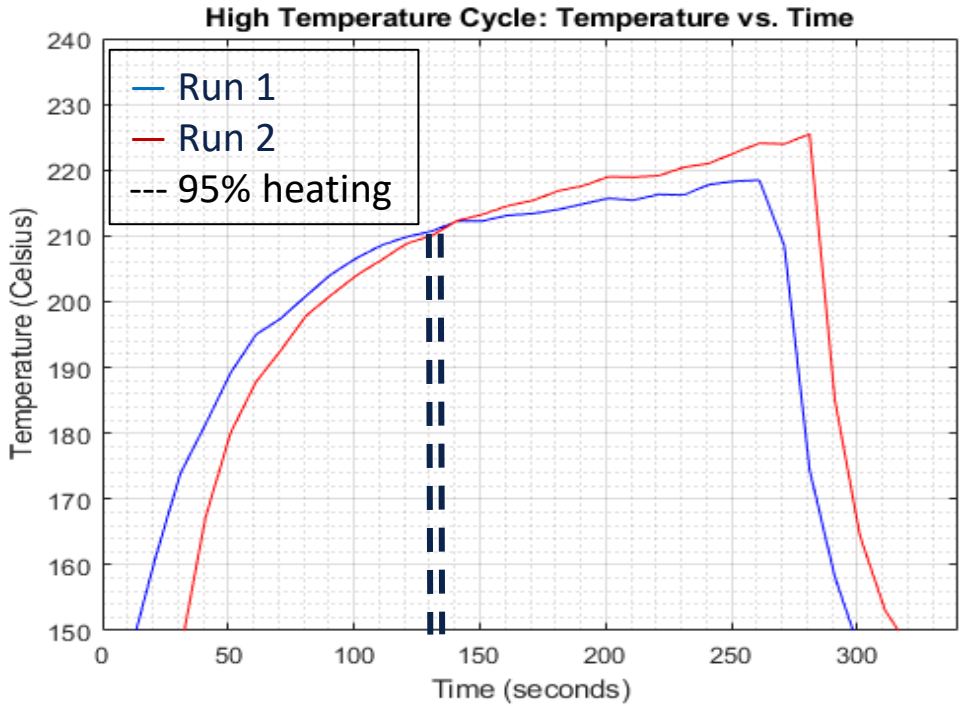
* Possible emissivity change could result in the change in heating curve after the surface blackened

10K Experiment 2

Heating and Cooling Times 200°C Experiment		
	Run 1	Run 2
95% heating	4:40	3:20
Cooling Time Constant	434 (s)	474 (s)

Heating and Cooling Times 225°C Experiment		
	Run 1	Run 2
95% heating	2:10	2:15
Cooling Time Constant	90.4 (s)*	67.7 (s)*





*Time constants are so different to other experiments likely due to only having data to take from the early portion of cooling which do not follow Newton's Law of cooling

** Only two data sets shown due to technical problems with the IR camera and no valuable data taken from third test of each experiment

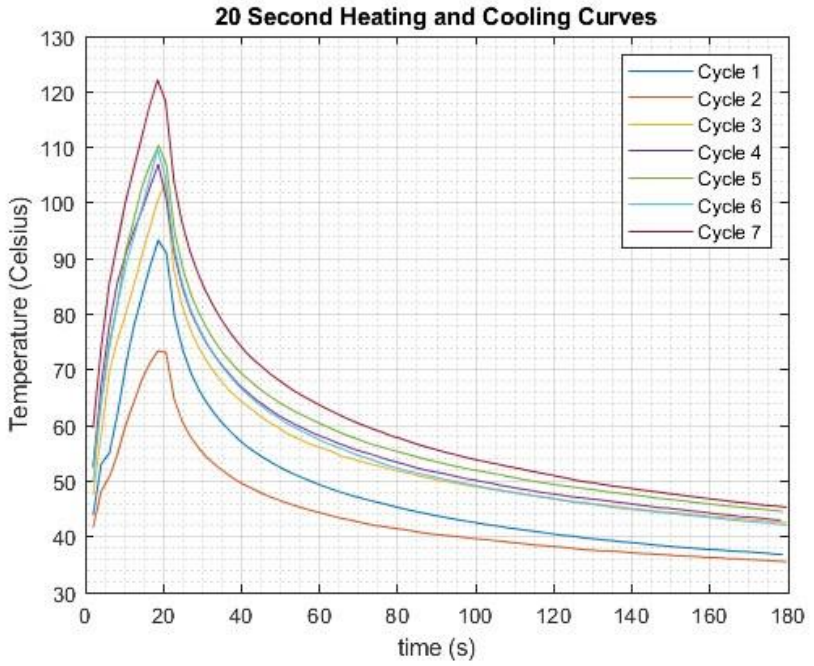
10K Experiment 3

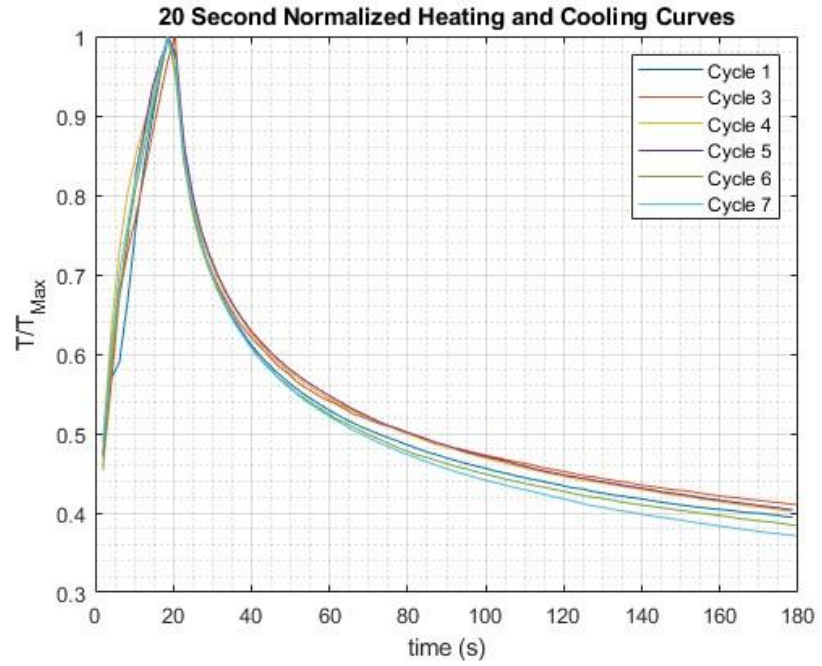
- Test cycled 7 times for 20 seconds under heat gun (heat gun preheated to max setting before each run), then cooled until model reached roughly 45-55°C
- Peaks occur at different temperatures due to human error – heat gun held manually and distance from model was approximated

Run	1	2	3	4	5	6	7
Time Constant (s)	211	219	229	231	237	227	218

- Time Constants Estimated ± 15s accuracy

*Cycle 2 not shown on normalized graph due to peak temperature not getting hot enough to be comparable to other runs





Experiment 4 time constants

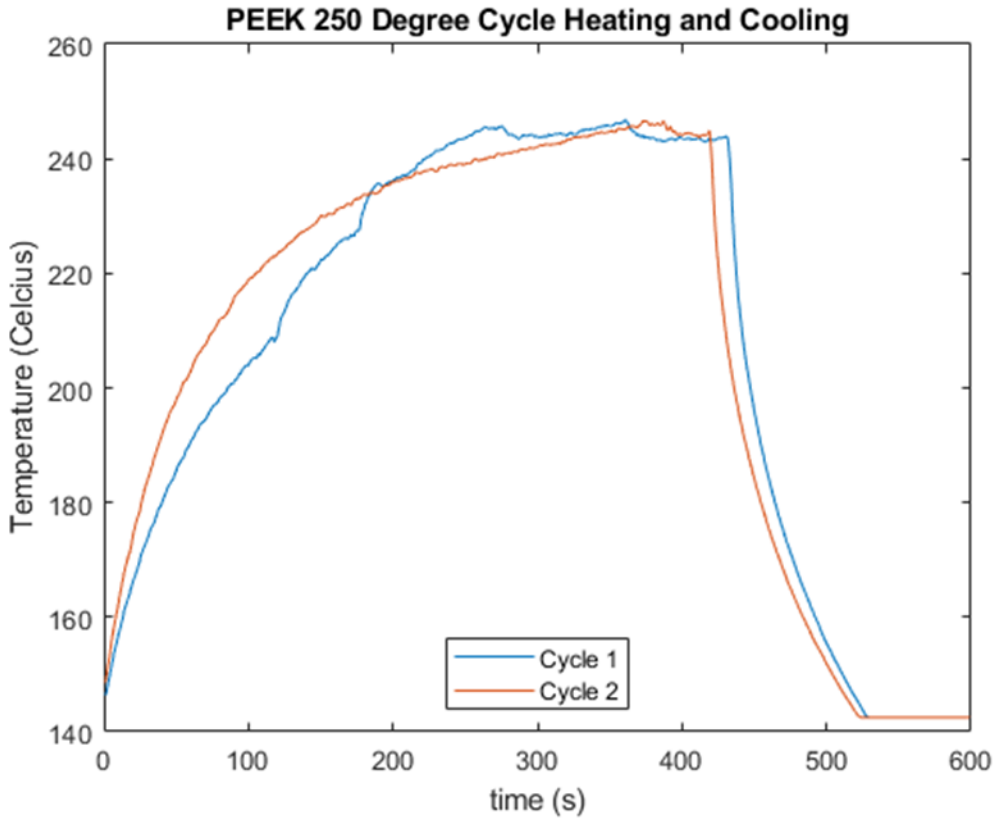
Run	1	2	3	4	5	6	7
Time Constant (s)	163	180	174	179	176	175	182

10K Experiment 3

- Boxed Area indicates where the heat gun was directed
- The model looks and feels unchanged from this heating
- Cooling time constant (τ) for each test remained relatively constant – no material degradation

PEEK Experiment 2 – 250°C test

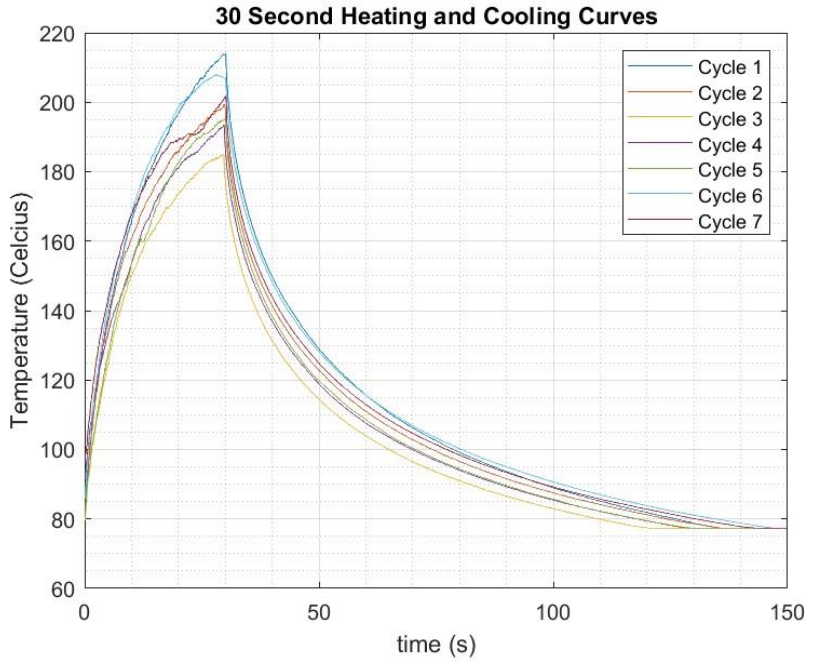
- Gun was placed at a precise distance to make the material reach 200°C, 250°C, and 280°C and stabilize
- Heated for approximately 7 minutes
- 2 cycles performed (except 280°C – material melted on first test)
- Material saw yellowing and then browning
- Yellowing disappeared for 200°C test and browning disappears after heat gun is removed
- No material degradation, and no change between cycles

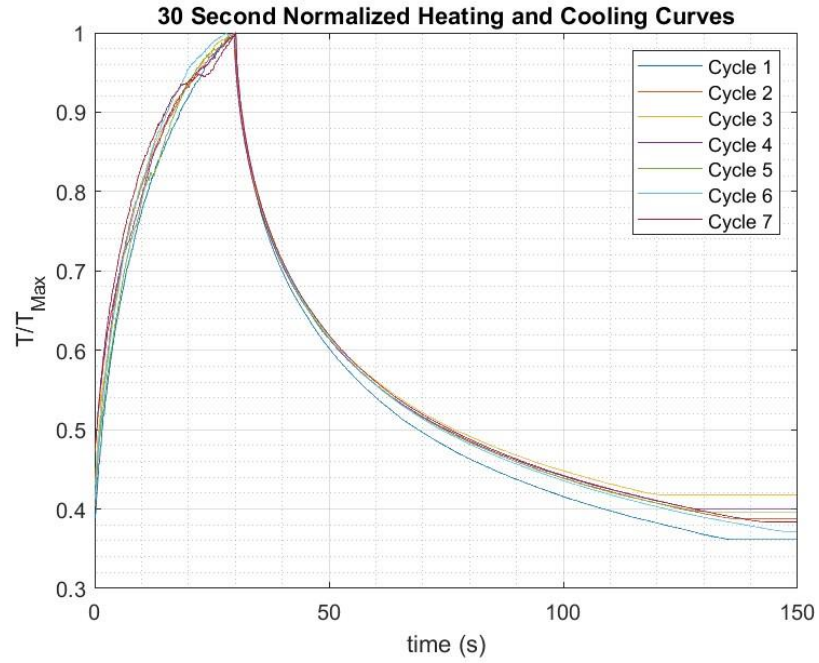


Final result from 250°C cycling

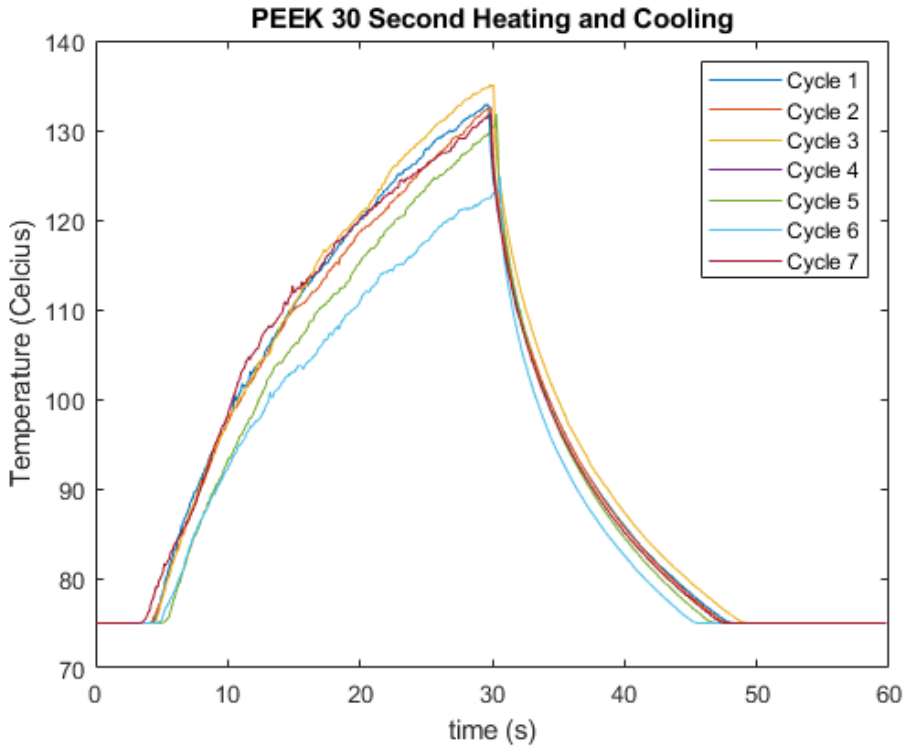
Experiment 3

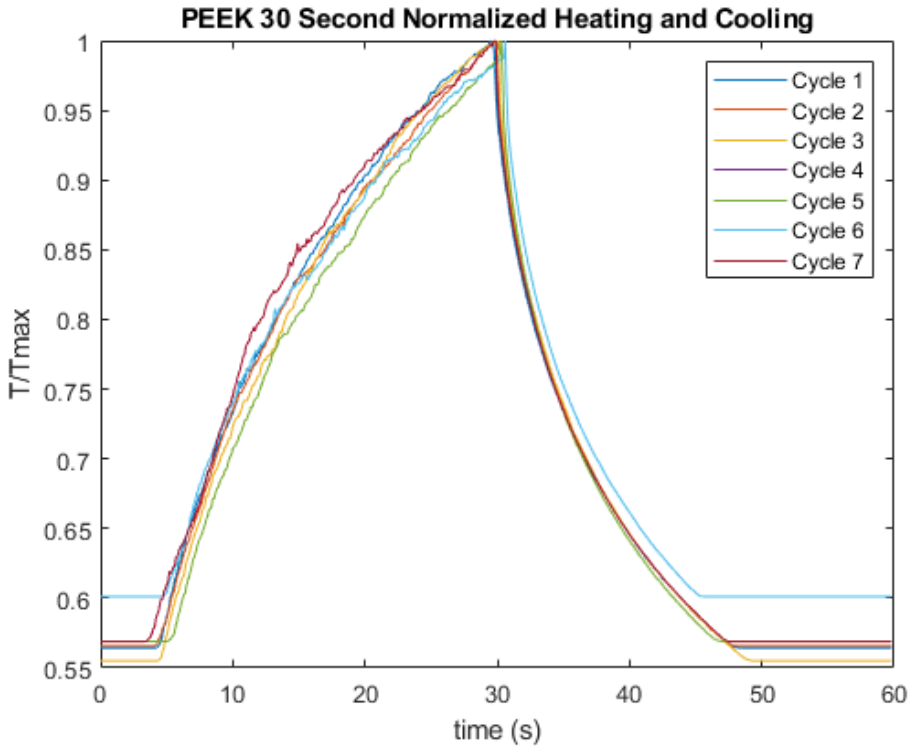
- Gun was placed about 4 inches from model and was cycled with 30 seconds of heating 7 times
- Cooled to around 30°C between each cycle





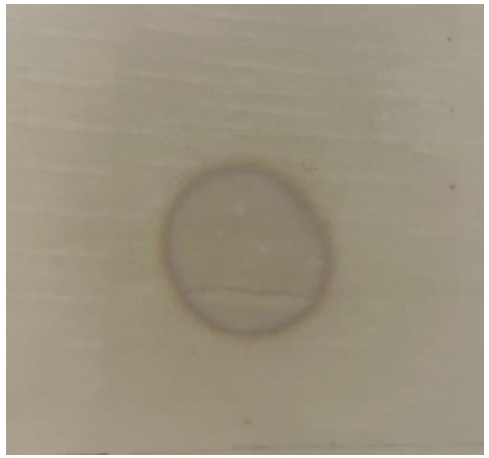
PEEK Experiment 3



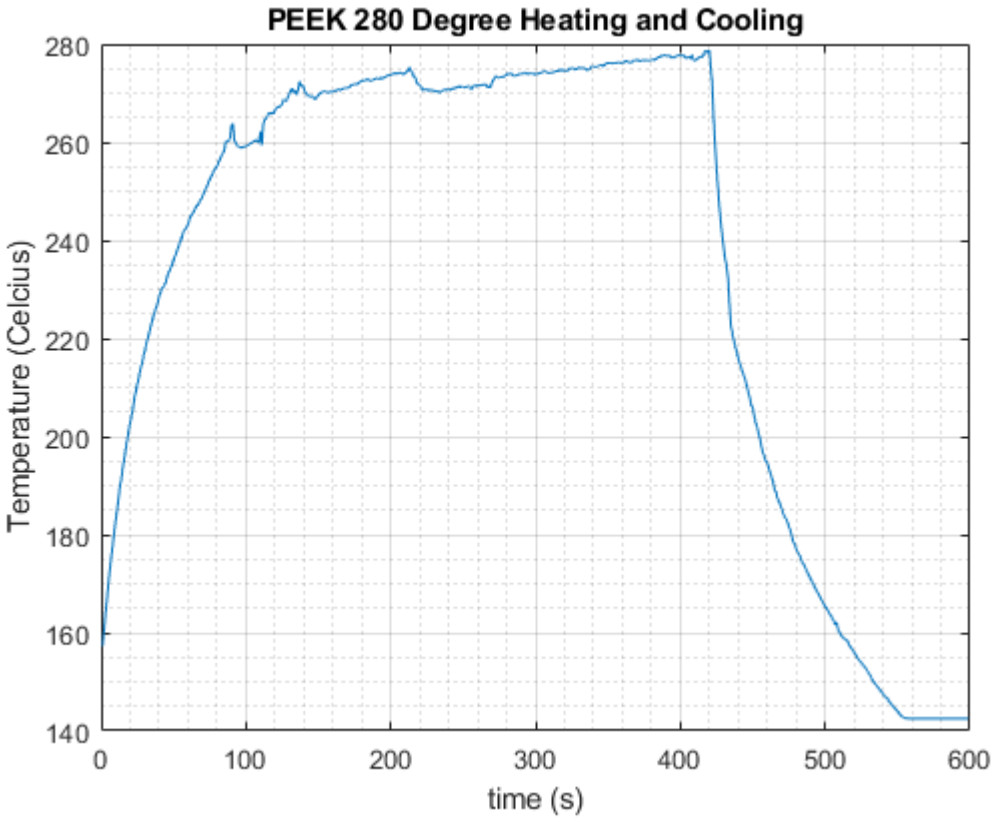


PEEK Experiment 2 – 280°C test

- 280°C test was performed to confirm when the material started to melt
- Material began melting at around 270°C
- Noticed bubbles formed
- Uneven heating at around 260°C due to adjusting heat gun distance to reach stable temperature



Final result after 280°C test



10K and PEEK Comparison

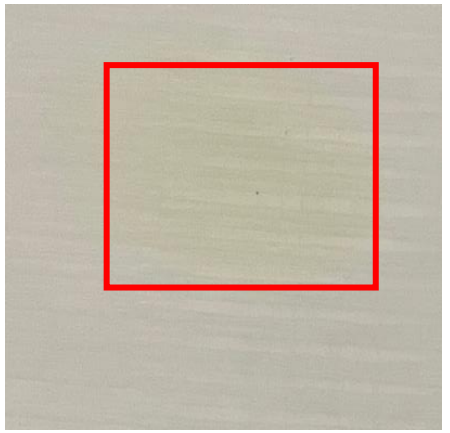
Event	Material	Time	Temperature (°C)
Color Change	10K	1:05	215
	PEEK	0:50	208
Blackening	10K	2:25	263
	PEEK	2:10	255
Material Deformation	10K	4:08	269
	PEEK	4:00	270
Final	10K	7:00	280
	PEEK	7:00	290

- Above is a direct comparison of how the 10K and PEEK reacted from experiment 1

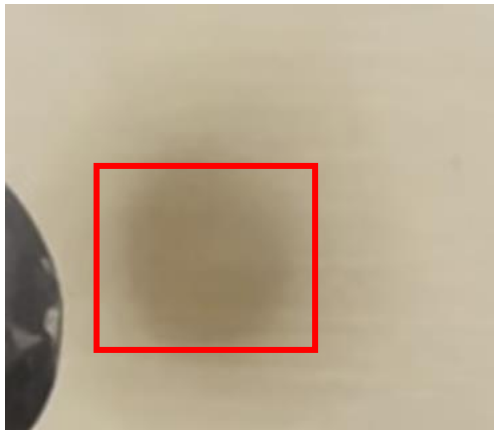
PEEK Experiment 1 Results

Event	Time (m:s)	Temperature (°C)
Color Change	0:50	208
Blackening	2:10	255
Material Deformation	4:00	270
Bubbling	5:30	275

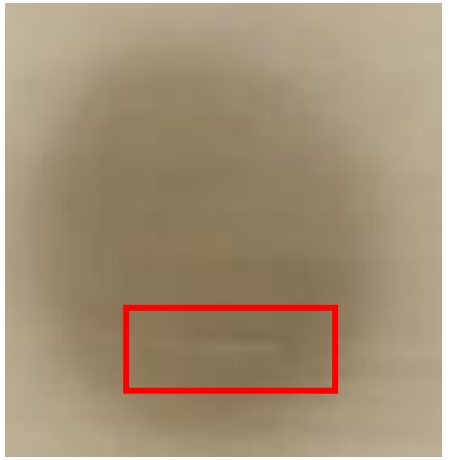
- First sign of color change was a slight yellowing
  - Color get darker over time
- Material then forms a blacker color and gets darker over time
- Material formed a "line" where it seemed like it was caving in
- Material then began to bubble



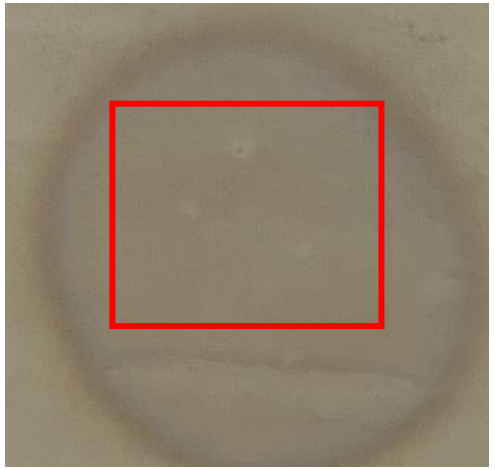
First sign of yellowing



First sign of blackening



First sign of material degradation



Results of bubbling

10K Experiment 1 Results

- The model could be scratched after blackening (shown in final image)
  - Suggests high-speed air over the model could fly off if damaged
- Emissivity may have changed around the blackening stage – reported temperatures could be slightly lower than actual temperatures after this

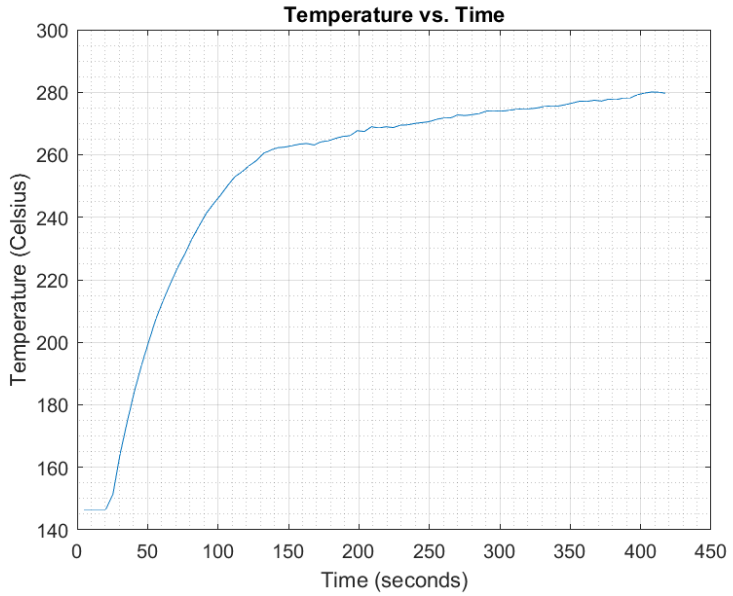
Stage	Temperature Range (°C)	Time
Browing	215 – 220	1:05
Blackening	263 – 264	2:25
Cracking	269 – 273	4:08
Final	280	7:00

Final image and final IR of the model after first experiment

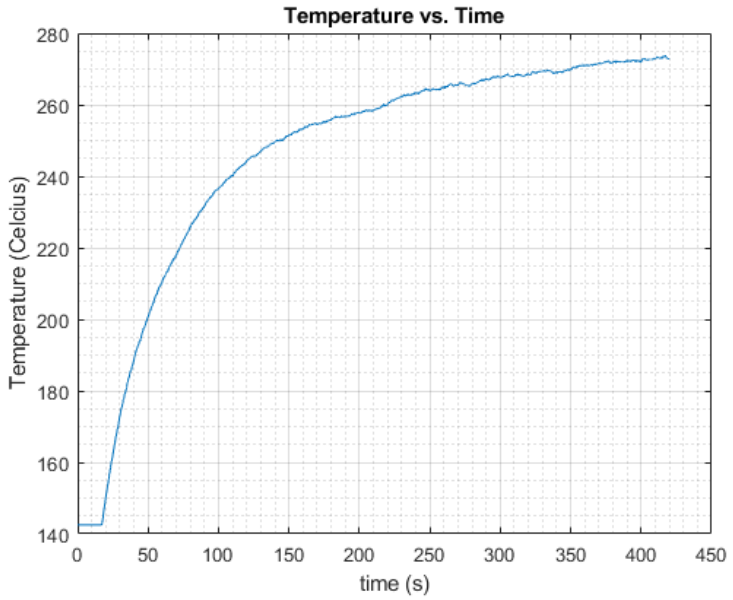
Experiment 1

- 10K and PEEK models were heated for 7 minutes with the heat gun approximately 4 inches from the model
- A synchronized IR camera and traditional camera were used to identify at what temperatures the surface changes occurred
- Surface changes were noticeable in the IR in this test with clearly visible cracking

10K



PEEK



Redo Comments

- Consistent with all tests:
  - 10K could maintain above 180°C for 15 seconds and reach around 200°C for short periods of time (a few seconds) with no material degradation – possibly could withstand more, but this was consistent
  - Half inch 10K model cracks at around 250°C, but no material degradation below this
  - PEEK began to melt at around 270°C, but no other material degradation occurred below this

Summary

- PEEK performed better than 10K under higher temperatures
- 10K material degraded at lower temperatures than PEEK
- Cycling likely did not change the material properties of either material – reheating just prolonged heating exposure and continued the effects of that temperature
- PEEK took much longer to heat up compared to the 10K (possibly due to geometry)
- Both materials performed well for the 30 second cycles where there was a slight color change during the run, but went away once the heat was removed
- Notable difference is that PEEK was a ½ inch thick block whereas the 10K was a 1 inch thick model with a more complex geometry
- Cooling may have occurred from the back of the PEEK block for higher temperature tests, but we believe this did not affect the 30 second cycles as the back did not appear to get hotter when we touched it