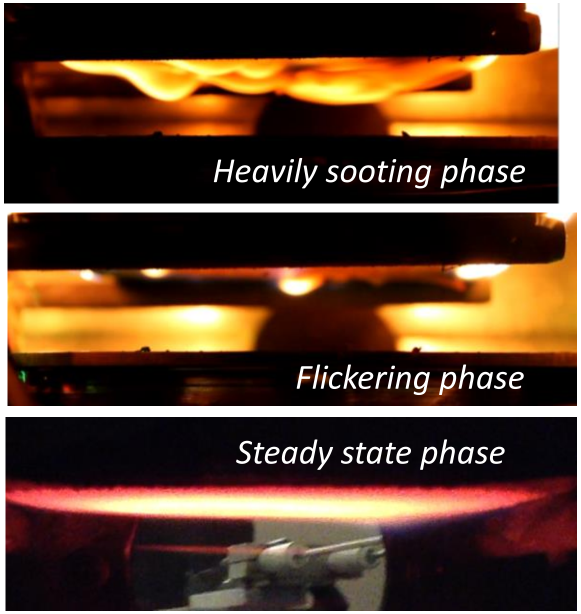
SAND2015-0616C

GAS TEMPERATURE AND CONCENTRATION MEASUREMENTS IN THE VICINITY OF A BURNING/DECOMPOSING CARBON-EPOXY AIRCRAFT COMPOSITE MATERIAL



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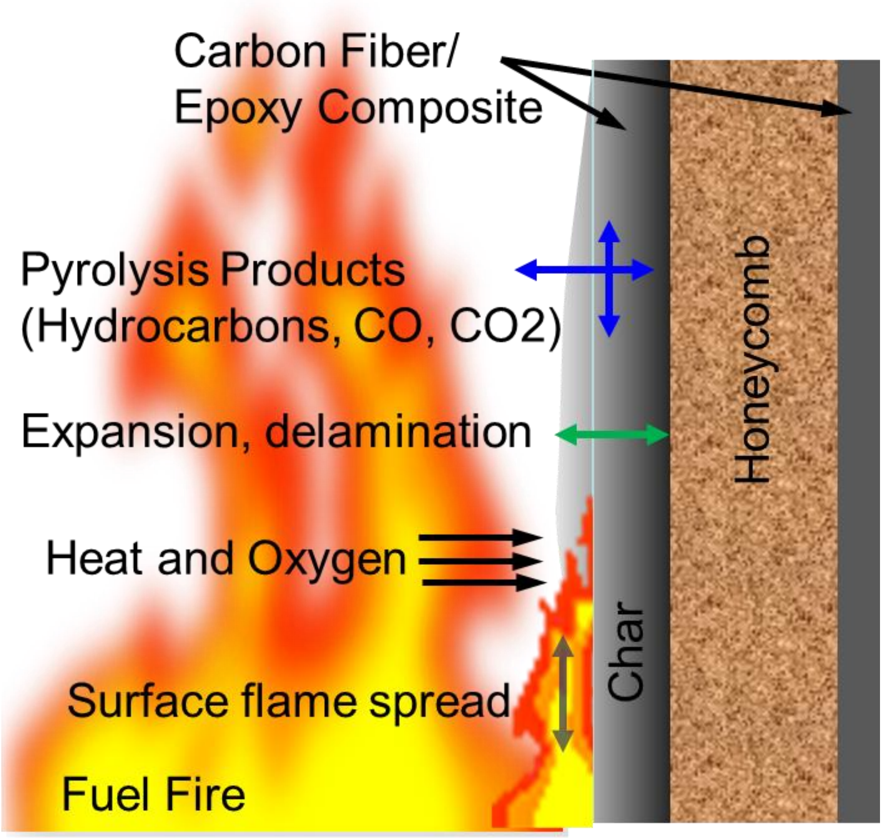
Preview

- Background and Motivation
- Controlled Composite Burn Experiments
- CARS Diagnostics
  - Point measurements
  - 1-D line imaging measurements
- Results and discussion
  - Observed burning/decomposition characteristics
  - Point measurements
  - 1-D line imaging measurements
- Summary and conclusions

Composite aircraft fires provide a unique set of poorly understood additional thermal hazards

- The behavior of the composite fires is not well characterized
  - Fuel fire heats composite
  - Composite thermal decomposition contributes to fuel loading
  - Heat and mass is transported into interior
  - Additional decomposition of internal layers causes increased fuel loading and internal heat generation
- Improved basic understanding is required for reliable risk assessment
  - Decomposition
  - Char formation
  - Heat and mass transfer



Reaction Mechanism for Carbon-Fiber/Epoxy Composite Decomposition

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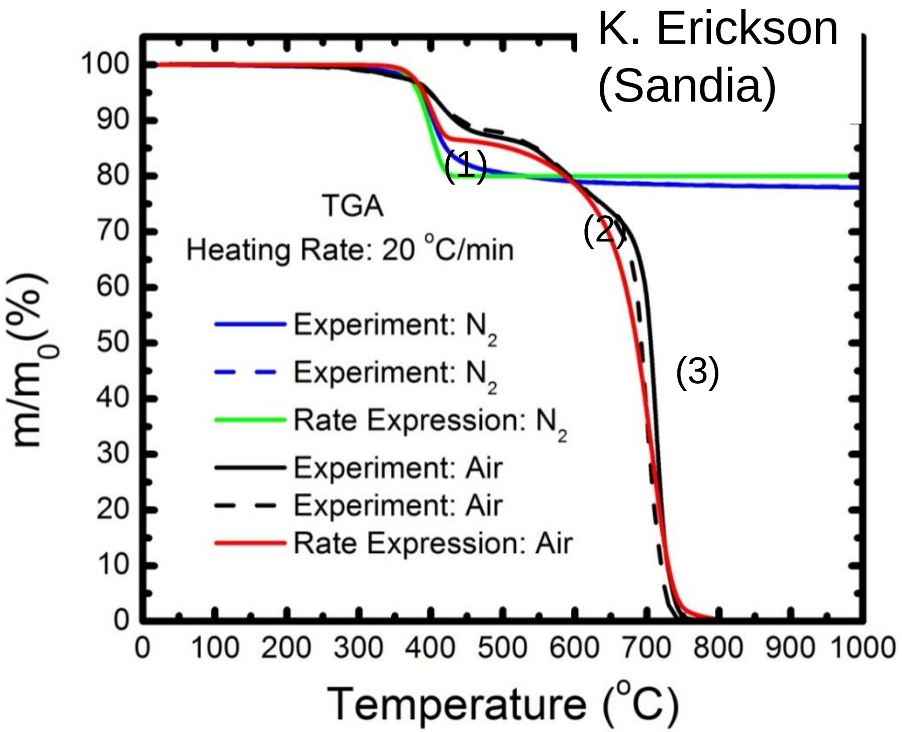
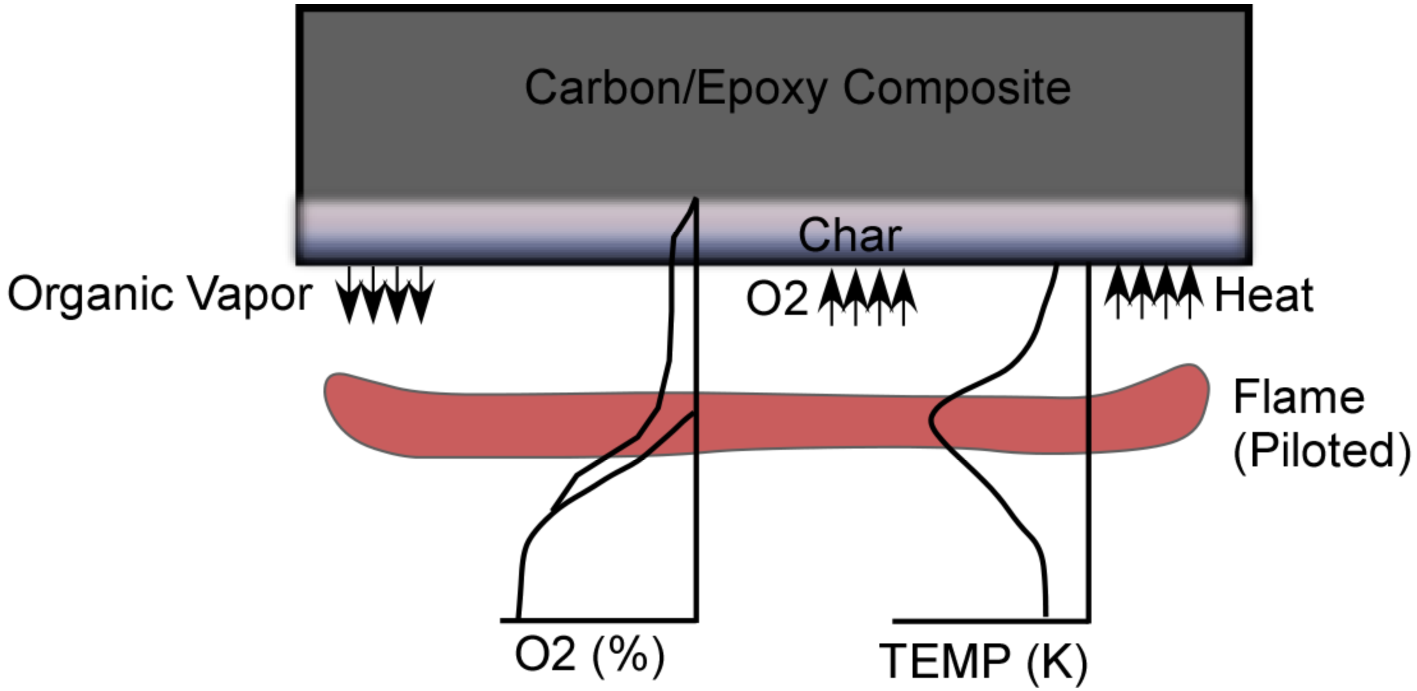


- TGA data for Carbon-Composite materials reveal dramatically different response in oxidizing vs. non-oxidizing environments
- Epoxy pyrolyzes to form organic vapors (fuel) and char in both oxidizing and inert environments
- In air, the char is oxidized, generating more heat followed by carbon-fiber combustion
- Char formation inhibits combustion of carbon fibers
- Char oxidation occurs BEFORE carbon fiber oxidation

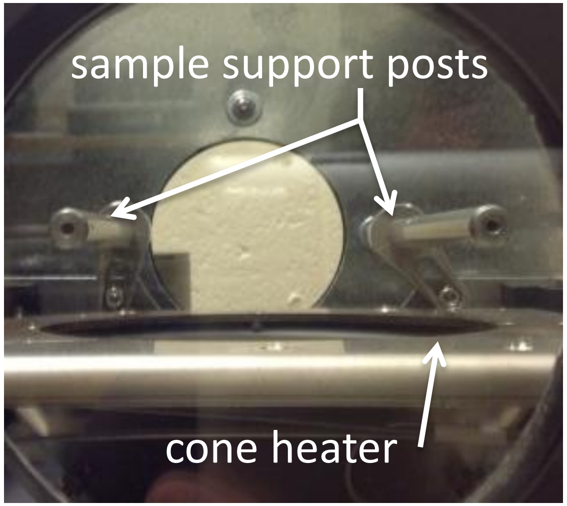
(1)	Epoxy	→	Organic Vapors + Char	
(1)	Epoxy + O_2	→	Char+ Organic Vapors	
(2)	Char + O_2	→	CO	Exothermic Reaction
(3)	Carbon Fibers +O_2	→	CO_2	Highly Exothermic Reaction

Small Scale Experiment: Assess Temperature and O_2 Profiles Near the Surface of a Heated or Burning Composite Sample

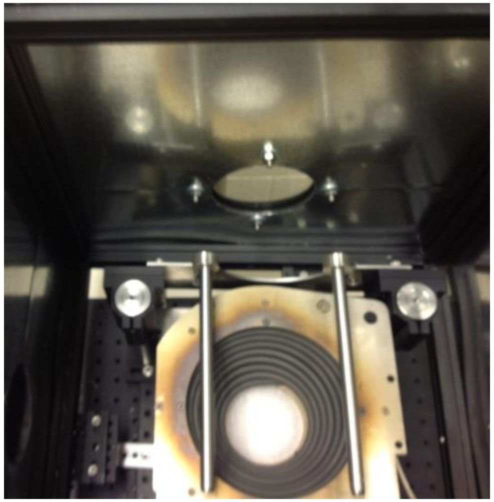


- Mass transfer: Is *oxygen* transport present at the surface? Gradient?
- Heat transfer: Characterize the *surface heat flux* for relevant mass transfer and chemistry to occur
- Expose surface to well-controlled radiative heat flux
- Monitor temperature and O_2 profiles and estimate heat flux with a single diagnostic

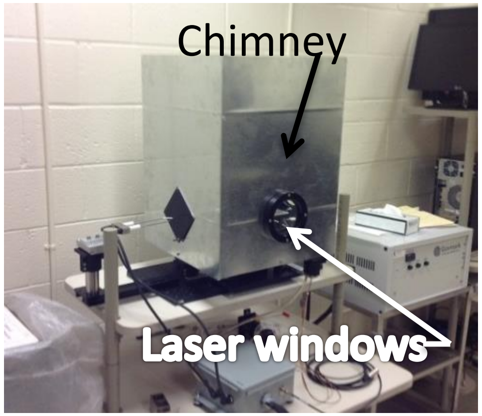
Composite Burn Experimental Facility



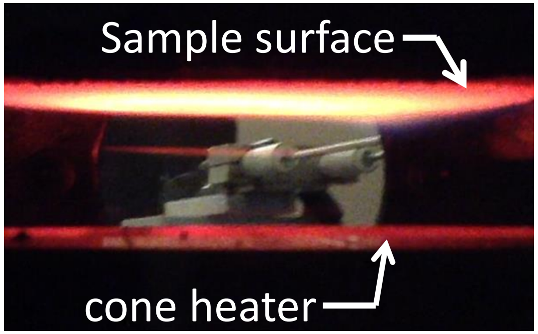
Side view through window



View from top of chimney



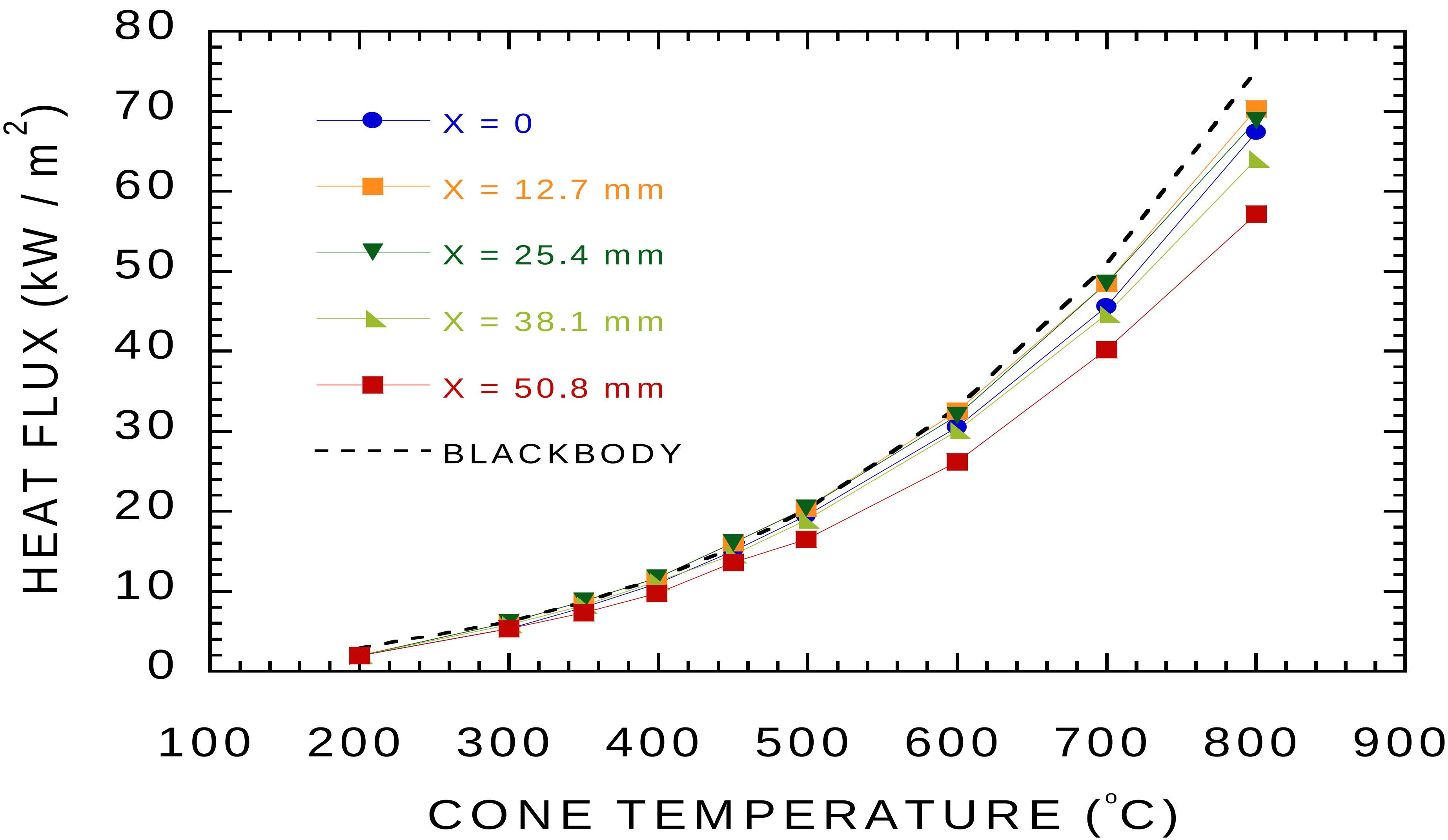
Full system view



Sample above cone heater

- HEXCEL 3501-6 carbon-epoxy composite samples
  - 3 mm thick
  - 100-mm × 150-mm cross section
- Exposed to uniform radiative flux by GBH cone heater
- Heat flux applied to lower surface of sample
- 25-mm fiberboard insulation on upper sample surface
- Sample/heater assy. enclosed in sheet-metal chimney
- Windows for optical access

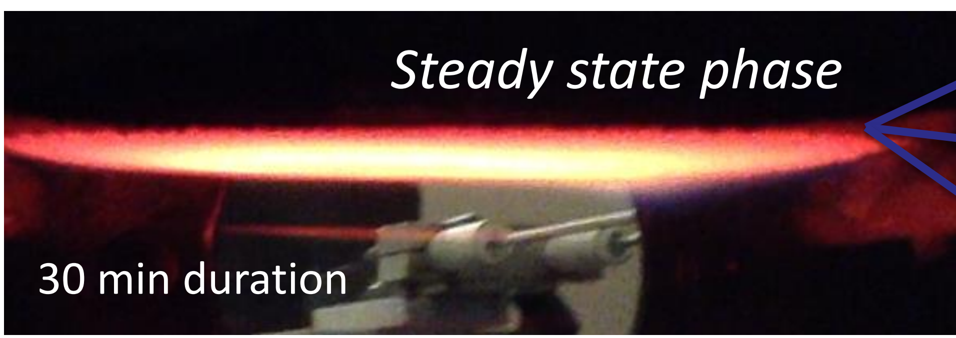
Cone Heater Calibration Curve



Observed sample decomposition/burning behavior

- Autoignition at heater temperature ~600 °C or q" = 31 kW/m^2
- Combustion of ***epoxy binder*** material
- ***Heavily sooting***—absorbs almost all laser light near surface

- Transitional phase
- Binder nearly consumed
- Pockets of sooty flame meander about surface



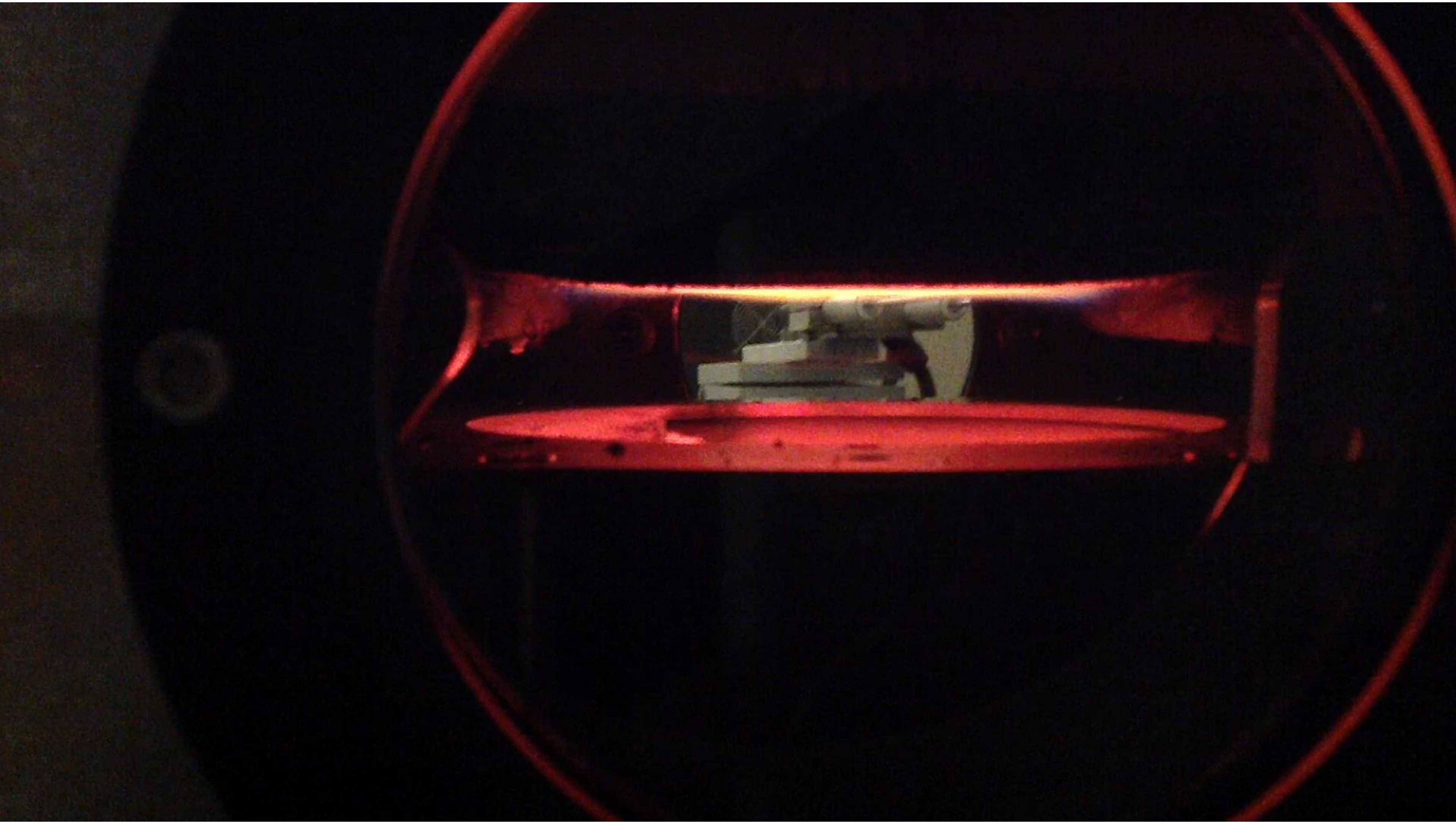
- Consumption of carbon fibers
- Perhaps some char consumption
- Both blue and yellow/orange flame emission

Thermal decomposition, debonding, autoignition, sooting burn

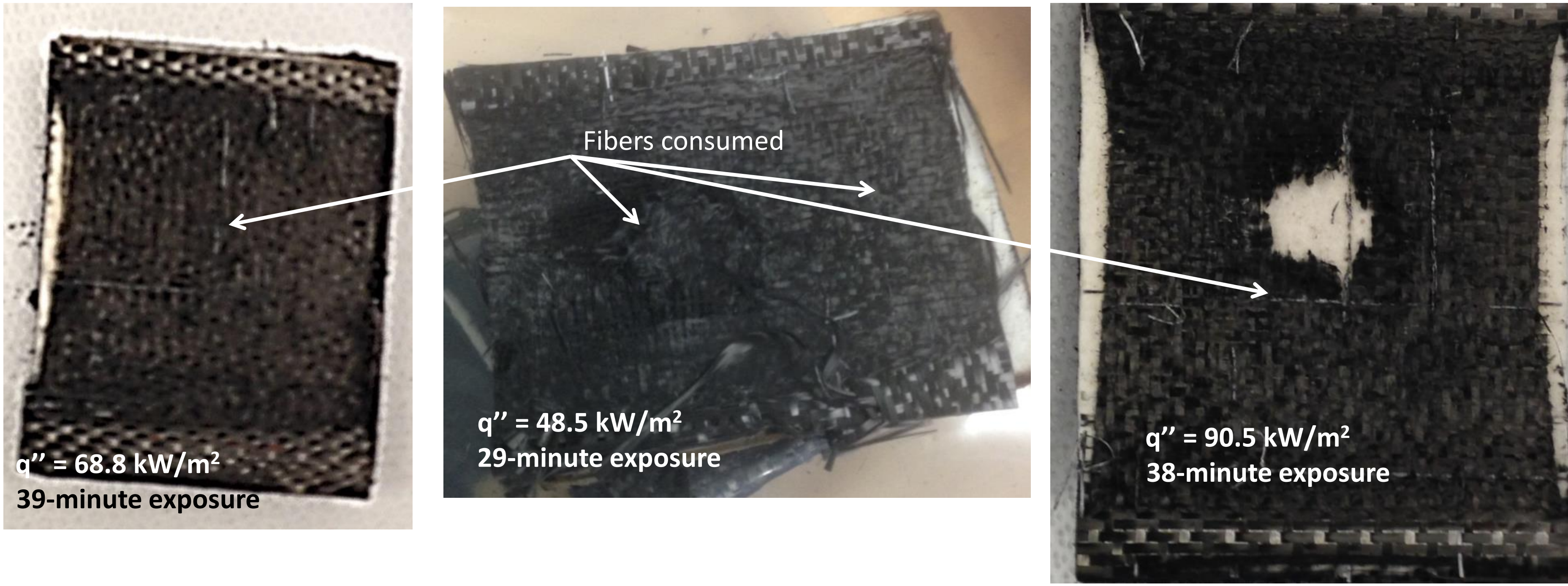
Sooting burn: late time

"Flickering"

"Steady" behavior w/ fibers consumed

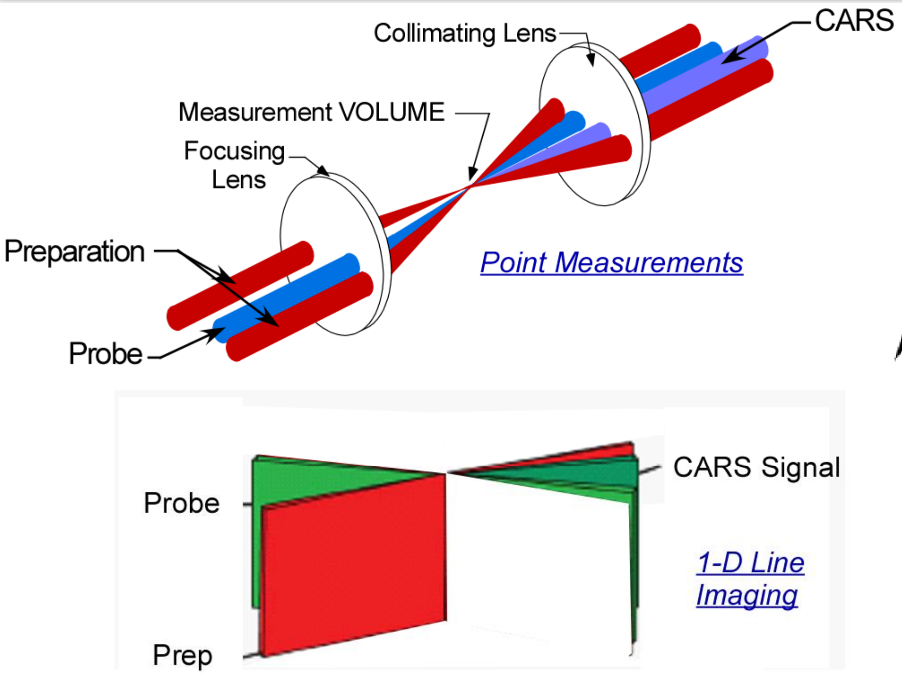


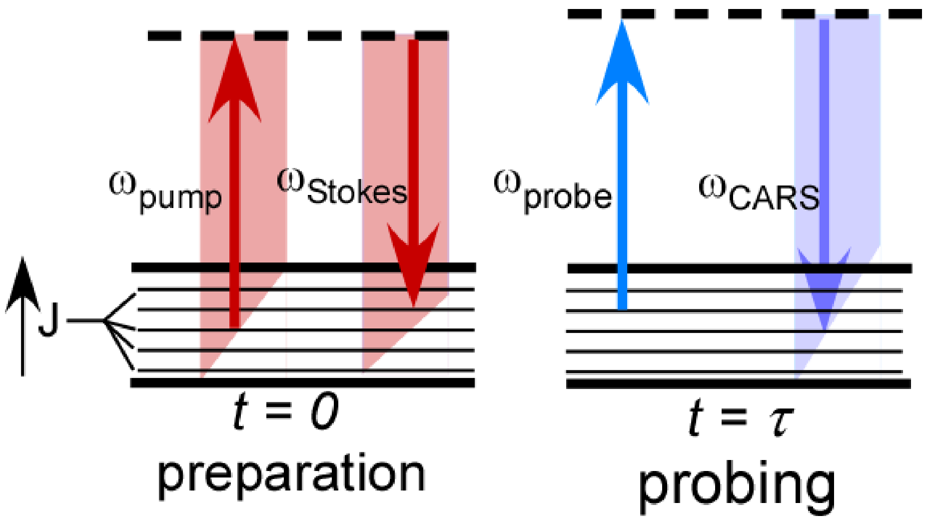
Postmortem samples



- Edges of samples insulated by mounting posts – binder remains
- Bulk of samples experienced complete loss of binder and significant consumption of carbon fibers
- Little, if any structural rigidity across the full range of heat fluxes employed

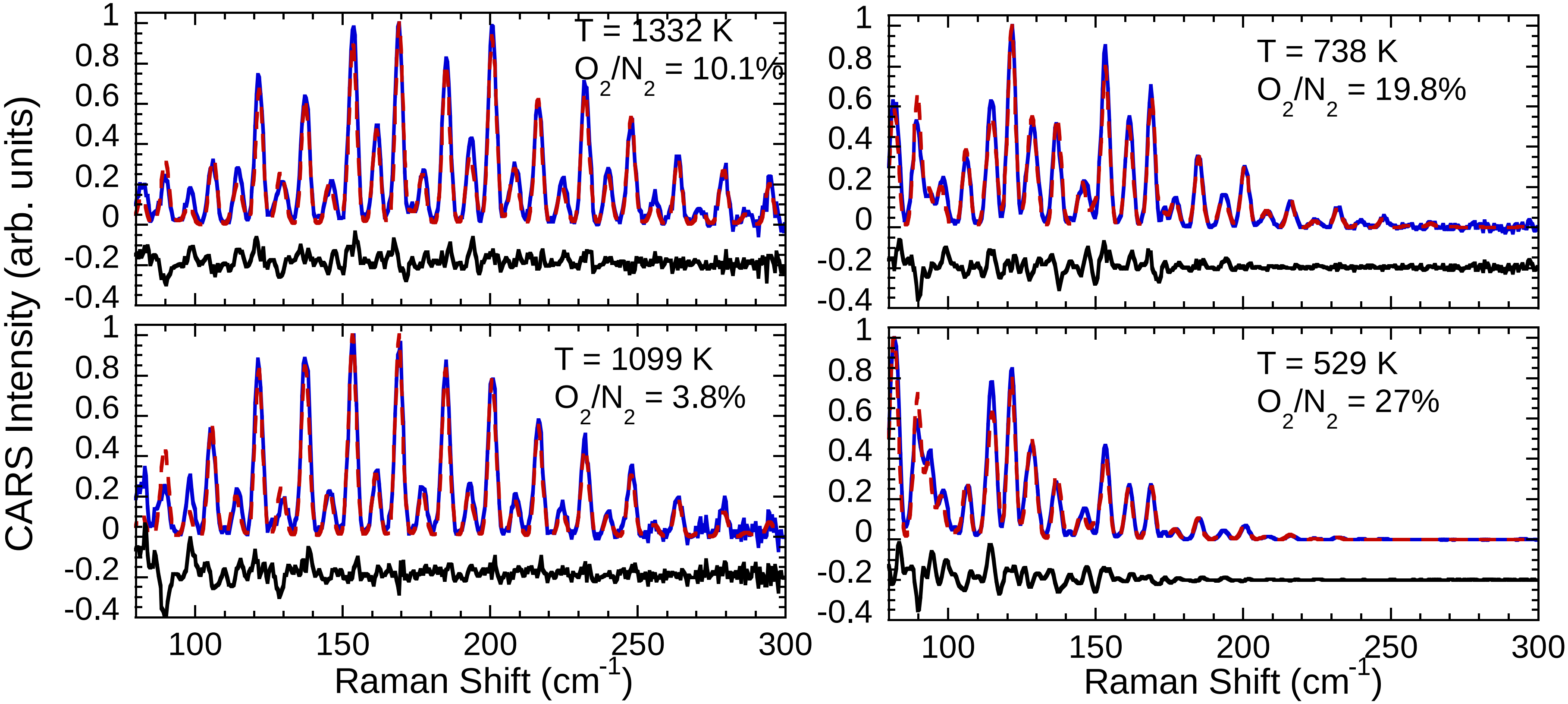
Coherent anti-Stokes Raman scattering (CARS)





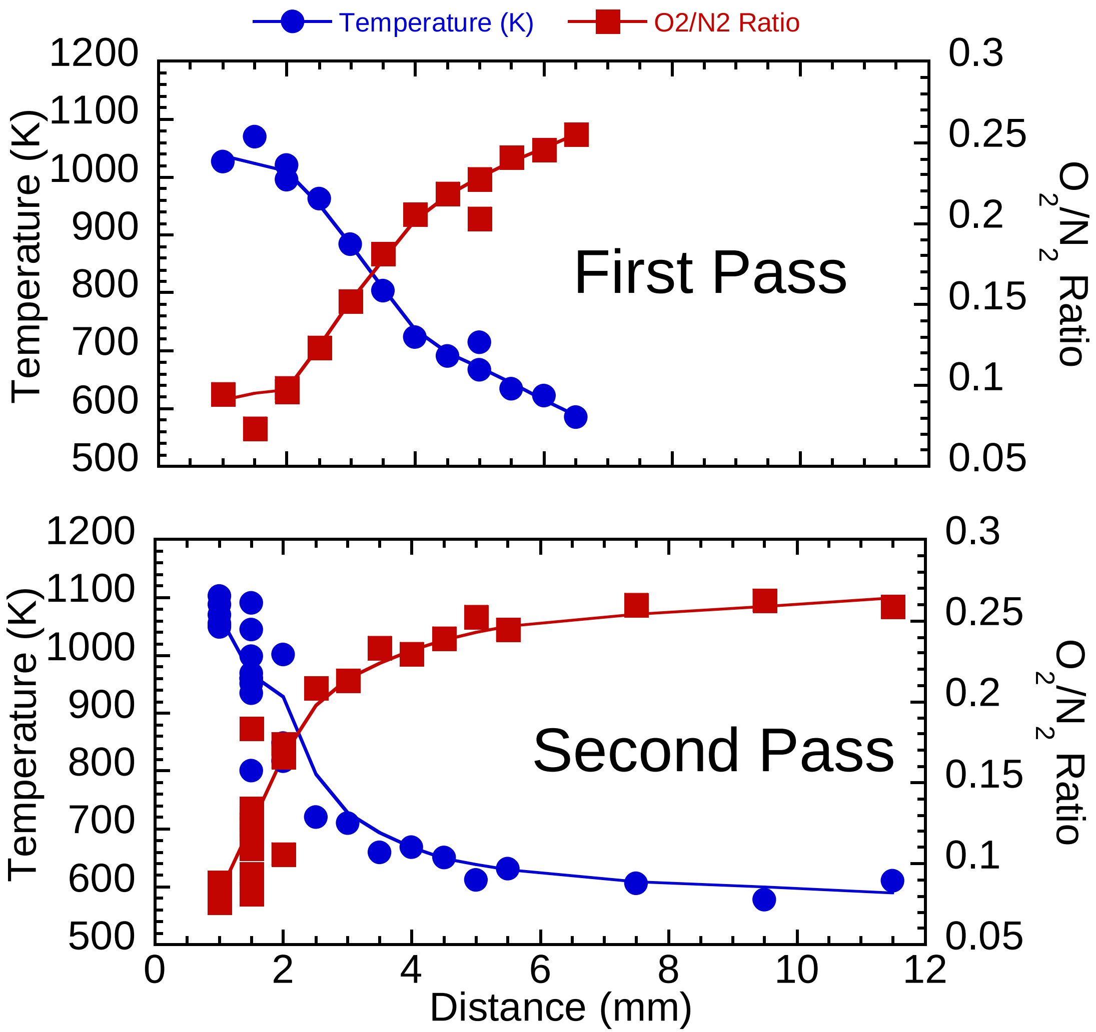
- Laser-based Raman spectroscopic tool
- Essentially infinite temporal resolution ~15-300 ps
- High spatial resolution: $10^{-5} – 10^{-6}$ cm^3
- No conduction or radiation errors
- Noninvasive – insertion errors are eliminated
- Multi-parameter: temperature, species, pressure
- Accuracy ~3-5%
- Precision ~1-2%

CARS spectra: point measurements



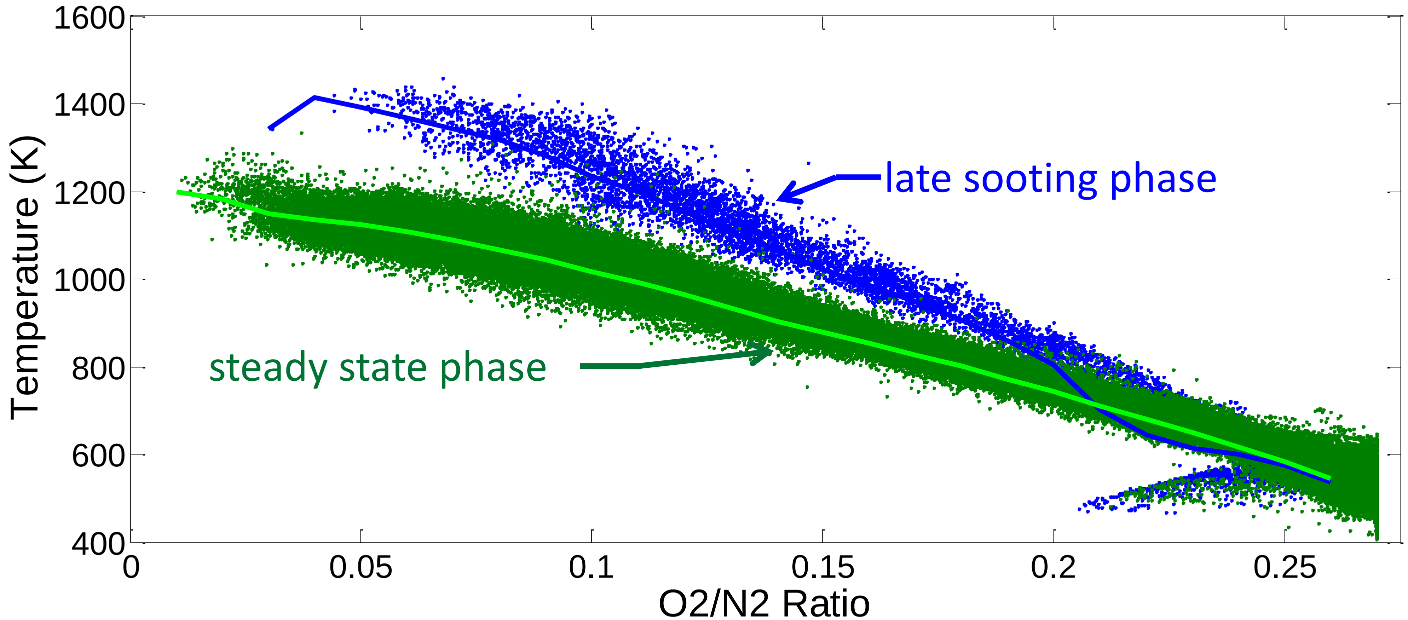
- Recorded at heat flux of $q'' = 68.8$ kW/m^2
- Short-duration probe beam – O_2 lines not individually resolved
- O_2 sensitivity provided by modulation of overall peak "envelope"
- CO_2 information provided below 80 cm^{-1}

Temperature/O_2 Profiles***: time-averaged*** point measurements



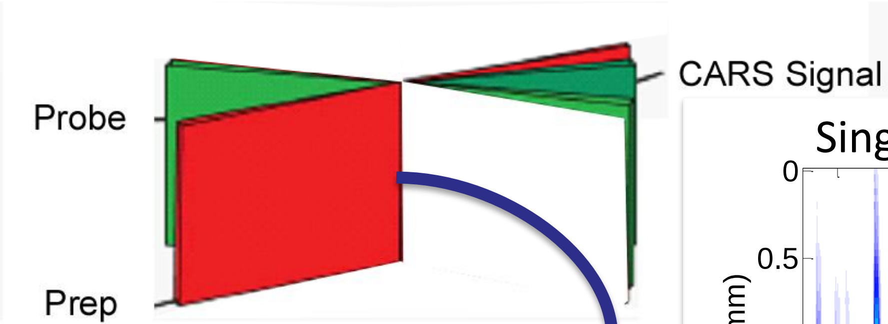
- Conducted at heat flux of q" = 68.8 kW/m^2
- Acquired during steady state phase
- Sampled for 10 seconds (10,000 laser shots) at each point. Average shown here
- Sample/chimney/heater translated vertically
- Two passes moving away from the surface shown here
- Constant surface recession during measurements
- First pass profile shifted 2.5 mm to obtain agreement

Scatter plots obtained from point measurements

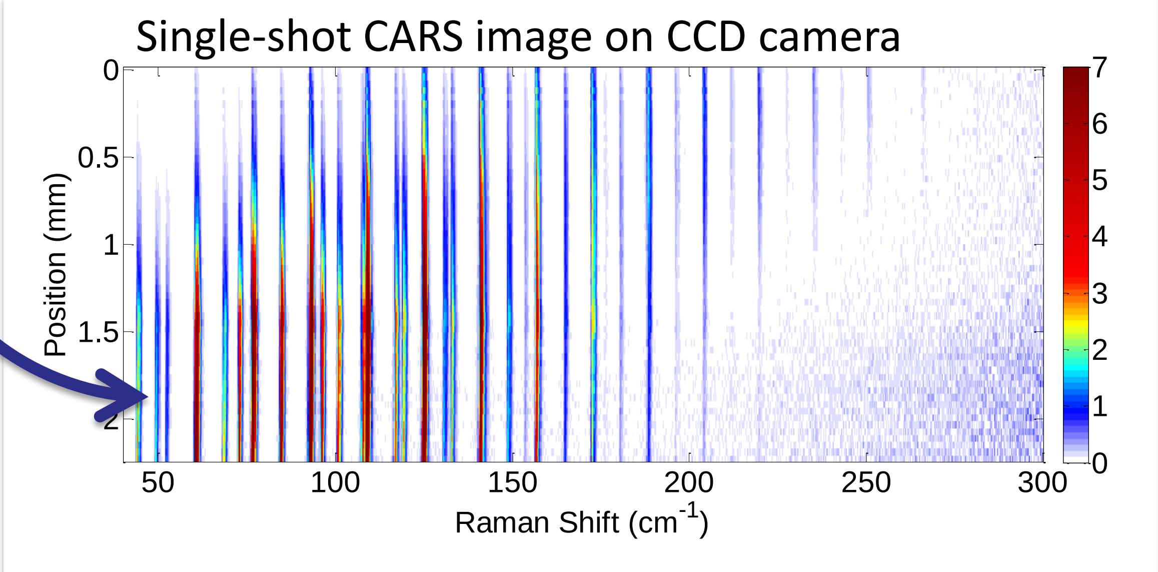


- High-data-rate, 1 kHz, point measurement scheme provides joint T/O_2 statistics
- Late soot phase measurements
  - 10,000 single-laser-shot measurements
  - Single point ~4 mm from sample surface
- Steady-state data record
  - Over 400,000 single-shot measurements
  - Obtained throughout 12-mm near-wall region
- Different scalar state relationships as fuel shifts from binder to fiber/char

1D CARS line-imaging at Sandia/CA

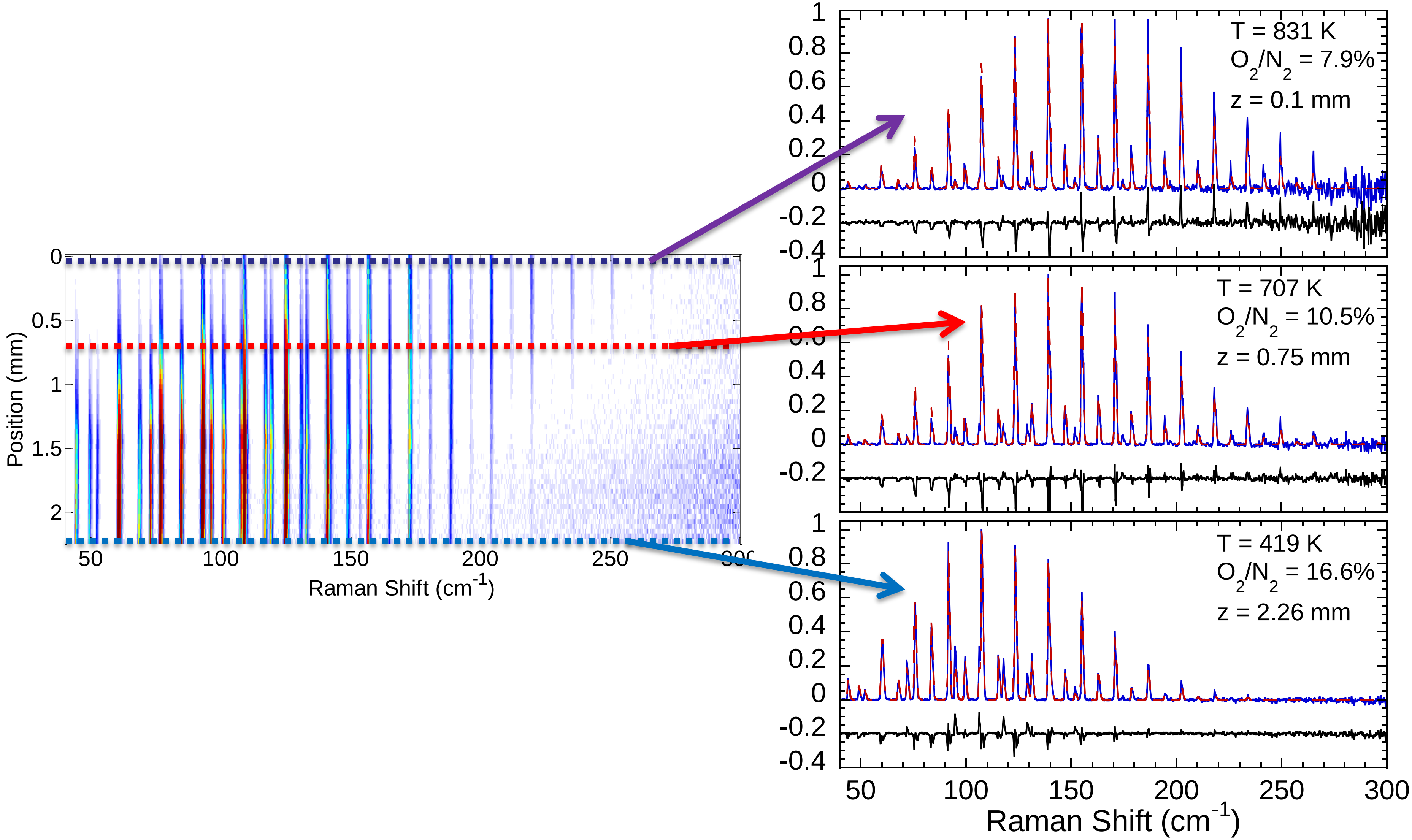


Intersection of light sheets imaged onto spectrometer



- Continuous sample consumption makes spatial correlation of point data difficult
- 1-D CARS scheme allows instantaneous measurement of ***<u>near-surface profiles</u>***
- Data rate reduced to 20 Hz
- Some degradation of uncertainty results from refractive index distortion in images
- Spectra are obtained from “line-outs” on CCD array
- Wall-normal resolution is better than 100 μm

Sample 1-D Spectral Fits



Sample 1-D Temperature/O_2 Profiles, $q'' = 48.5$ kW/m^2

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- Single-shot spatially correlated data reveal instantaneous state of near-wall layer
- "Steady State" portion of experiment
- Data reveal low-temperature consumption of O_2 during consumption of carbon fibers
- Periods of uniform high-temperature "products" (no or little O_2 also observed

Summary and Conclusions (1)

- Hybrid fs/ps CARS been utilized to probe the “near-surface” region of a carbon-epoxy aircraft composite under controlled, uniform heat-flux conditions of 48.5 and 68.8 kW/m^2
- HEXCEL 3501-6 material autoignites in air close to 30 kW/m^2 critical flux previously observed in lab experiments (Quintiere et al. 2007)
- Three-phase process for sample burning/decomposition
  - Heavily sooting phase – combustion of epoxy binder
  - Transitional phase
  - “Steady State” phase – consumption/oxidation of carbon fibers at low temperature
- Simultaneous T/O_2 measurements yield information on near-surface convective heat and oxygen transport – wall location remains uncertain

Summary and Conclusions (2)

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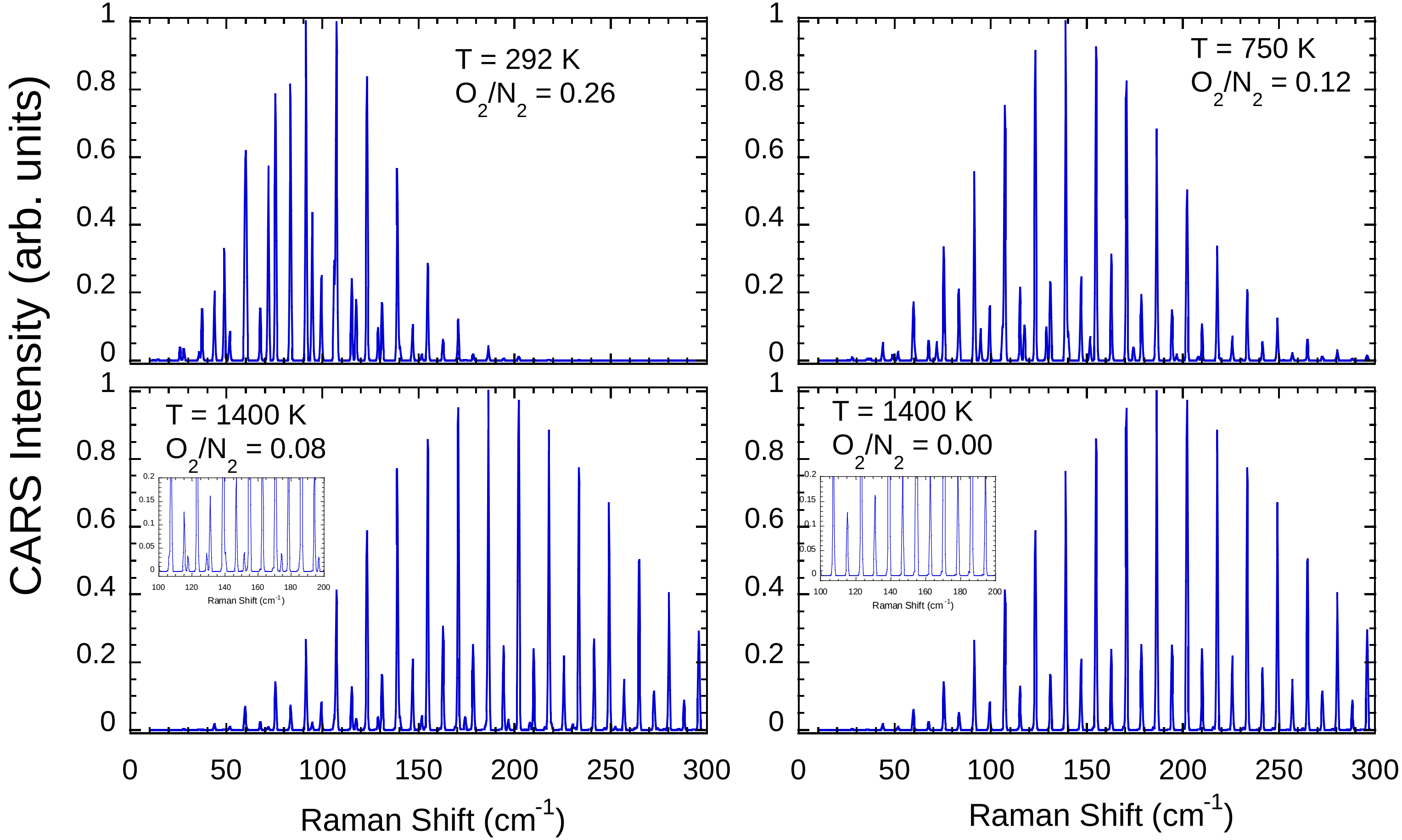
- Point measurements at 1 kHz show two distinct scalar state relationships as process switches from burning of epoxy binder to lower temperature consumption of carbon fibers
- O_2 is present throughout the near-wall region during point measurements -- no observations below detection limit
- One-dimensional CARS imaging provides a complement to point measurements
  - Single-shot spatially correlated data
  - Two different types of qualitative behavior
- Results have been obtained for heat fluxes up to 90 kW/m^2 and are currently being analyzed

CARS spectra – sensitivity to Temperature and O_2/N_2 Ratio



- Spectra reflect the thermal population of rotational states
- Primary contributions are from O_2 and N_2 – although effects of CO and CO_2 are seen
- Calculated spectra (shown here) are fit to measurements to determine T and O_2/N_2

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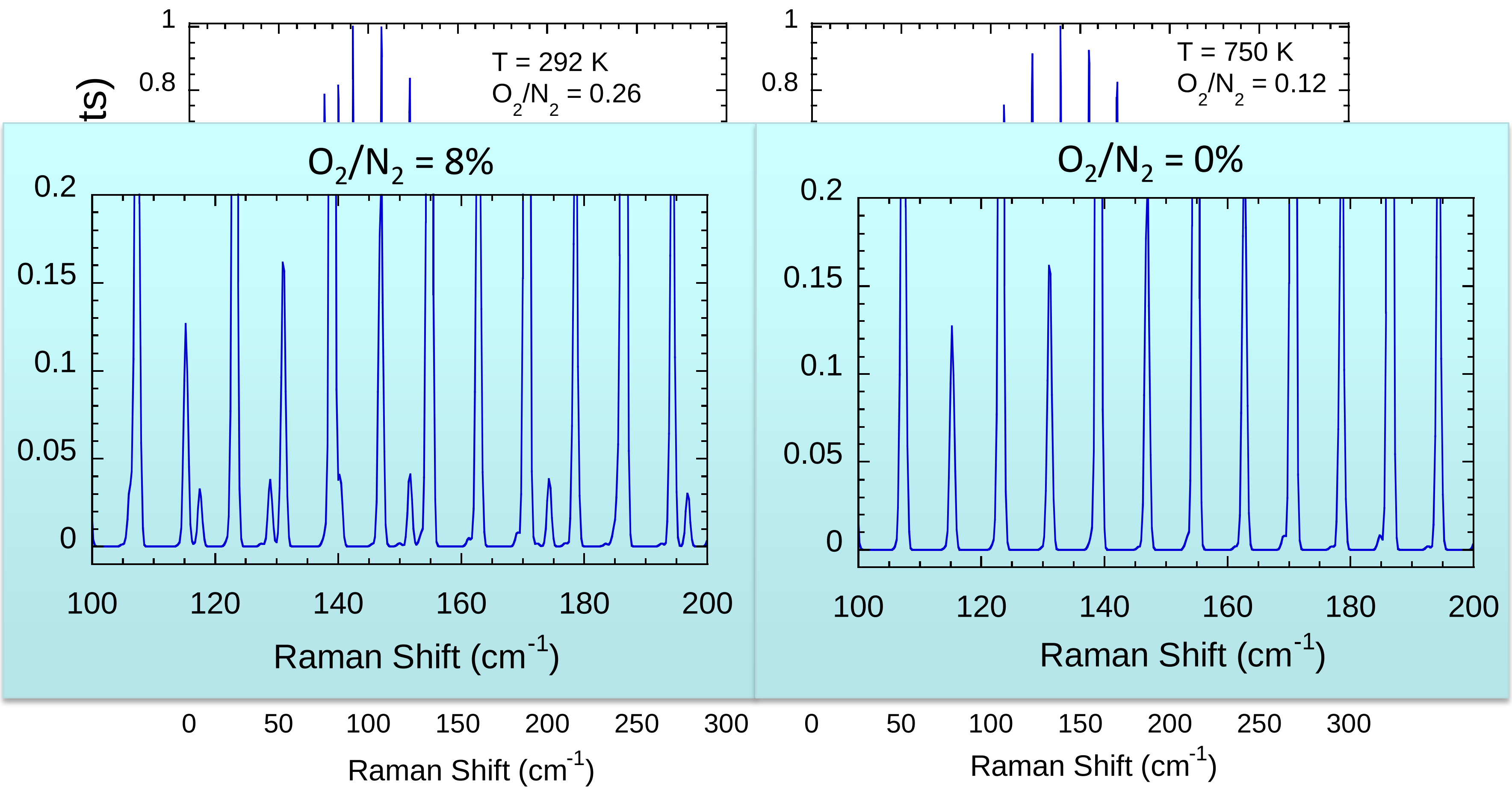

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