Transient Thermal Measurements Using Thermographic Phosphors for Temperature Rate Estimates

P.R. Crim
D.G. Walker
Vanderbilt University

S.W. Allison
Oak Ridge National Laboratory

ASME Summer Heat Transfer Conference
July 21, 2005

Why are we studying this?

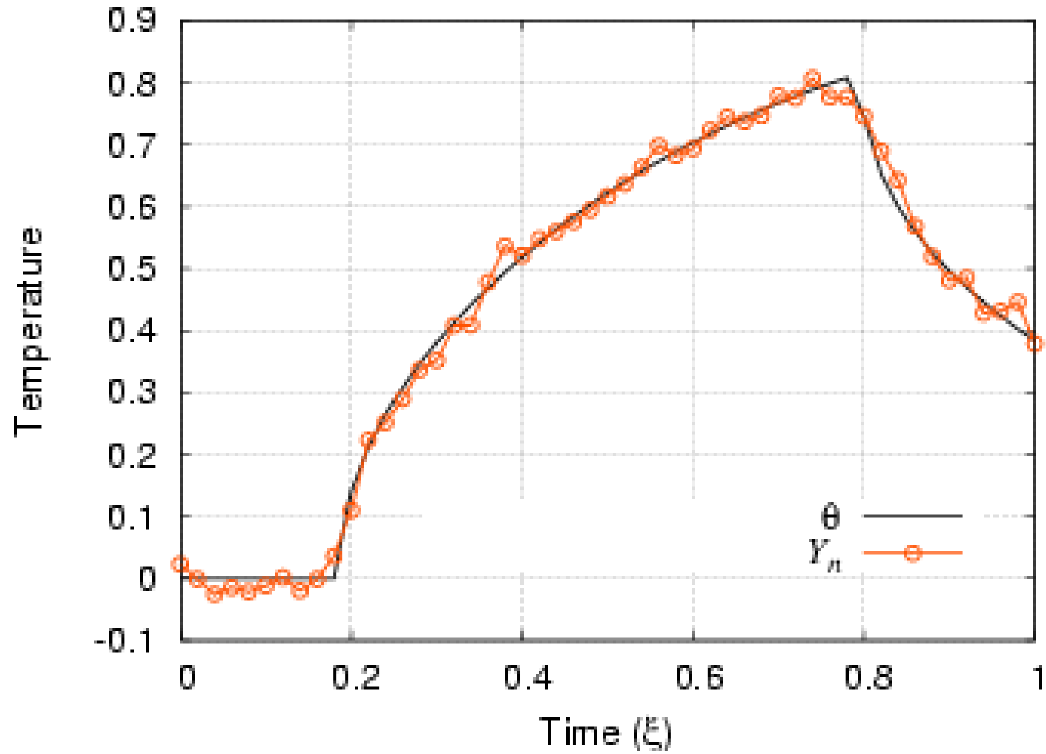
- Want alternative method of determining heat flux
- Current methods
  - Direct measurement – expensive, difficult to calibrate
  - Data reduction using temperature measurements – ill-posed, uncertainty is amplified
    - Temperature measurements are preferred due to reliability and cost
    - This method is known as the inverse heat conduction problem
    - Noise and uncertainty in the data are amplified during differentiation

Inverse heat conduction problem

- Solution for heat flux from temperature measurements is generally an integral equation of the first kind
- Solution for heat flux from heating rate measurements involves an integral equation of the second kind
- Second kind integral equations are inherently more stable than integral equations of the first kind
- Heat flux estimates from heating rate should be more stable with less error

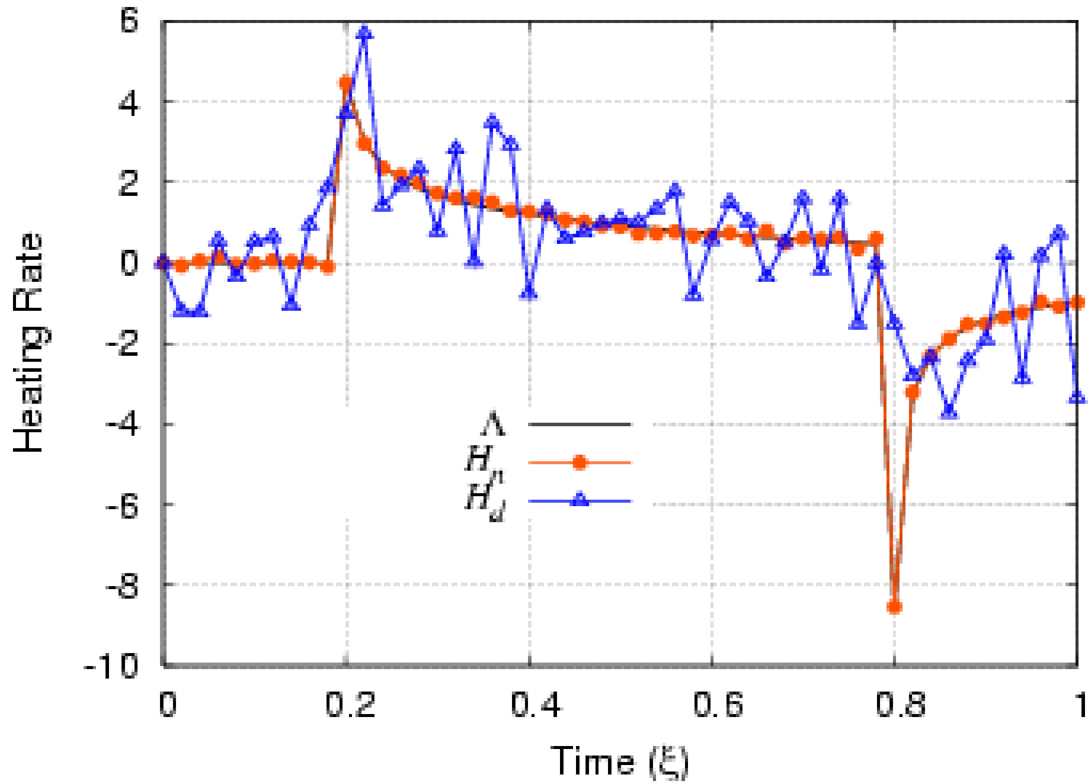
Inverse heat conduction problem

- Forward solution to the conduction problem
  - Temperature
  - Temperature with added noise



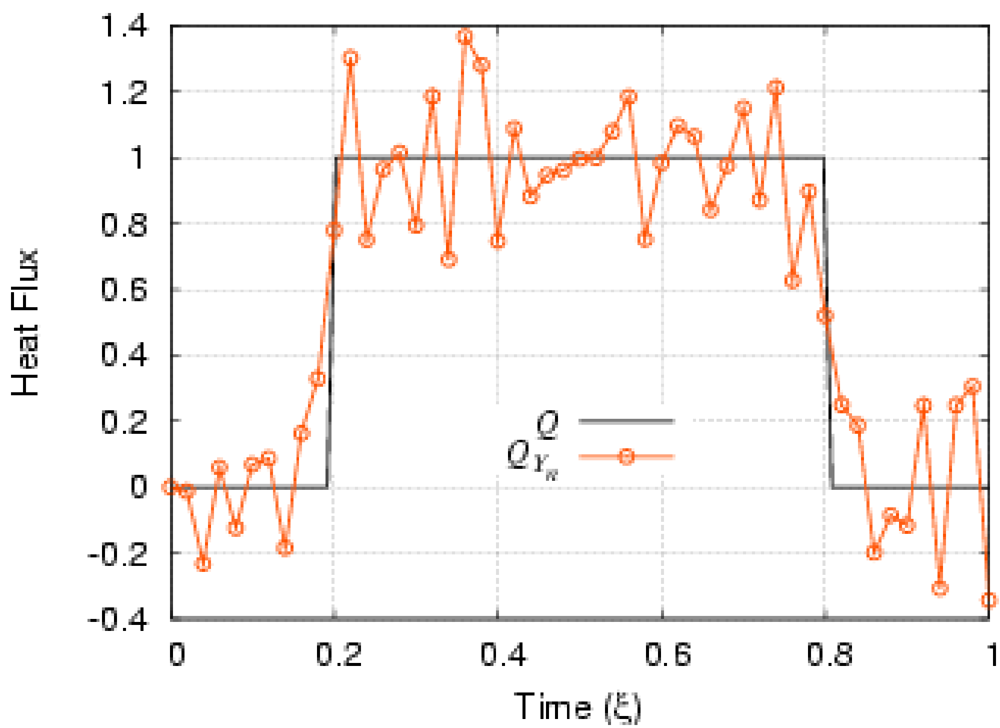
Inverse heat conduction problem

- Heating Rate
  - Exact solution
  - Exact solution with added noise
  - Differentiated measured temperature



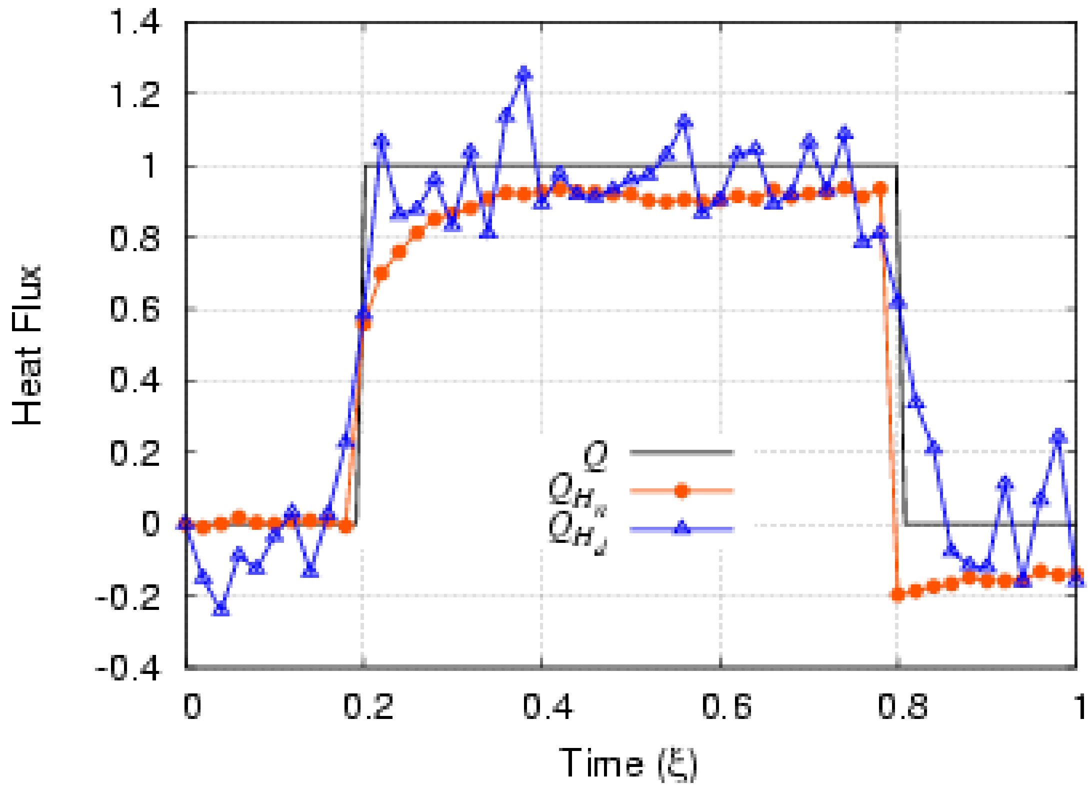
Inverse heat conduction problem

- Heat flux
  - Original square heat flux wave
  - Solution to the IHCP using measured temperature



Inverse heat conduction problem

- Heat flux
  - Original square heat flux wave
  - IHCP solution using measured heating rate
  - IHCP solution using differentiated measured temperature

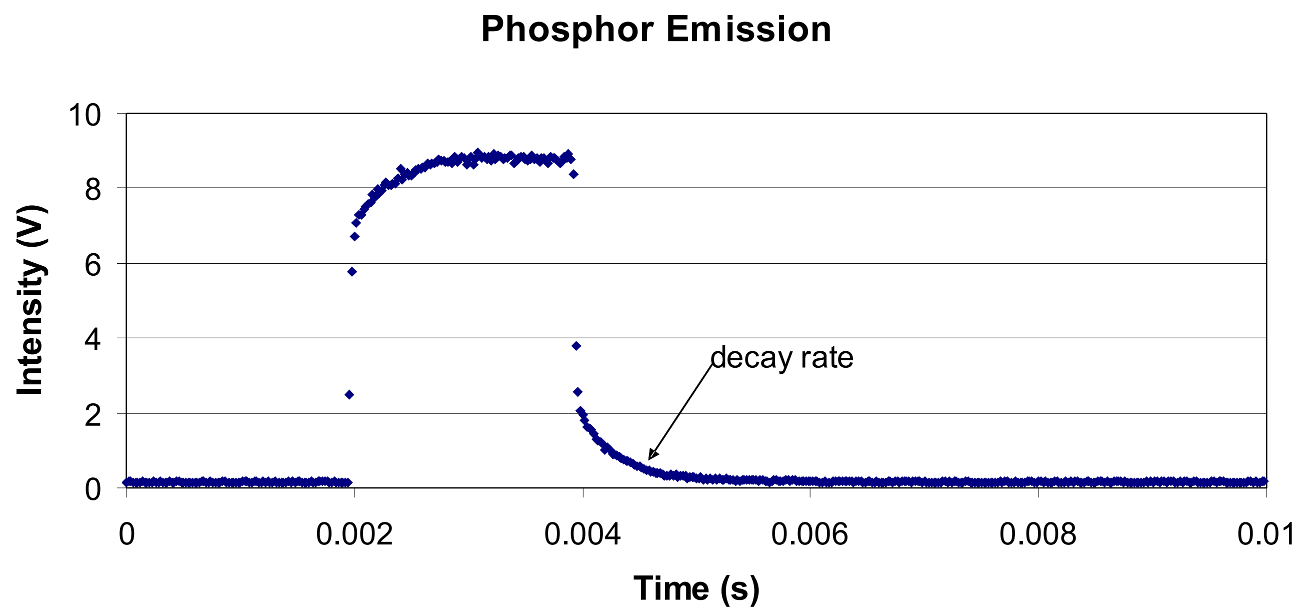


Our New Approach

- Measure a different quantity to make the inverse heat conduction problem more stable
- Estimate heating rate using thermographic phosphors

Thermographic Phosphors

- Rare-earth doped ceramics that fluoresce when exposed to light
- Emission intensity, decay rate, and wavelength are temperature dependent



Mathematical models

- Steady model

$$\frac{I}{I_0} = \exp\left(-\frac{t}{\tau}\right)$$

- Power model

$$\frac{I}{I_0} = \left(\frac{\tau_0}{\tau_0 + \frac{d\tau}{dt}t}\right)^{1/\frac{d\tau}{dt}}$$

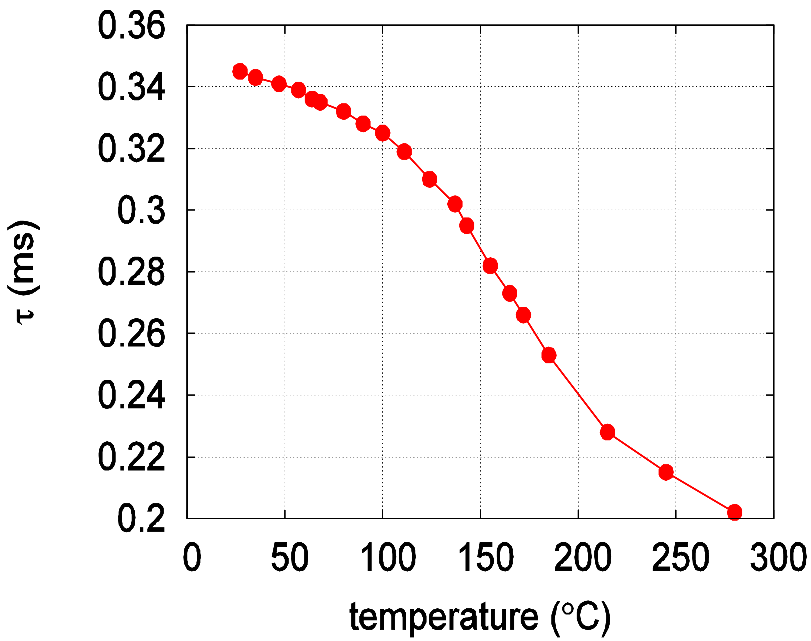
- Exponential model

$$\frac{I}{I_0} = \exp\left(-\frac{t}{\tau_0 + \frac{d\tau}{dt}t}\right)$$

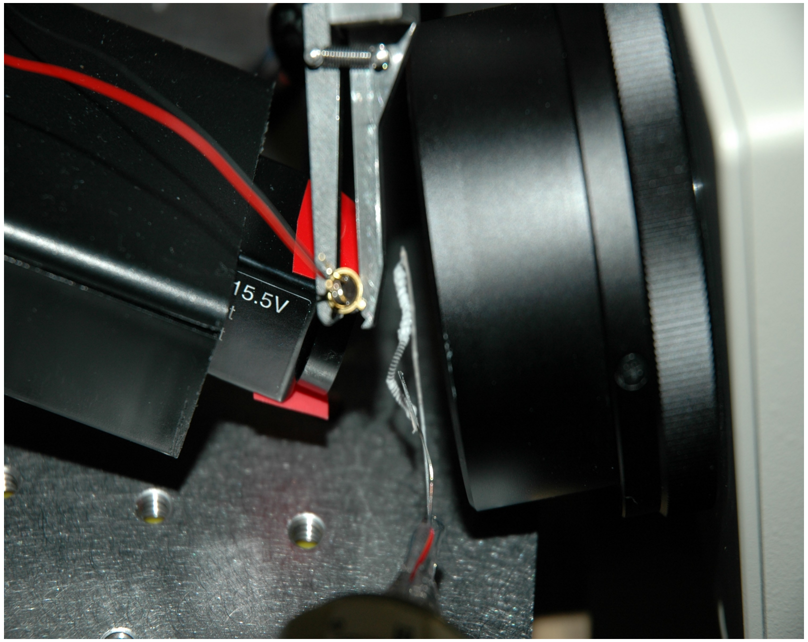
Heating rate

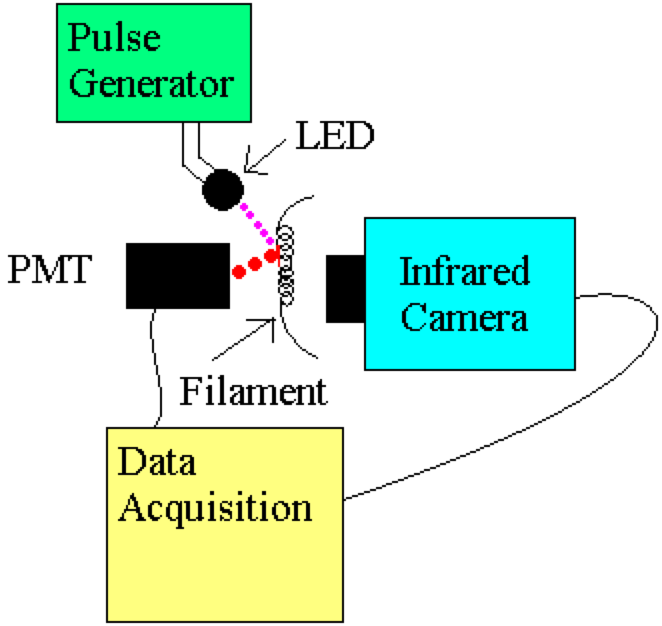
- Chain rule
- Use power model or exponential model to estimate derivative of decay time
- dT/dτ comes from the calibration curve
- Calibration curve gives the relationship between the decay time and temperature
- We used europium-doped lanthanum oxysulfide, $La_2O_2S:Eu$

$$\frac{dT}{dt} = \frac{dT}{d\tau}\frac{d\tau}{dt}$$



Experimental Setup



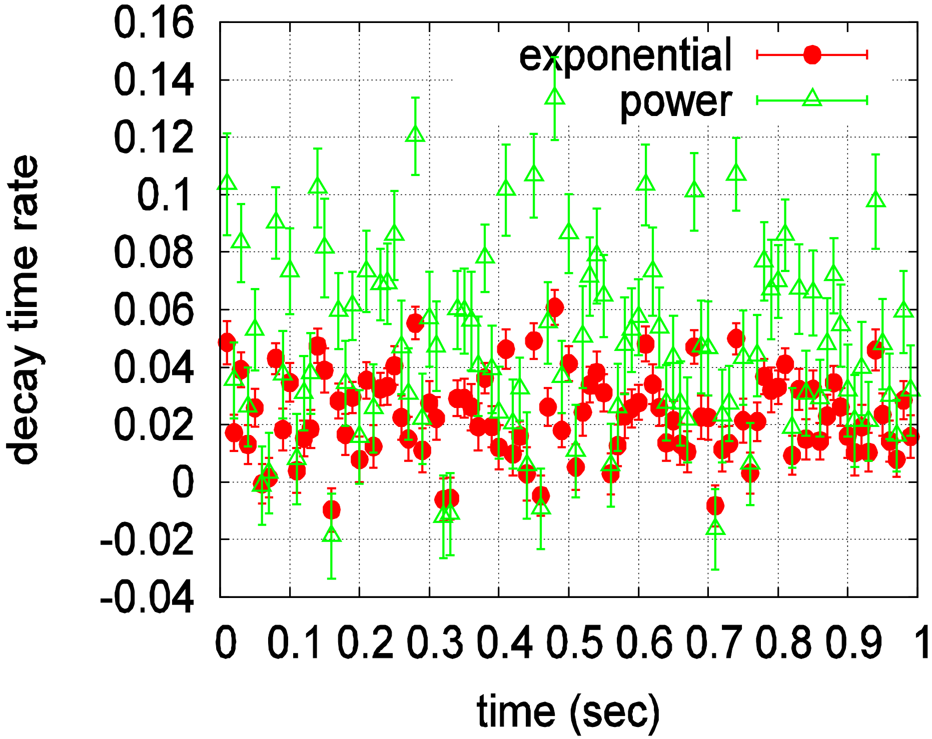


Experiment

- LED excites phosphor at 350nm, phosphor reemits at 630nm
- LED is pulsed at 100Hz, with a 20% duty cycle
- Photomultiplier tube converts emission intensity to voltage
- Voltage data is recorded at 50,000 Hz
- Tungsten filament heats phosphor to 300 °C in one second
- Infrared thermal imaging camera records the temperature of the phosphor as it is heated

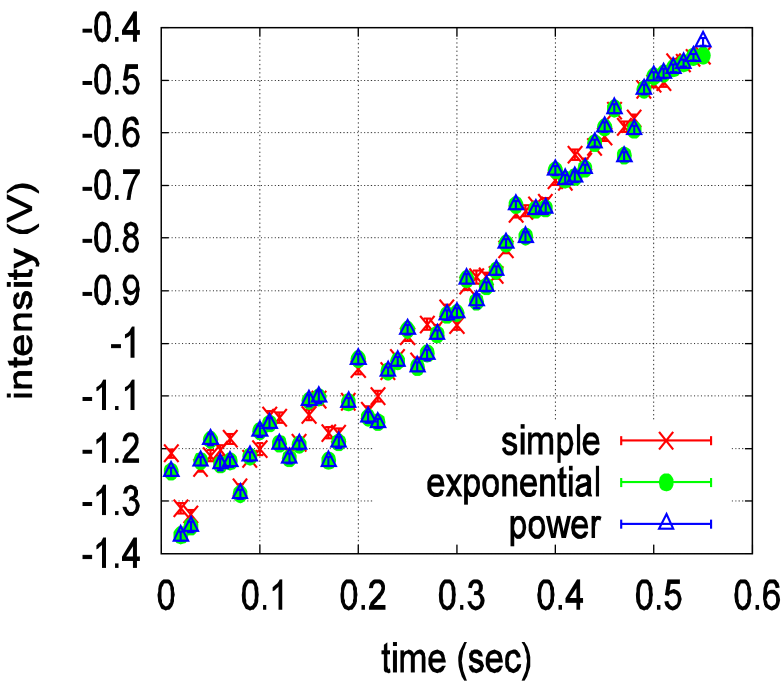
Steady State

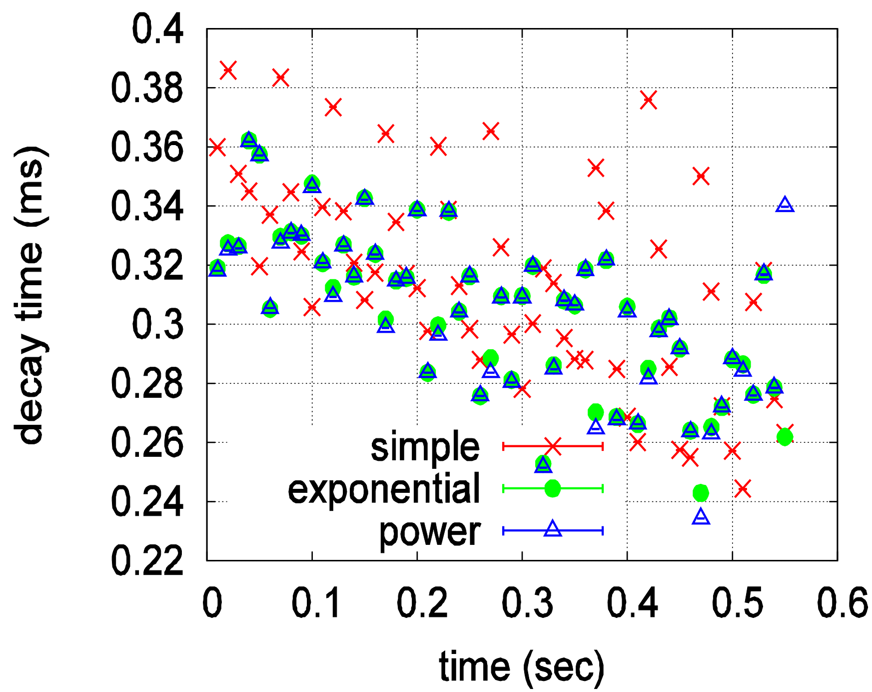
- At steady state, the decay time is constant (~0.345 ms at room temperature)
- The change in decay time should then be constant and zero
- The graph shows constant but non-zero
- Inconsistency in expectations and results suggests a bias in the data



Transient data

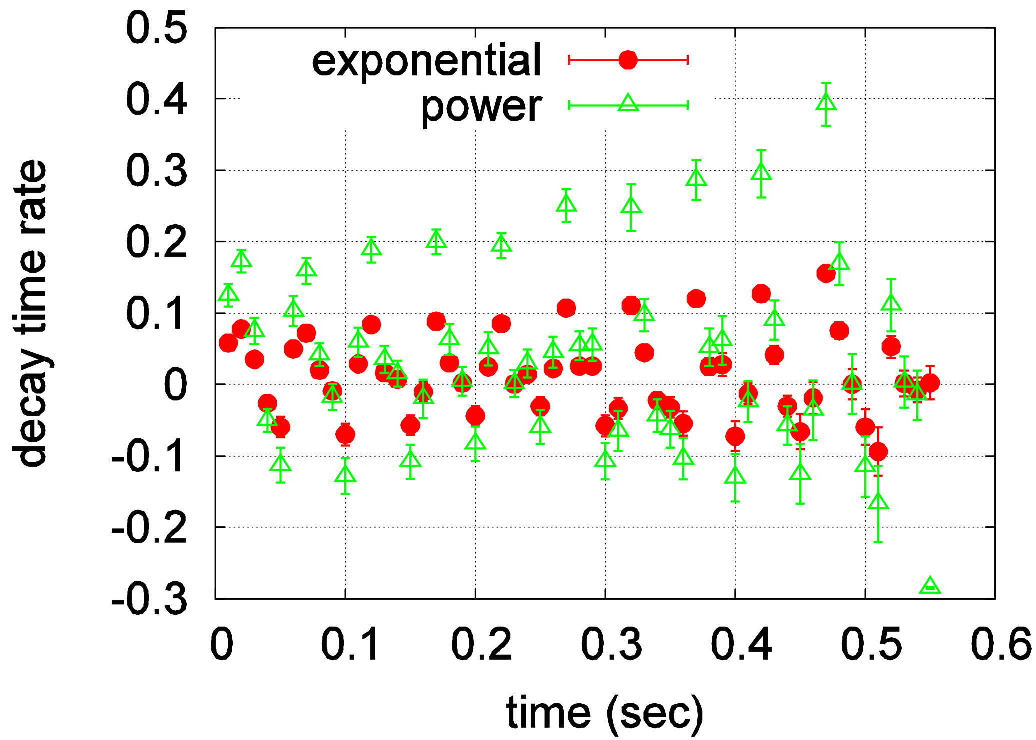
- During heating, emission intensity and decay time decrease





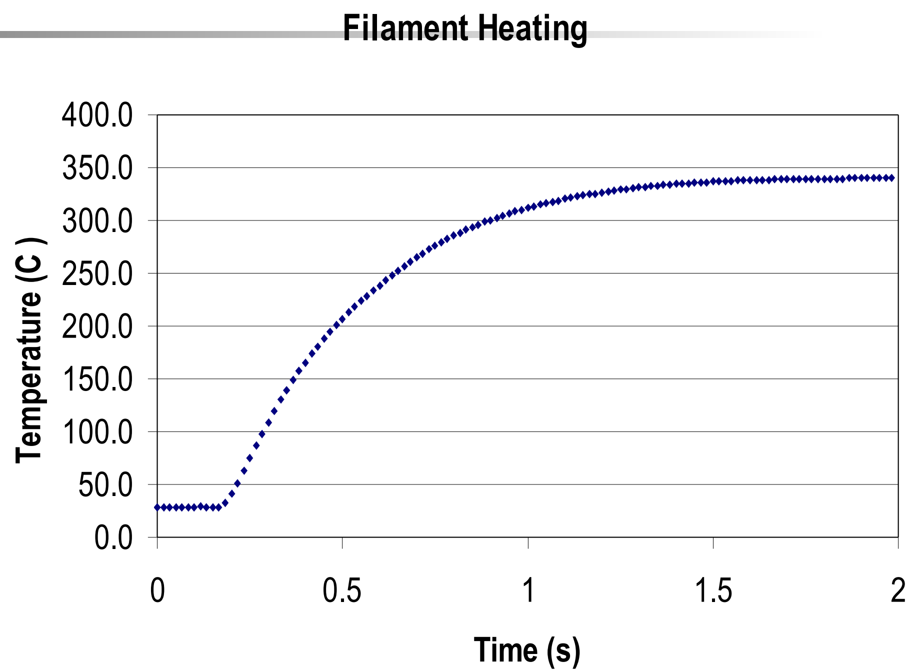
Transient data

- From negative trend in plot of decay time, change in decay time should be negative



Results

- Slope of transient decay time plot ($d\tau$ /dt) is about -0.00013
- At 50˚C, $dT/d\tau$ is about 4,430˚C/s
- From chain rule, heating rate should be about 575˚C/s
- From filament heating plot, $\Delta T/\Delta t$ is about 640˚C/s at 50˚C
- Heating rates agree from decay time data and temperature data



$$\frac{dT}{dt} = \frac{dT}{d\tau}\frac{d\tau}{dt}$$

Conclusions

- Match of intensity and decay time estimates is good for the three models
- Results of change in decay time for steady state and transient conditions suggest periodic bias
- Bias is present, so current results are inconclusive
- Bias must be removed to see results of decay time rate
- Same order of magnitude of heating rate using different methods