Temperature Mapping of Air Film-Cooled Thermal Barrier Coated Surfaces Using Cr-Doped $GdAlO_3$ Phosphor Thermography

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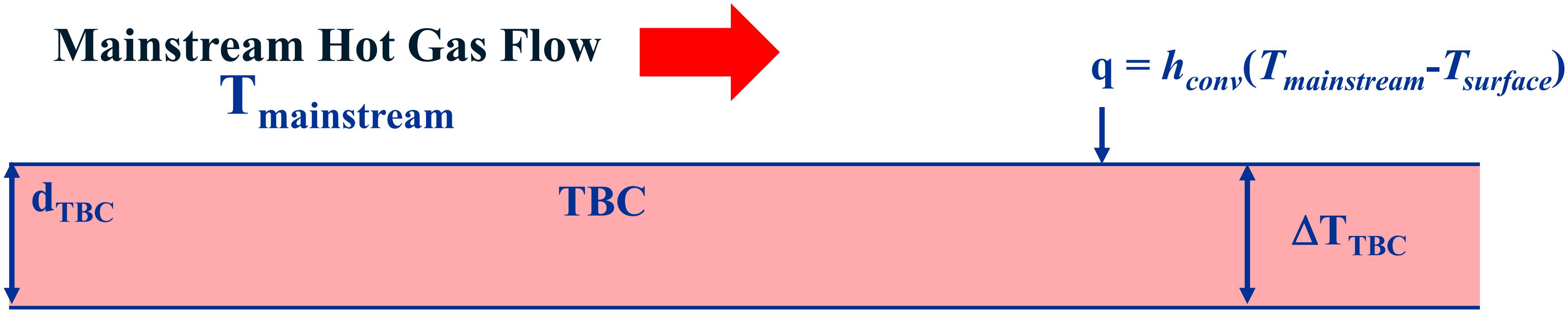
Motivation for Evaluating Combined TBC + Air-Film Cooling

- TBC and air film cooling effectiveness usually studied separately.
- TBC and air film cooling contributions to cooling effectiveness are interdependent and are not simply additive.
- Combined cooling effectiveness must be measured to achieve optimum balance between TBC thermal protection and air film cooling.

Heat Transfer Through TBC

TBC-centric view



$$q = h_{conv}(T_{mainstream} - T_{surface})$$

Heat flux across TBC: $q = -k_{TBC}\frac{dT}{dx} = \frac{k_{TBC}}{d_{TBC}}\left|\Delta T_{TBC}\right|$

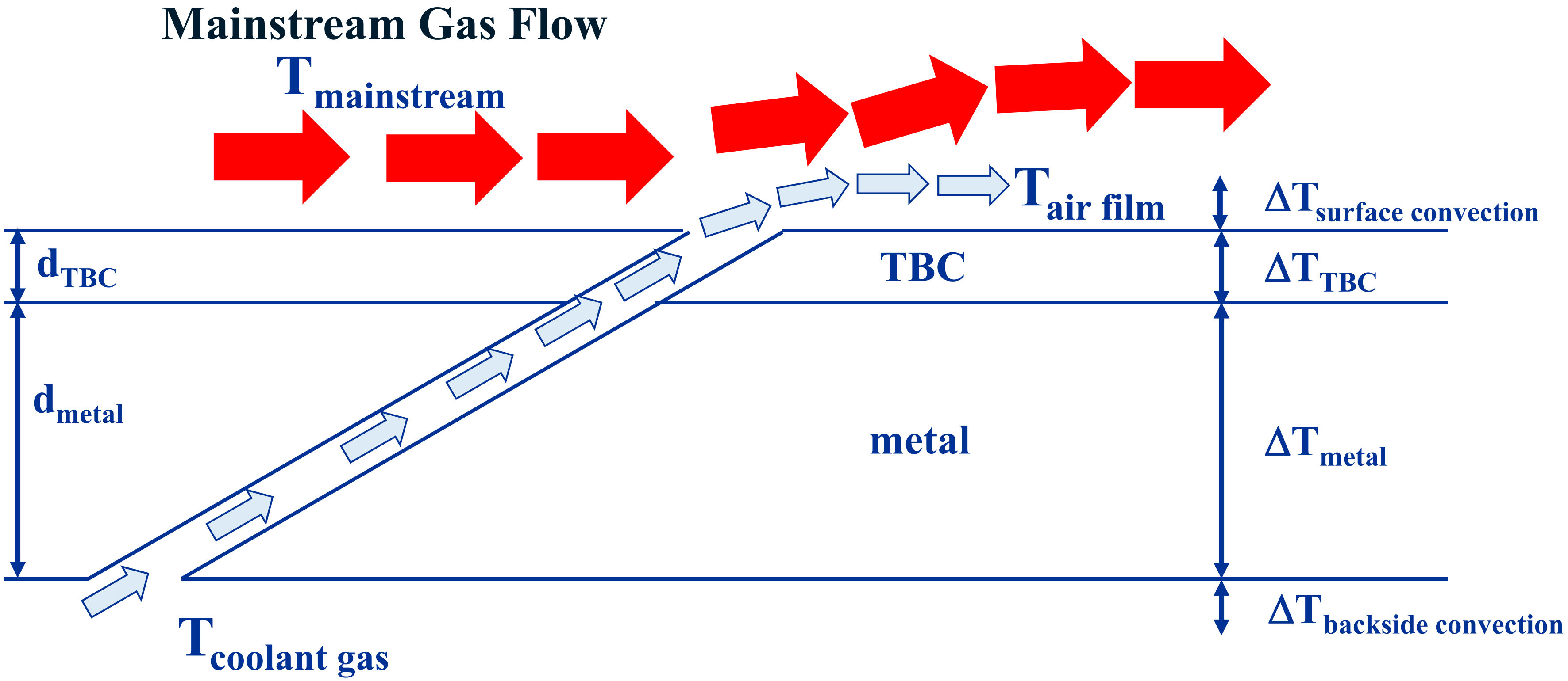
Fixed *q* drives heat transport.

Thermal protection: $T_{mainstream} - T_{metal} = q[\frac{1}{h_{conv}} + \frac{d_{TBC}}{k_{TBC}}]$

For $d_{TBC}/k_{TBC} >> 1/h_{conv}$, thermal protection linearly increases with d_{TBC}/k_{TBC}

Heat Transfer Through Turbine Blade/Vane

overall heat transfer view



Total heat flux: $q = U[T_{mainstream} - T_{coolant}] = U\Delta T_{total}$

Overall heat transfer coefficient: $\dfrac{1}{U} = \dfrac{1}{h_{conv}} + \dfrac{d_{TBC}}{k_{TBC}} + \dfrac{d_{metal}}{k_{metal}} + \dfrac{1}{h_{backside}}$

Cooling effectiveness: (fraction of ΔT_{total} that occurs above metal surface)

$$\Phi = \frac{T_{mainstream} - T_{metal}}{\Delta T_{total}} = \frac{\dfrac{1}{h_{conv}} + \dfrac{d_{TBC}}{k_{TBC}}}{\dfrac{1}{h_{conv}} + \dfrac{d_{TBC}}{k_{TBC}} + \dfrac{d_{metal}}{k_{metal}} + \dfrac{1}{h_{backside}}}$$

Increasing d_{TBC} & decreasing k_{TBC} will have diminishing returns, especially with air film cooling.

TBC & Air-Film Contributions to Cooling Effectiveness

TBC contribution:

$$\Phi_{TBC} = \frac{\dfrac{d_{TBC}}{k_{TBC}}}{\dfrac{1}{h_{conv}^{eff}} + \dfrac{d_{TBC}}{k_{TBC}} + \dfrac{d_{metal}}{k_{metal}} + \dfrac{1}{h_{backside}}}$$

- Air film cooling greatly reduces effective h_{conv} and therefore greatly reduces Φ_{TBC}
- Air film cooling greatly reduces q and therefore ΔT_{TBC}
- TBC does not carry significant penalty for engine efficiency.

Air film cooling contribution:

$$\Phi_{airfilm} = \frac{\dfrac{1}{h_{conv}^{eff}}}{\dfrac{1}{h_{conv}^{eff}} + \dfrac{d_{TBC}}{k_{TBC}} + \dfrac{d_{metal}}{k_{metal}} + \dfrac{1}{h_{backside}}}$$

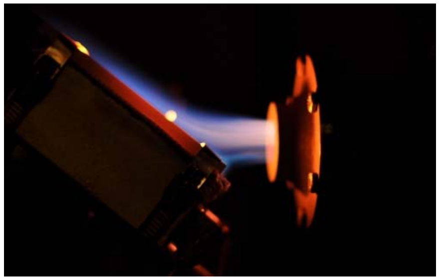
- TBC reduces $\Phi_{airfilm}$
- Putting insulator between air film and metal decreases effectiveness of air film cooling.
- Air film cooling carries significant penalty for engine efficiency.

- $\Phi_{overall} > \Phi_{TBC}$, $\Phi_{airfilm}$ (TBC, air film cooling always beneficial)
  - But returns can be diminishing.
- TBC is better for reducing air film cooling requirements (increasing engine efficiency) than increasing temperature capability of air film cooled component.
- Experimental measurements of combined TBC + air film cooling effectiveness are needed to evaluate TBC/air-film-cooling tradeoffs.

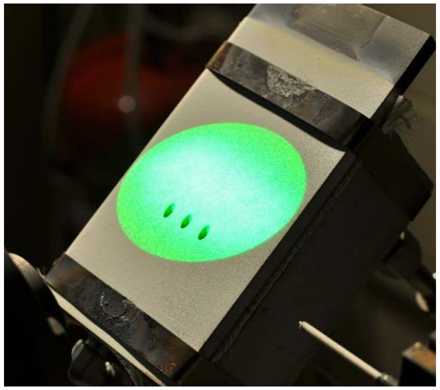
Objectives

- Experimentally map (2D) cooling effectiveness of air film cooling of TBC-coated surfaces.
  - Cooling effectiveness at the TBC surface (to be presented today)
  - Cooling effectiveness at the metal surface (future)
- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperature
  - Blowing ratio (cooling air flow)
- Examine interplay between air film cooling, backside impingement cooling, and through-hole convective cooling for TBC-coated substrate.

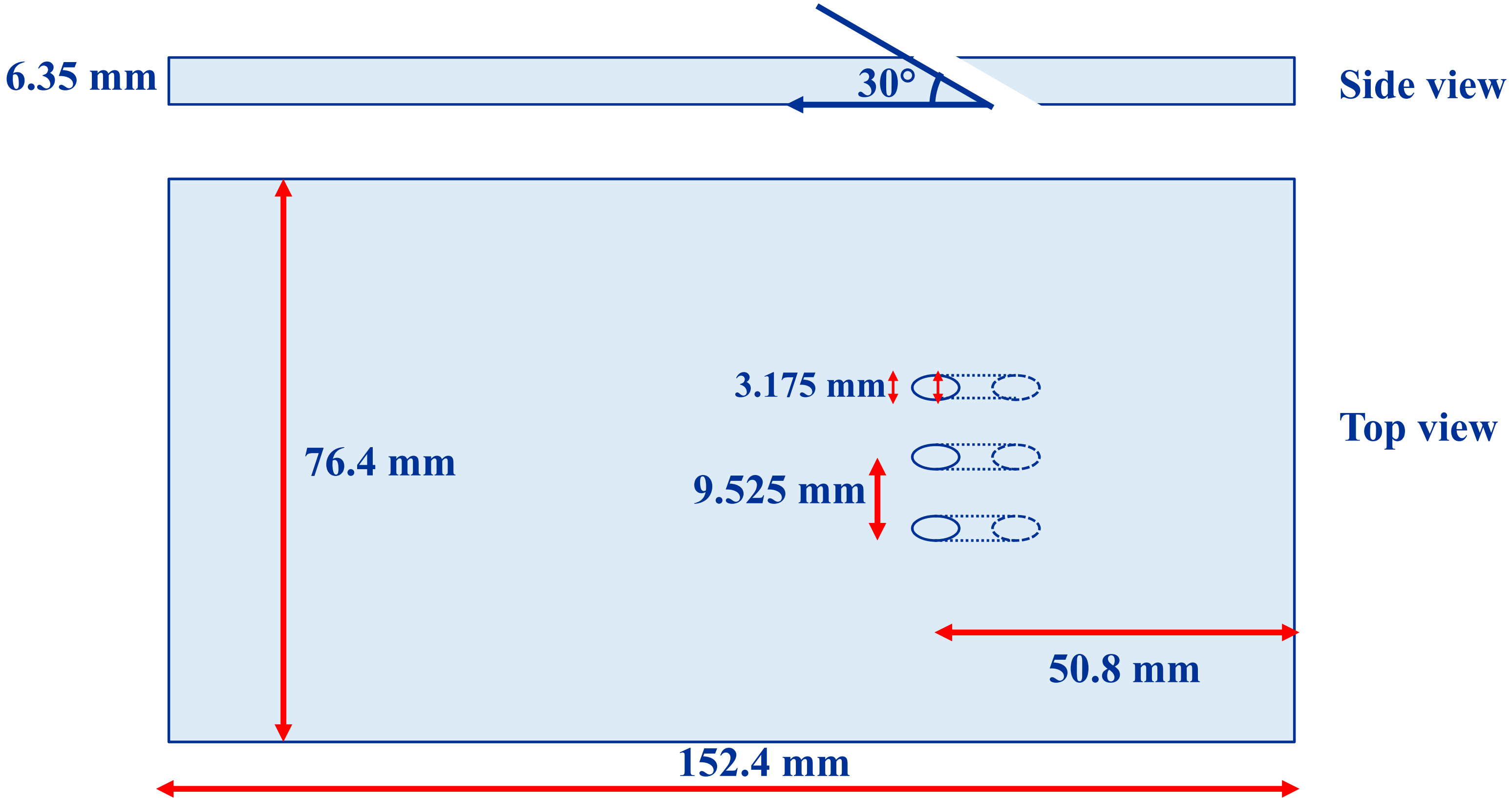
Approach

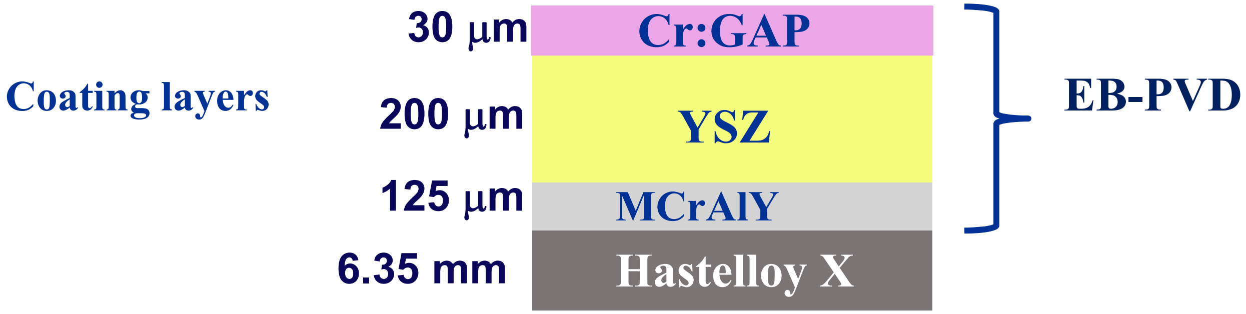


- Perform measurements in NASA GRC Mach 0.3 burner rig.
  - Vary flame temperature and blowing ratio.
- Perform measurements on TBC-coated superalloy plate.
  - 200 μm EB-PVD YSZ on Hastelloy X plate with MCrAlY bond coat
- Use scaled-up cooling hole geometry.
- Perform 2D temperature mapping using Cr-doped $GdAlO_3$ (Cr:GAP) phosphor thermometry.
  - $GdAlO_3$ exhibits orthorhombic perovskite crystal structure: gadolinium aluminum perovskite (GAP).
  - Ultrabright Cr:GAP luminescence emission enable surface temperature mapping using luminescence lifetime imaging by simply broadening the excitation laser beam to cover the region of interest.
  - Unbiased by emissivity changes and reflected radiation. ✓
  - Can be utilized for subsurface temperature mapping (future). ✓
  - Only applicable to steady state temperatures. ✗
- Convert temperature maps into cooling effectiveness maps.



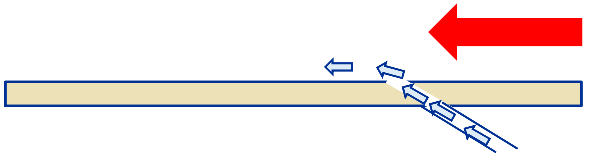
Cooling Hole Plate Geometry





Cooling Effectiveness Measurements

Conventional Air Film Cooling Effectiveness Test



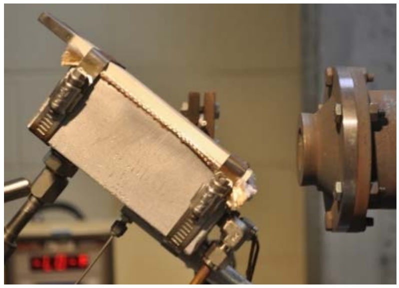
Ducted uniform mainstream flow

- Uniform mainstream flow (velocity & temperature)
- Typical surface temperatures: < 100°C
- Pure air film cooling
  - No heat flux (insulating substrate)
  - No backside impingement cooling
- Measure adiabatic air film cooling effectiveness, η

$$\eta = \frac{T_{mainstream} - T_{surface}^{adiabatic}}{T_{mainstream} - T_{coolant\ exit}}$$

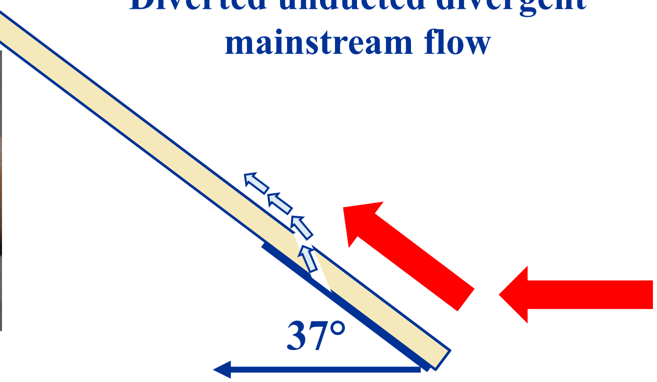
- η is a fundamental characterization of air film cooling effectiveness
- Measure η as a function of blowing ratio, M

$$M = \frac{\rho_{coolant} v_{coolant}}{\rho_{mainstream} v_{mainstream}}$$



Burner Rig Air Film Cooling Effectiveness Test

Diverted unducted divergent mainstream flow



- Divergent mainstream flow
- Typical temperatures: 600-1100°C
- Air film + backside impingement + thru-hole convection
- Measure overall surface cooling effectiveness, η'

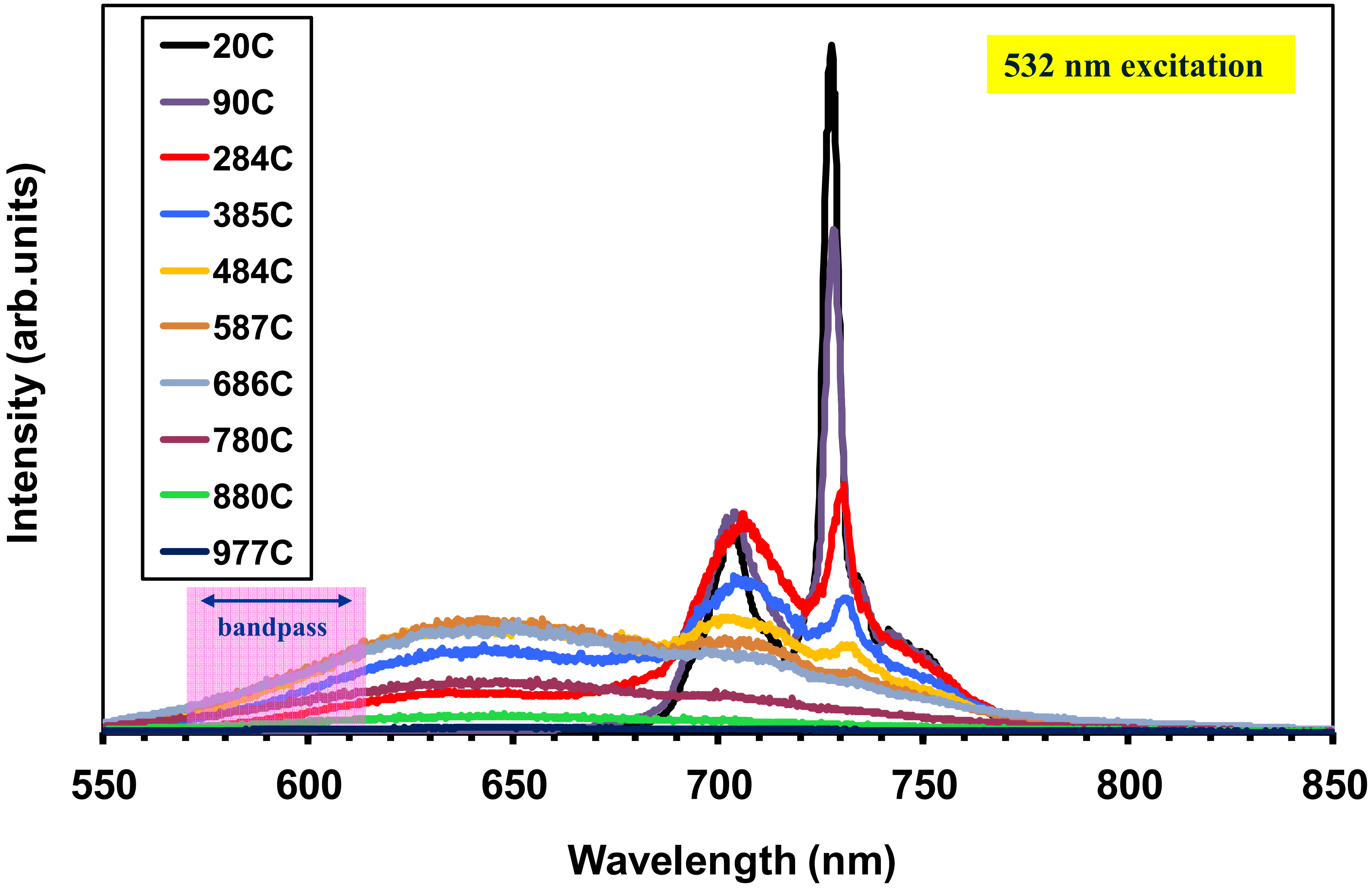
$$\eta' = \frac{T_{uncooled} - T_{cooled}}{T_{uncooled} - T_{coolant\ enter}}$$

- η' is a nonfundamental but realistic characterization of combined surface cooling effects
- Measure η as a function of M

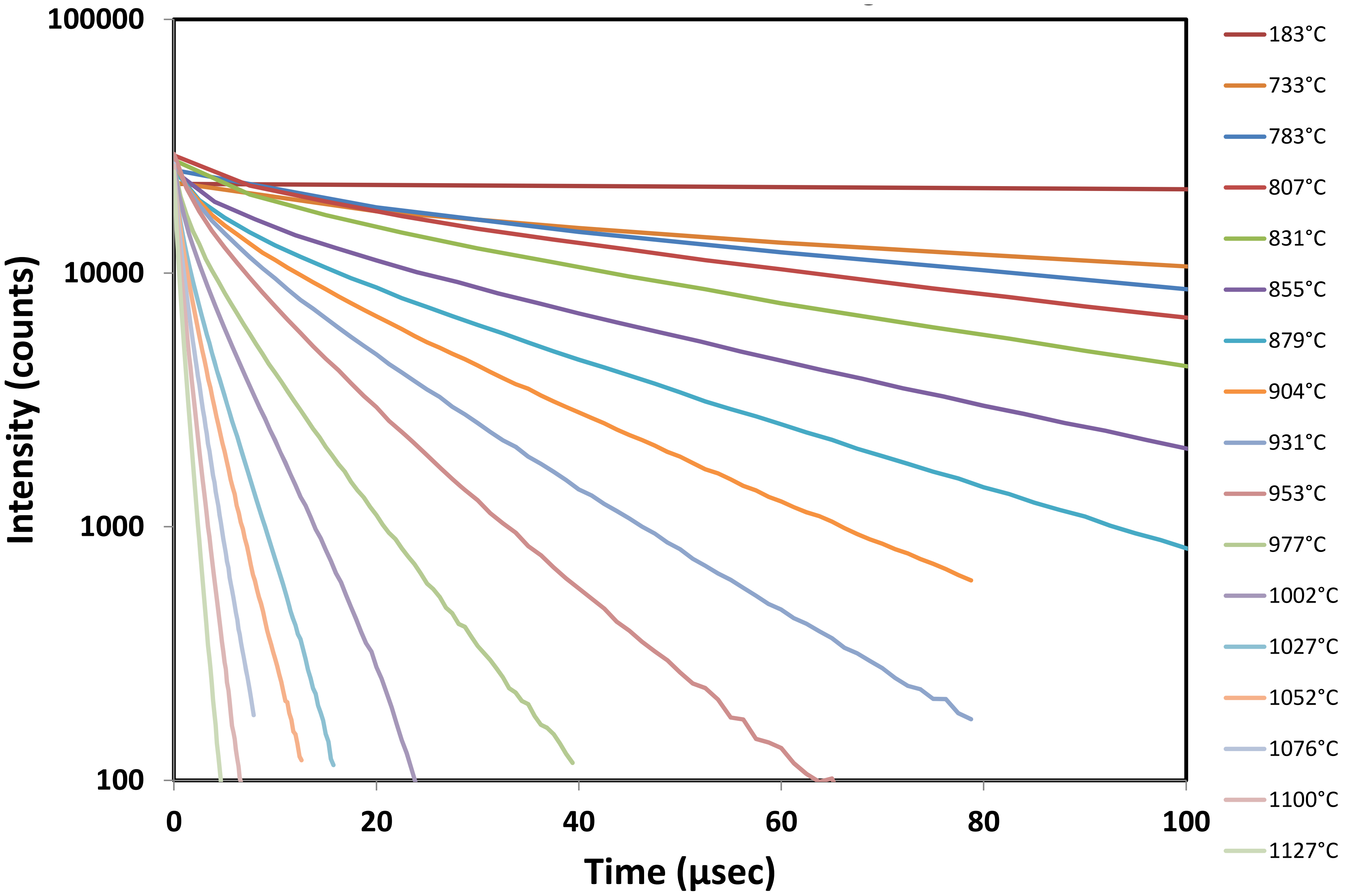
$$M' = \frac{\rho_{coolant} v_{coolant}}{\rho_{mainstream} v_{mainstream}^{\max}}$$

Demonstrating Temperature Measurement Capability

Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck
Temperature Dependence



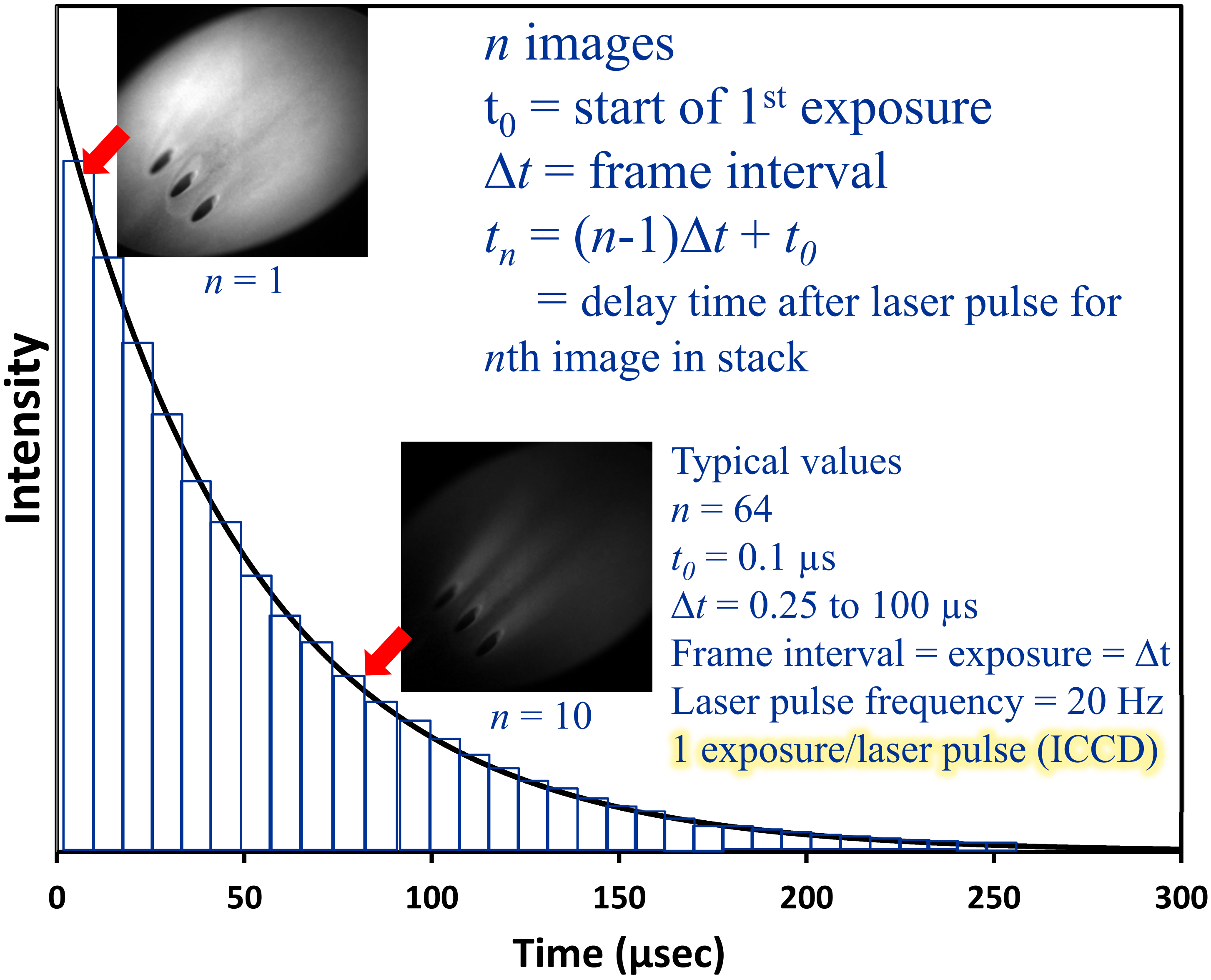
Luminescence Decay Curves Obtained by Time-Gated Imaging



2D Temperature Mapping by Luminescence Lifetime Imaging

- Image stack collection
- Background subtraction
- Data filtering
- Pixel by pixel lifetime analysis
  - Fitting window selection
  - Fit to exponential decay
  - Removing flame burst outliers
  - Use calibration curve to convert decay time to temperature
  - Convert temperature to cooling effectiveness

Luminescence Lifetime Image Stack



n images

t_0 = start of 1st exposure

Δt = frame interval

$t_n = (n-1)\Delta t + t_0$

= delay time after laser pulse for nth image in stack

Typical values

$n = 64$

$t_0 = 0.1$ µs

Δt = 0.25 to 100 µs

Frame interval = exposure = Δt

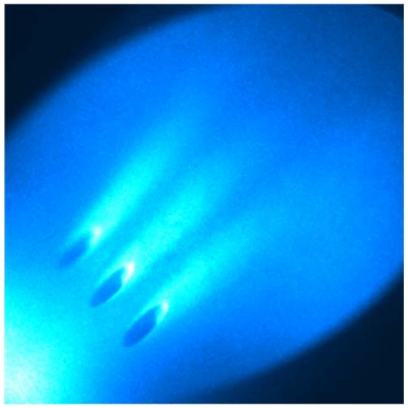
Laser pulse frequency = 20 Hz

1 exposure/laser pulse (ICCD)

2D Temperature Maps from Luminescence Lifetime Imaging

- Multi-step procedure:
  - Step 1: Remove thermal radiation background from each image collected.

Luminescence before background subtraction



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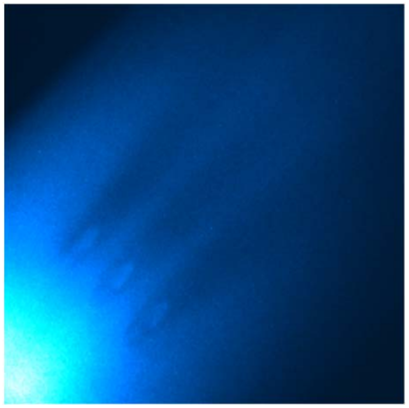
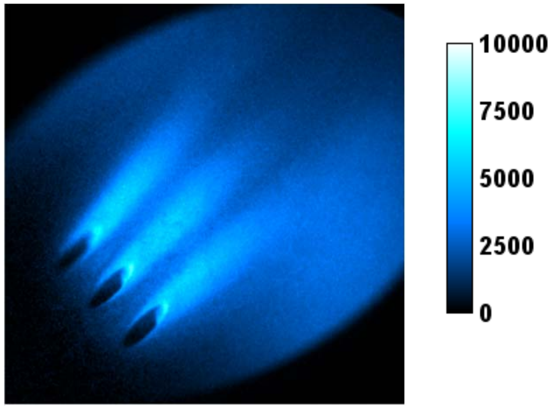
Background (no laser)

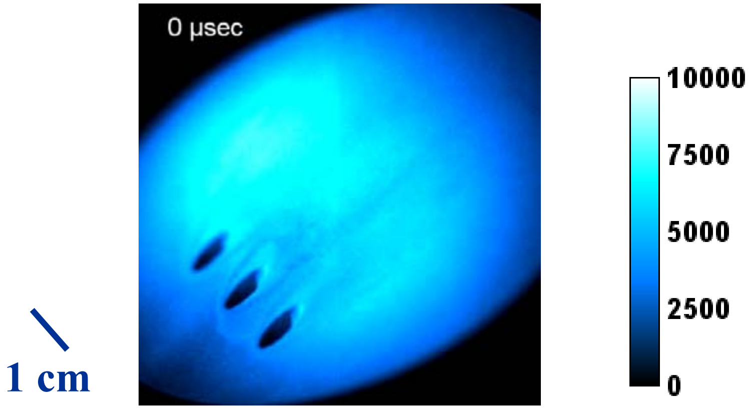


=

Luminescence after background subtraction



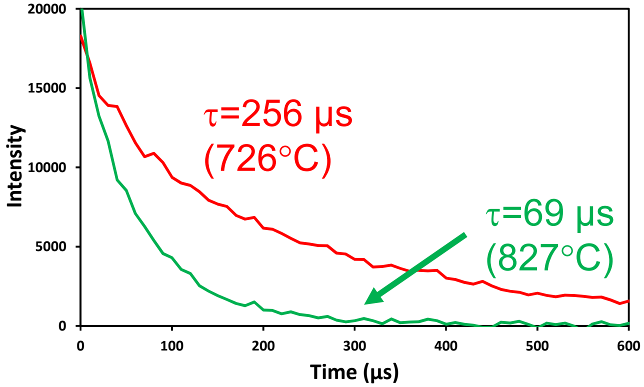
  - Step 2: Collect sequence of background-corrected time-gated images over sequence of delay times.



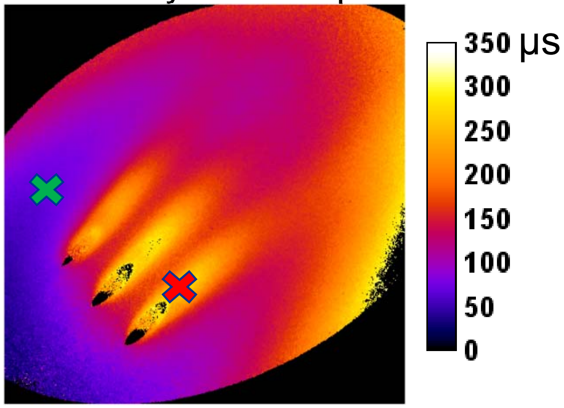
2D Temperature Maps from Luminescence Lifetime Imaging

- Step 3: Fit luminescence decay curve at each pixel to produce decay time map (Matlab routine).

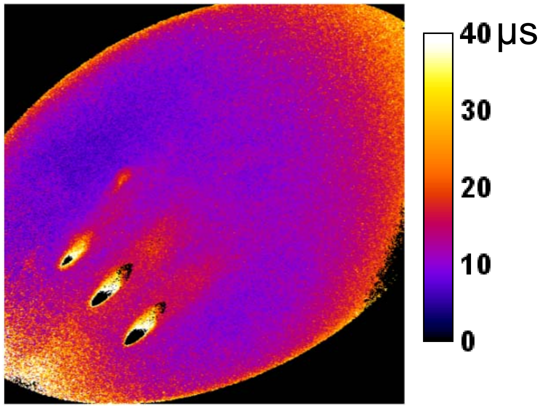
Individual Pixel Decays



Decay Time Map



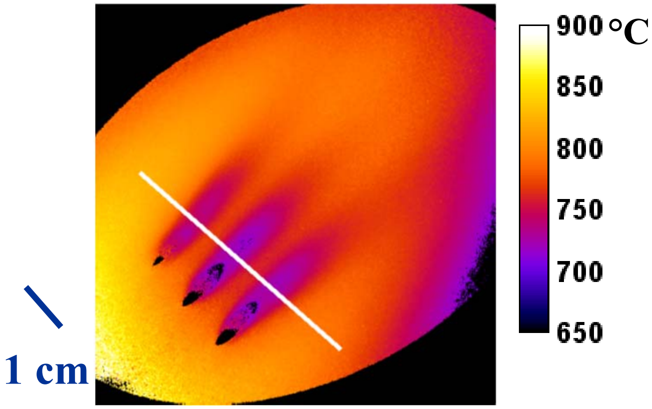
95% Confidence Interval



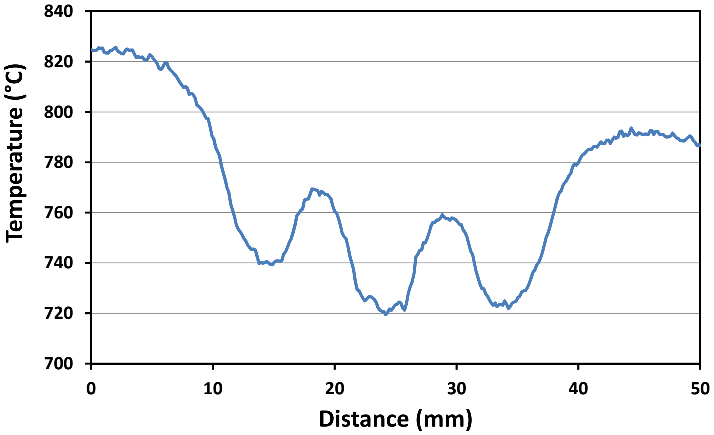
- Step 4: Use calibration data to convert decay time map to temperature map (Matlab routine).

$$\text{Find } T \text{ that gives know } \tau \text{ where } \tau = \tau_{2E}^{R} \frac{1+3e^{-\Delta E/kT}}{1+\alpha e^{-\Delta E/kT}+\beta e^{-(\Delta Eq+\Delta E)/kT}}$$

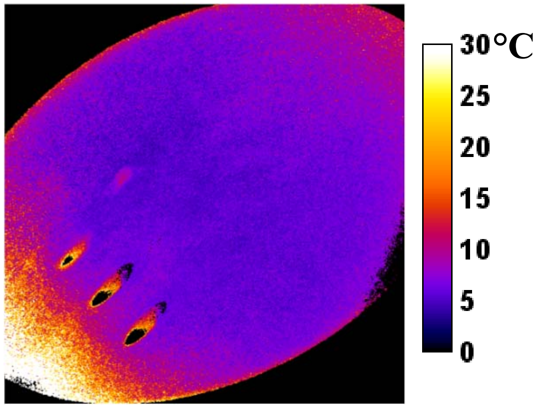
Temperature Map



Temperature Line Scan



95% Confidence Interval

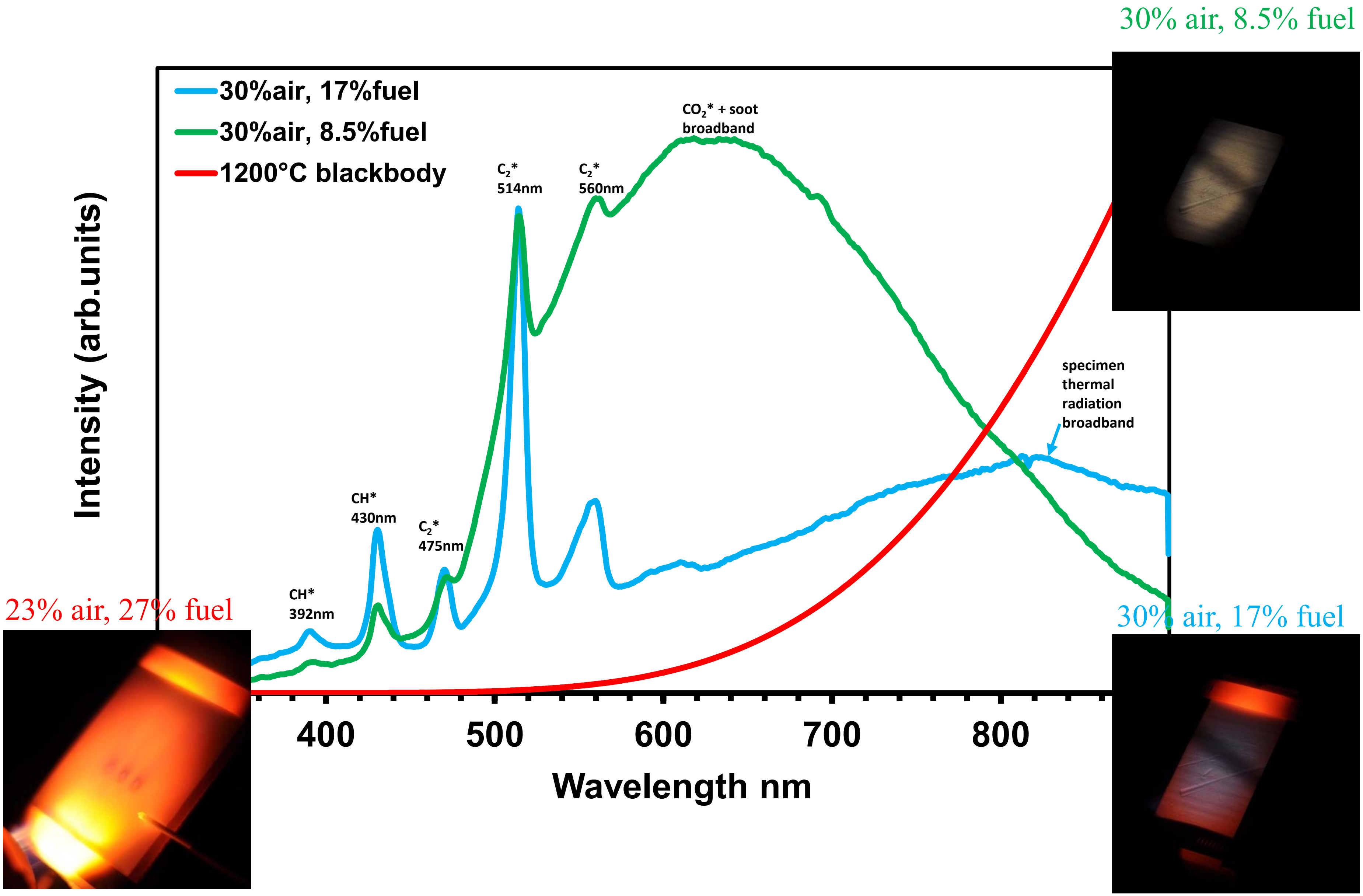


Background Radiation Sources

- Thermal (blackbody) radiation emitted by plate
- Reflected thermal and chemiluminescence radiation emitted from combustor.
- Luminous flame particles moving through field of view

Background Radiation Sources

Surface Thermal & Reflected Combustor Radiation



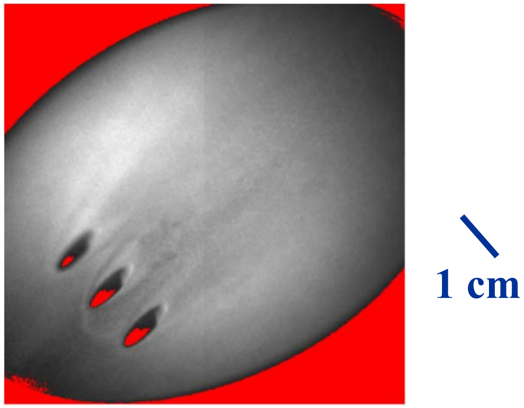
Pre-Fit Data Filtering

Pre-Fit Data Filtering

Pixel Removal Criteria

Minimum static threshold

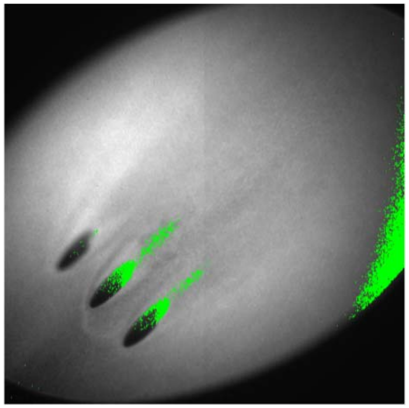
$I_{ij}(\text{frame 1}) < 3200$



Insufficient signal

Minimum dynamic threshold

$I_{ij}(\text{last frame}) > 10\%*I_{ij}(\text{first frame})$

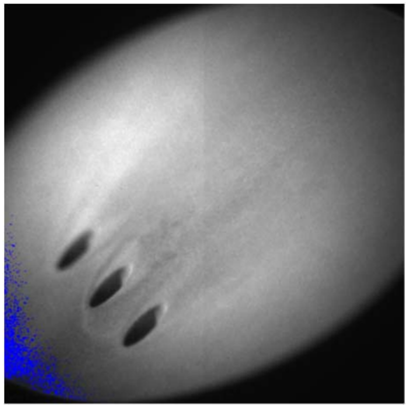


Too cold to capture sufficient percentage of decay

Minimum number of frames in fitting interval

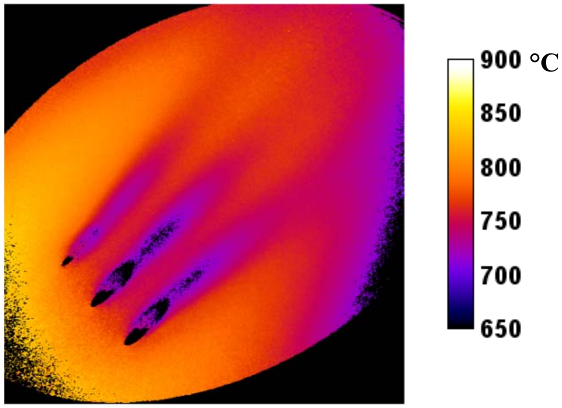
$10\%*I_{ij}(\text{first frame}) < I_{ij}(\text{frame n}) < 90\%*I_{ij}(\text{first frame})$

Number of frames <10

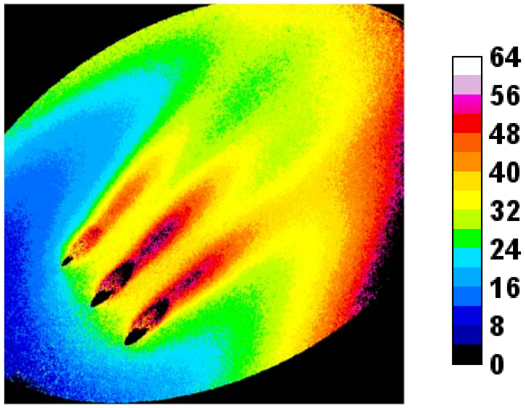


Too hot to capture sufficient number of frames in fitting window

Post-fit temperature map



Number of frames in fitting window

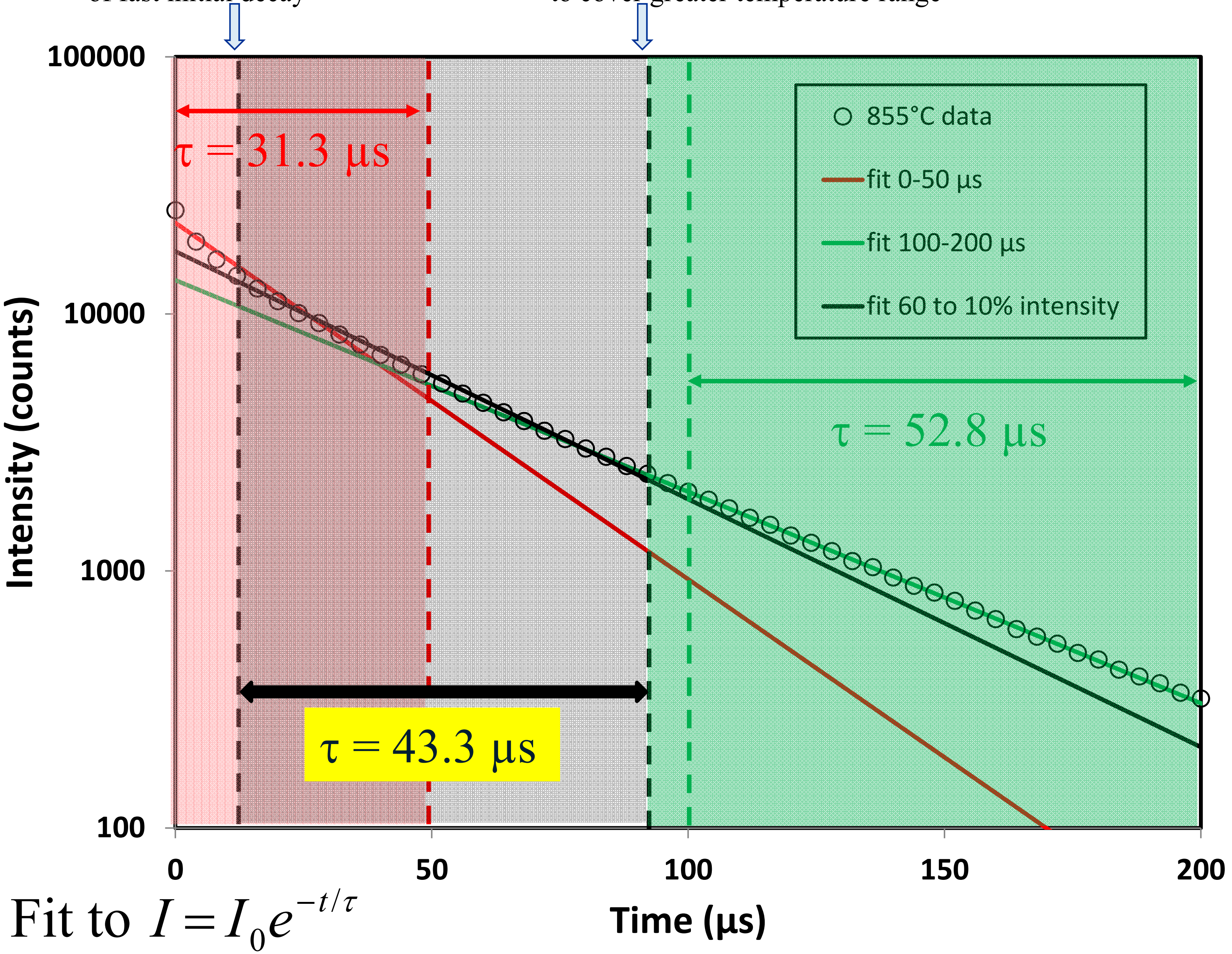


Fitting Window Selection

Effect of Fitting Window Selection

60% threshold reduces influence of fast initial decay

10% threshold can accept much longer decays to cover greater temperature range

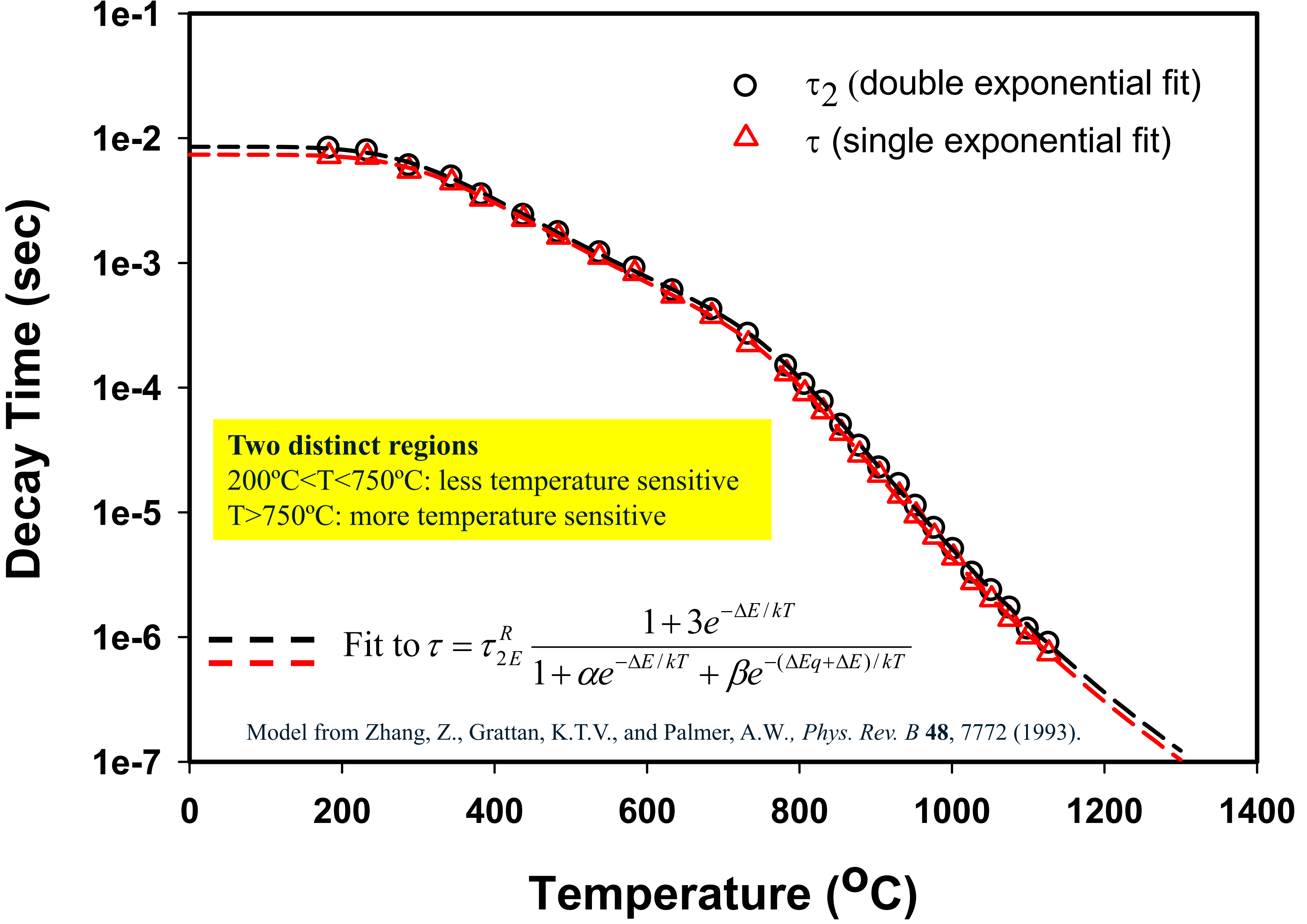


Fit to $I = I_0 e^{-t/\tau}$

Calibration

Calibration of Decay Time vs. Temperature for GAP:Cr Coating

60 to 10% Initial Intensity Fitting Window



Two distinct regions
200ºC<T<750ºC: less temperature sensitive
T>750ºC: more temperature sensitive

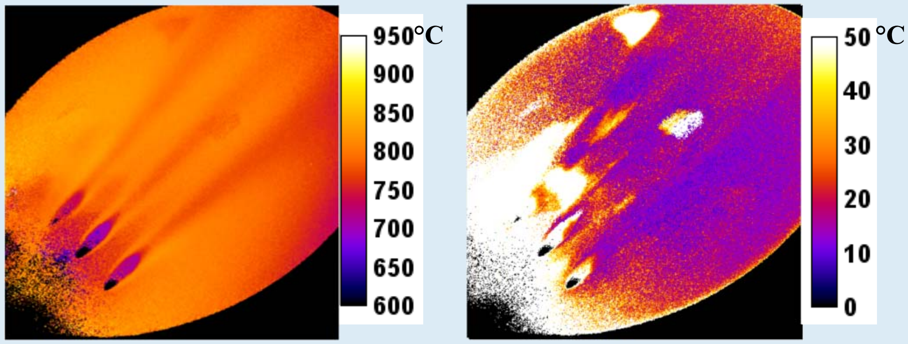
Fit to $$\tau = \tau_{2E}^{R}\frac{1+3e^{-\Delta E/kT}}{1+\alpha e^{-\Delta E/kT}+\beta e^{-(\Delta Eq+\Delta E)/kT}}$$

Model from Zhang, Z., Grattan, K.T.V., and Palmer, A.W., *Phys. Rev. B* **48**, 7772 (1993).

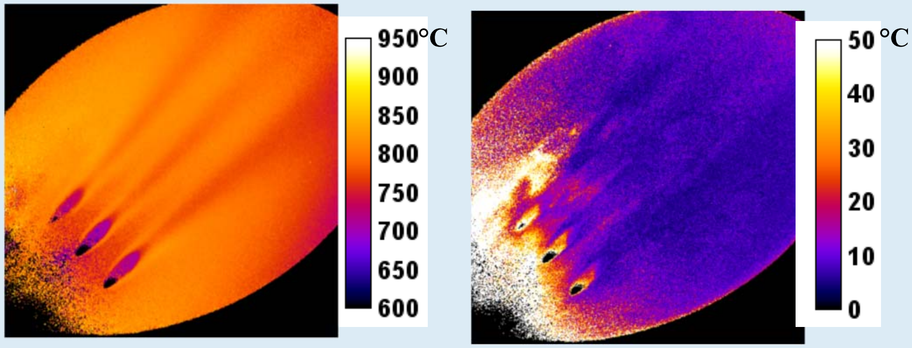
Removing Flame Burst Outliers

Effect of Luminous Flame Bursts

Decay time temperature maps 95% confidence interval

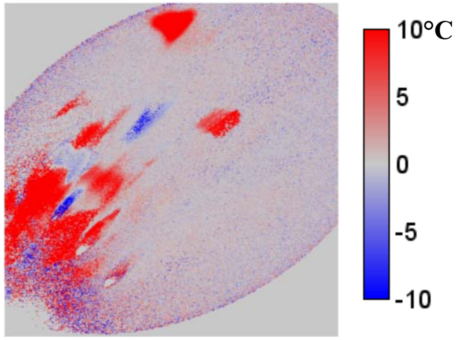


includes outlier pixels



excludes outlier pixels

$T_{excluded} - T_{included}$



1 cm

photo

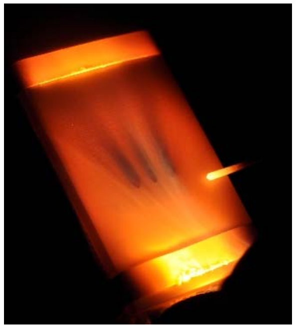
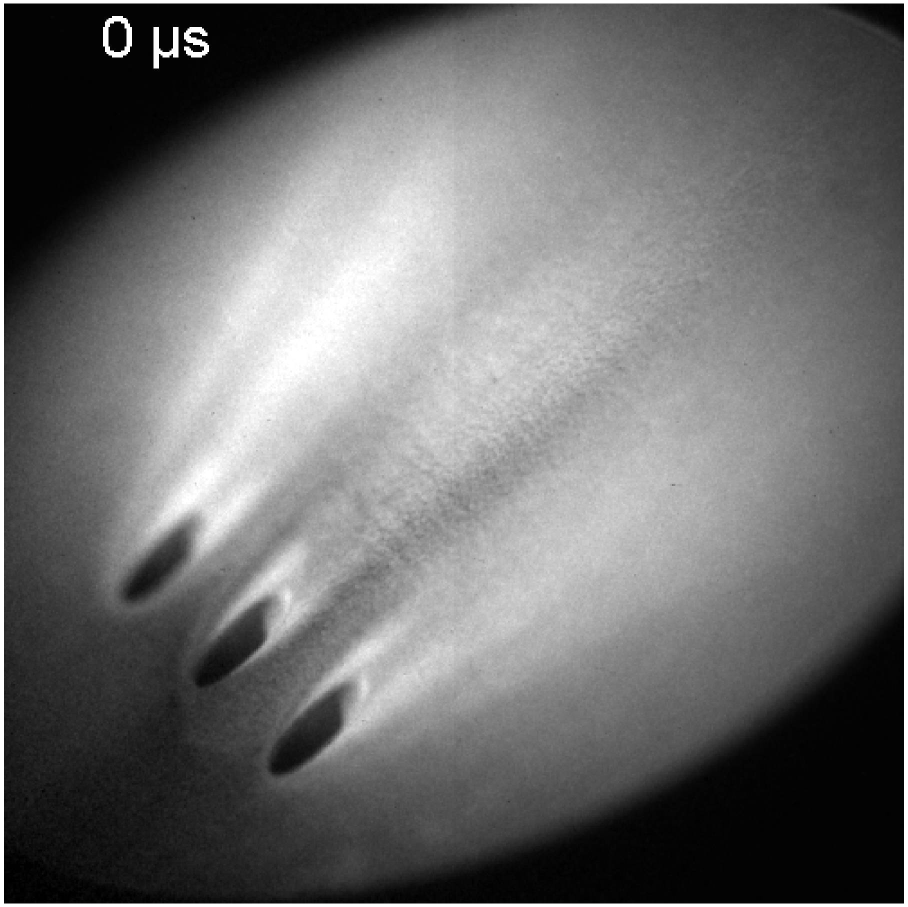
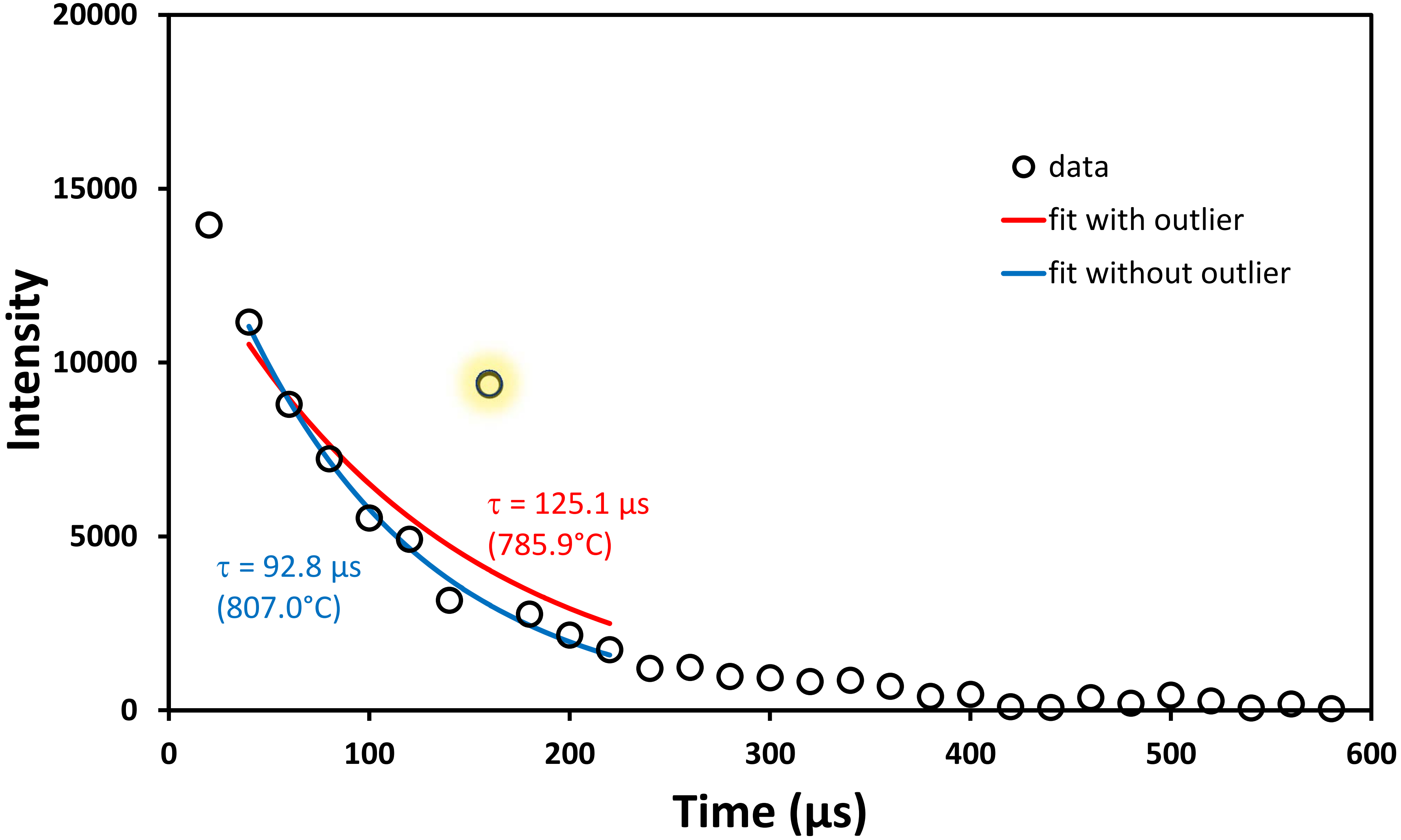


Image Stack



1 cm

Effect of Outlier Removal



$I_{ij}(t_n)$ is intensity of pixel ij in frame n of stack,

$t_n = (n-1)\Delta t + t_0$ where Δt is frame interval and t_0 is 1st frame time;

$I_{ij}(t_n)$ is an outlier *when* $\left|I_{ij}(t_n) - I_{ij}^{fit}(t_n)\right| > 1.5\sigma\left[I_{ij}(t_n) - I_{ij}^{fit}(t_n)\right]$

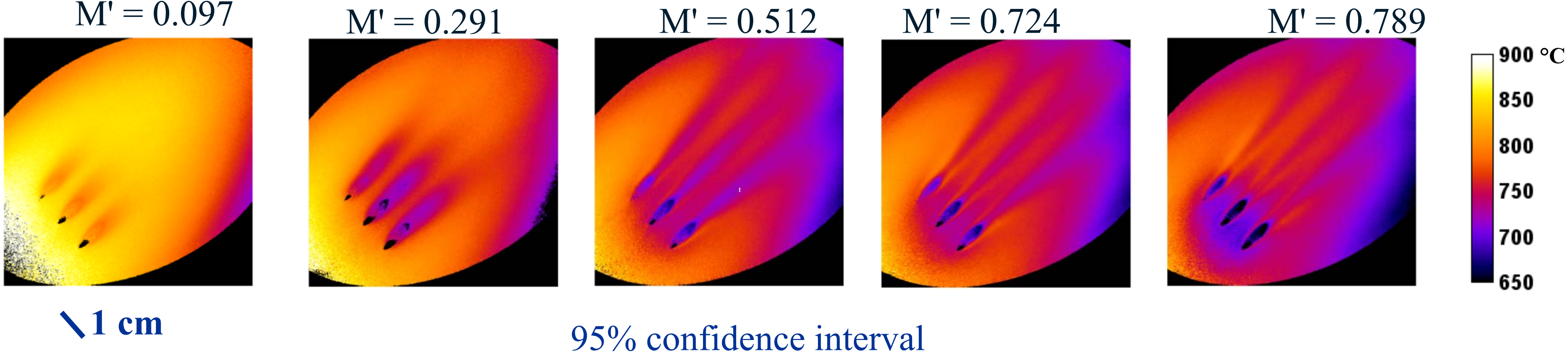
Air Film Cooling of TBC-Coated Surface Results

- Examine changes in cooling effectiveness as a function of:
  - Mainstream hot gas temperatures: 1424, 1552, and 1696°C
  - Blowing ratio: M' = 0 to 0.9

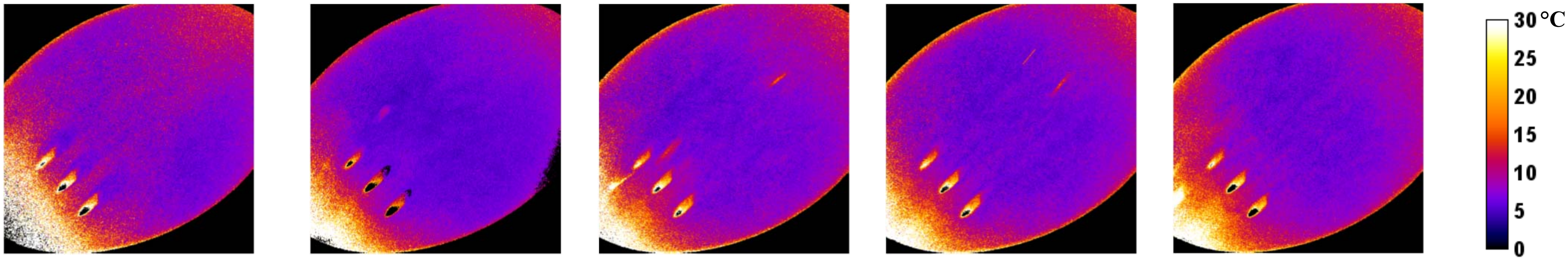
Burner Rig 2D Temperature Maps

$T_{mainstream} = 1424°C$

Decay time temperature maps



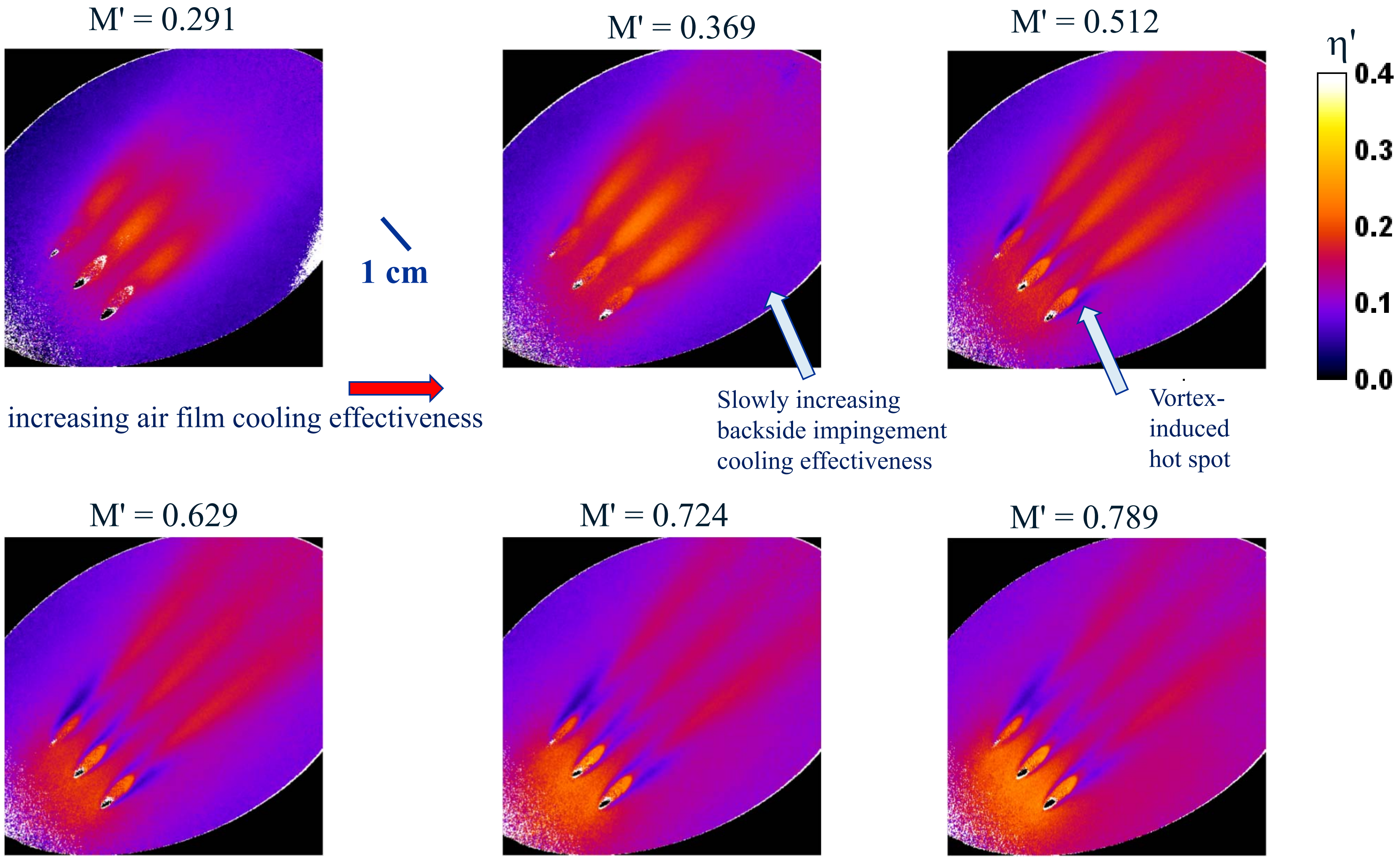
95% confidence interval



photos

Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1424°C$



M' = 0.291

M' = 0.369

M' = 0.512

M' = 0.629

M' = 0.724

M' = 0.789

Initially increasing air film cooling effectiveness

Slowly increasing backside impingement cooling effectiveness

Vortex-induced hot spot

Rapidly increasing through-hole convection cooling effectiveness

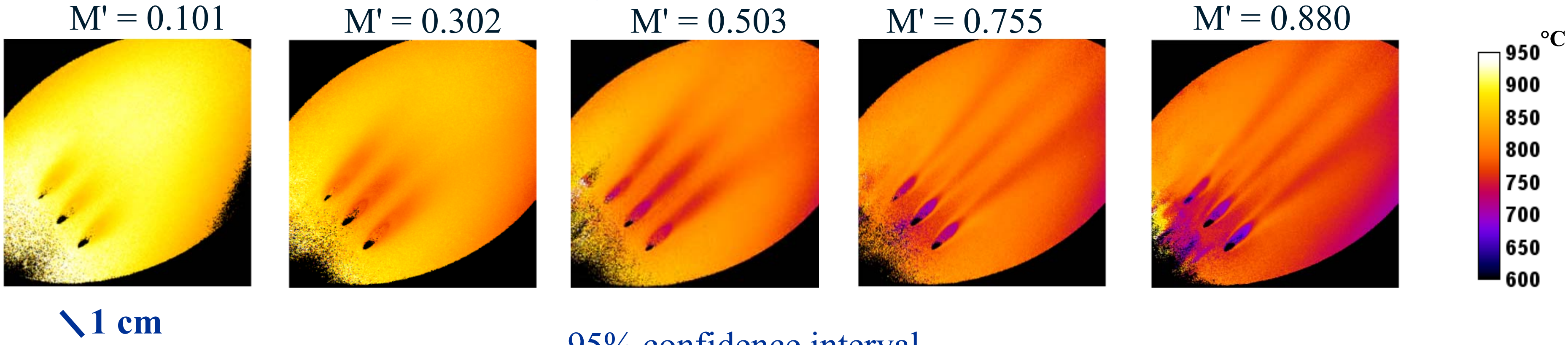
Diminishing air film cooling effectiveness

Vortex-induced hot streaks outlast air film cooling

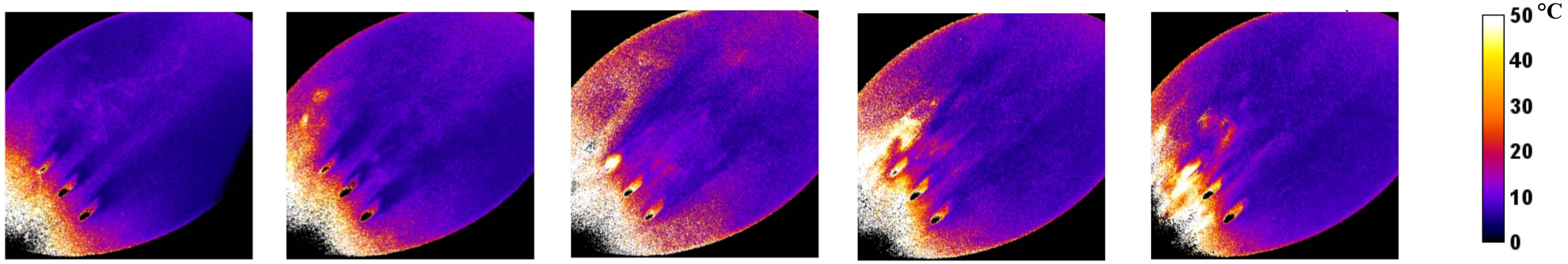
Burner Rig 2D Temperature Maps

$T_{mainstream} = 1552°C$

Decay time temperature maps



95% confidence interval



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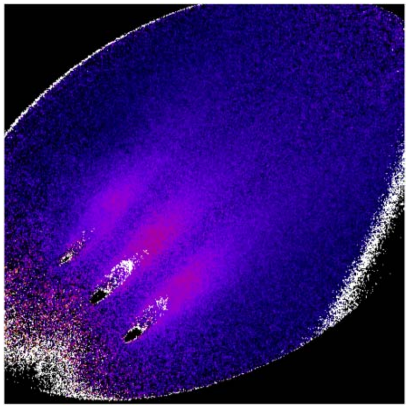
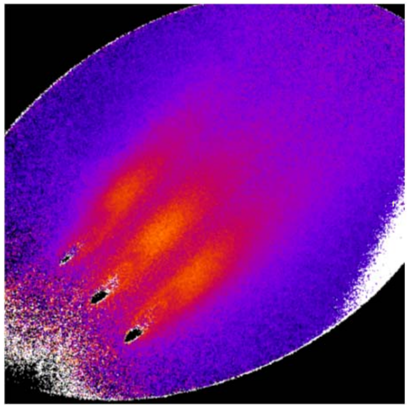
Burner Rig 2D Cooling Effectiveness Maps

$T_{mainstream} = 1552°C$

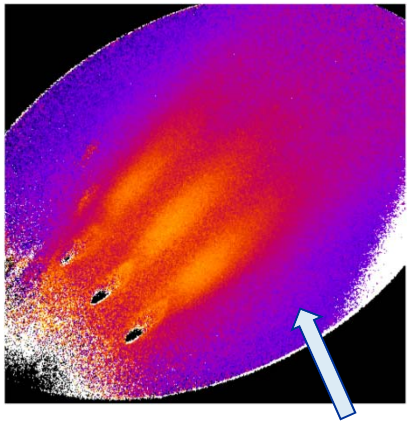
M' = 0.201

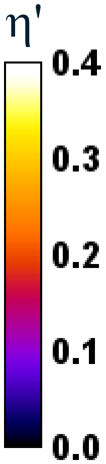


M' = 0.302



M' = 0.402

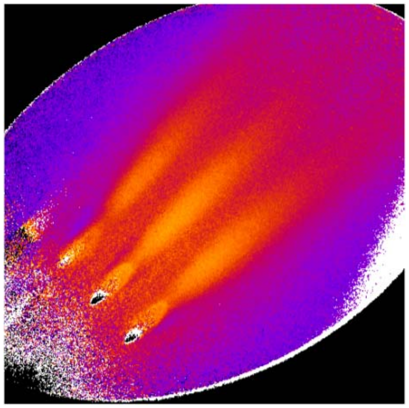




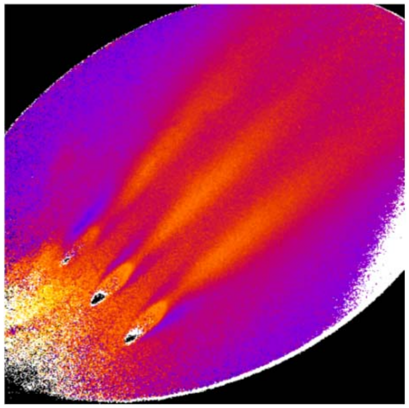
Initially increasing air film cooling effectiveness

Slowly increasing
backside impingement
cooling effectiveness

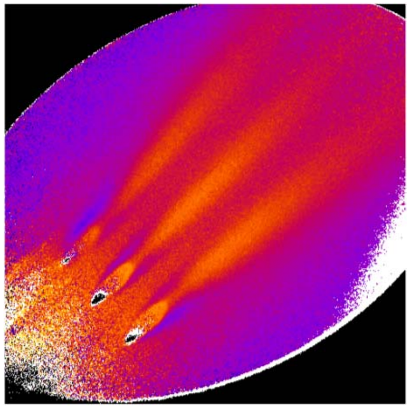
M' = 0.503



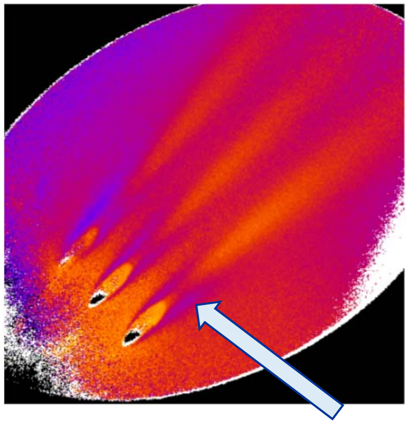
M' = 0.629



M' = 0.755



M' = 0.880



Increasing through-hole convection cooling effectiveness

Slowly decreasing air film cooling effectiveness

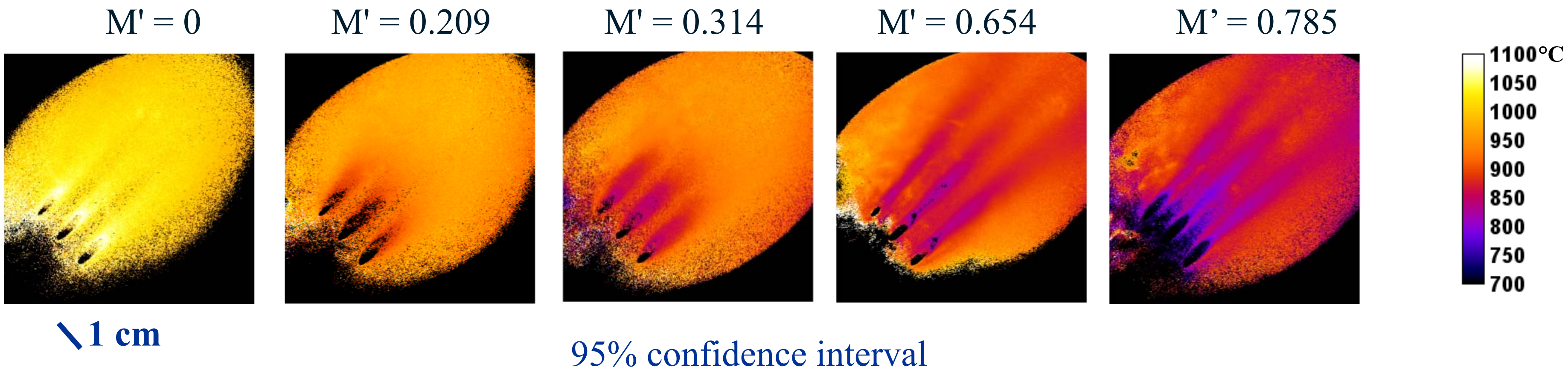
Weaker vortex-
induced hot
spot

Burner Rig 2D Temperature Maps

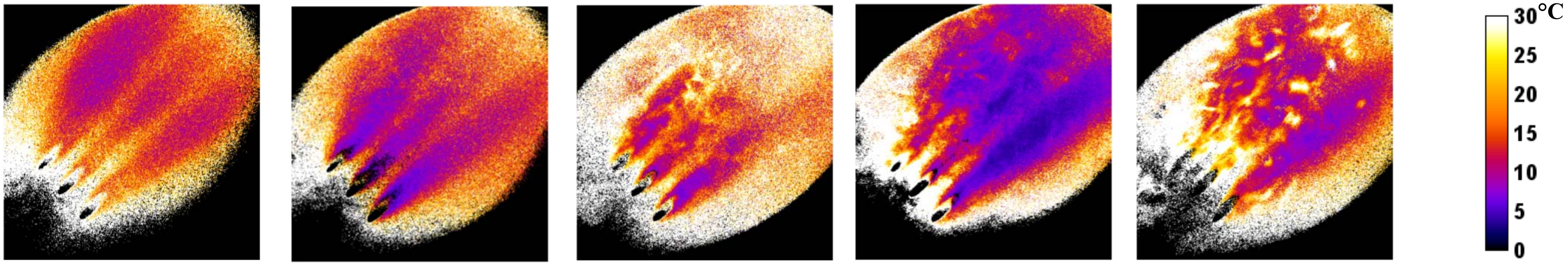
$T_{mainstream} = 1696°C$

Compromised by surface fouling and plenum leak

Decay time temperature maps



95% confidence interval

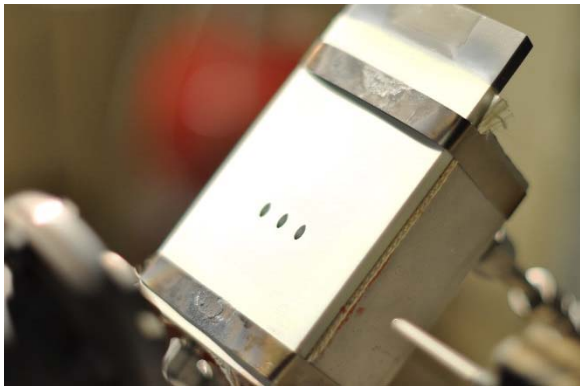


photos

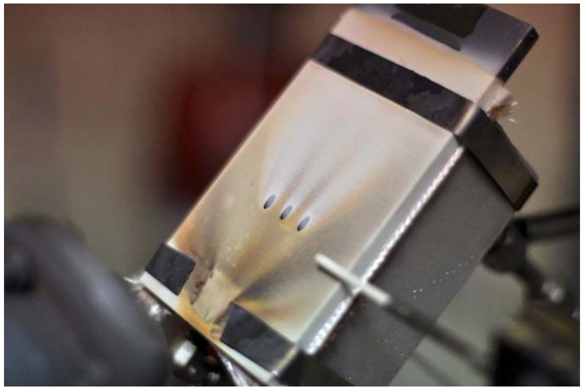
Effect of Surface Deposition/Fouling

$T_{\text{mainstream}} = 1424°C$

Pre-fouling



Post-fouling

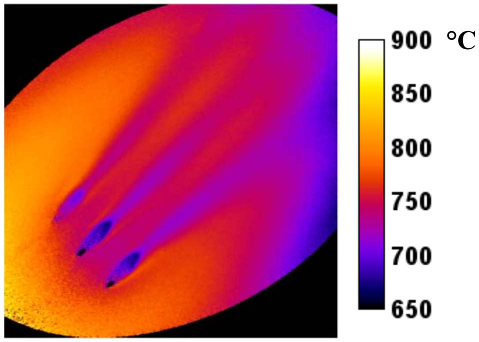


M’ = 0

Fouling changes emissivity

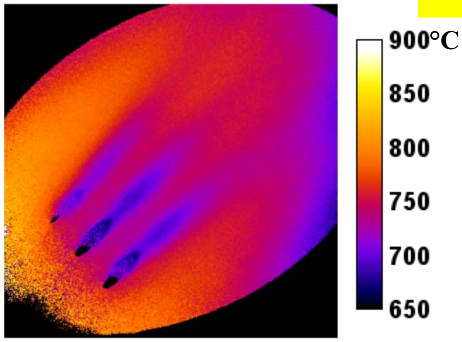
Decay time temperature maps

M' = 0.512

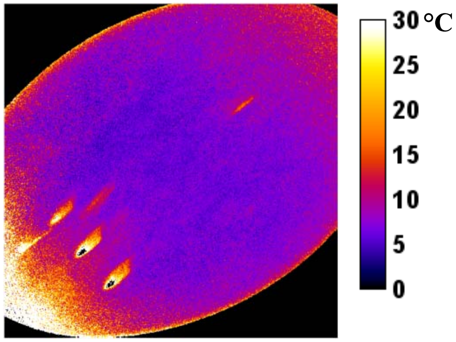


1 cm

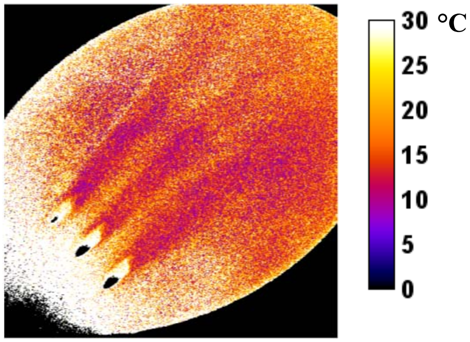
M' = 0.483



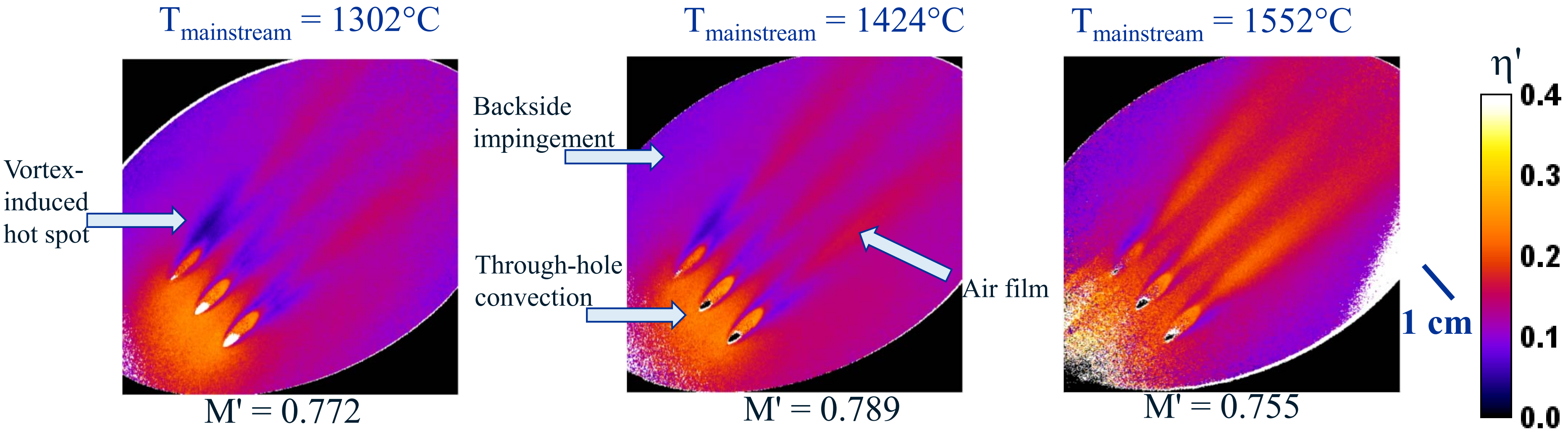
95% confidence interval



Deposition/fouling does not bias temperature measurement but does reduce measurement precision.

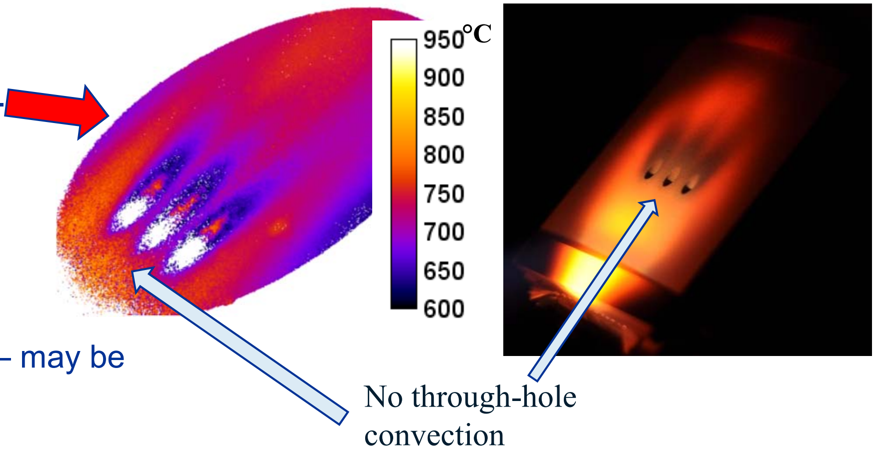


Combined Cooling Effects Summary



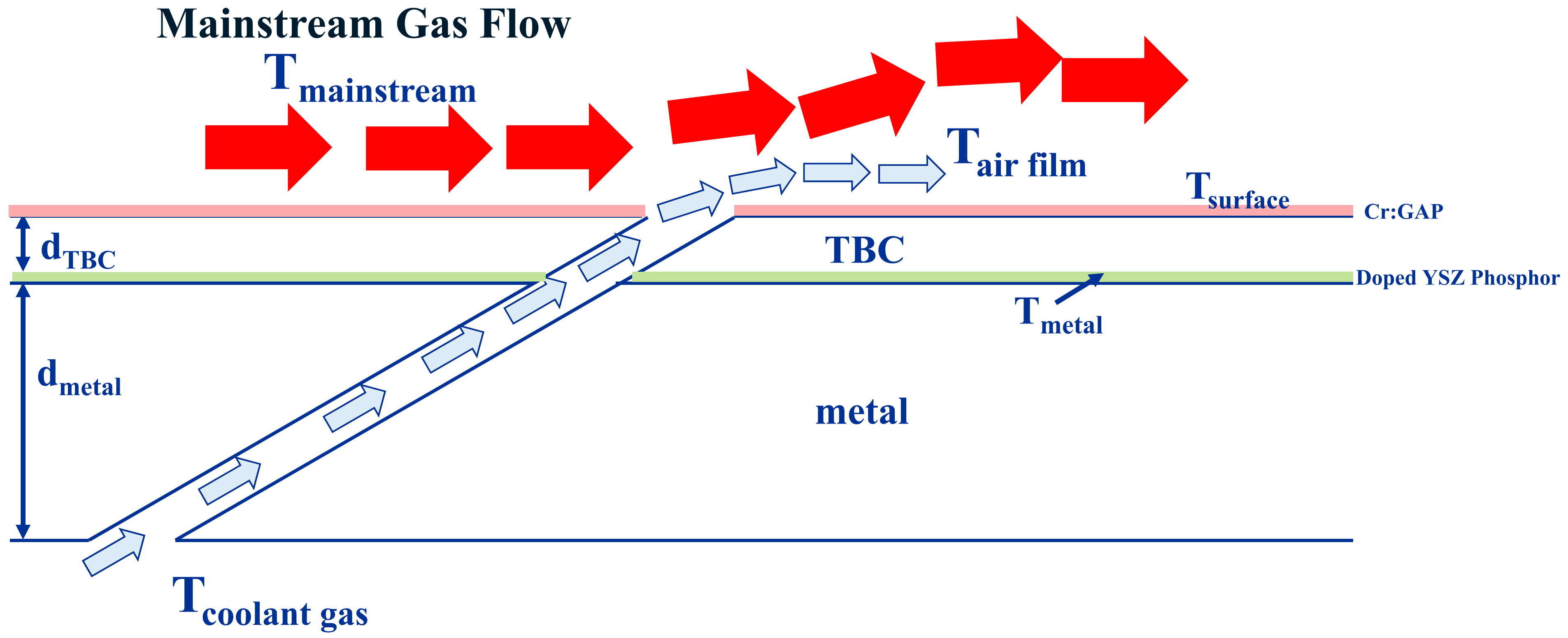
- Air film cooling
  - Effectiveness initially increases with increasing M, then diminishes with jet lift-off.
  - Effectiveness retained better at high flame temperature.
  - Vortex-induced hot streaks appear near cooling holes. Hot streaks remain prominent even when air film cooling is lost. May be worse on TBC-coated surface.
- Through-hole convective cooling
  - Effectiveness increases rapidly at high M.
  - Not observed in conventional air film cooling measurements.
- Backside impingement cooling
  - Slowly increases with increasing M.
- Effect of TBC
  - Will decrease air film cooling effectiveness.
  - Will increase through hole convective cooling effectiveness – may be useful for showerhead cooling.

alumina silicate (all ceramic) plate



Future Direction

Add Metal Temperature Maps



Surface cooling effectiveness from Cr:GAP layer:

$$\eta' = \frac{T^{surface}_{uncooled} - T^{surface}_{cooled}}{T^{surface}_{uncooled} - T_{coolant\ enter}}$$

Metal cooling effectiveness from doped YSZ layer:

$$\Phi' = \frac{T^{metal}_{uncooled} - T^{metal}_{cooled}}{T^{metal}_{uncooled} - T_{coolant\ enter}}$$

Conclusions

- Successfully demonstrated 2D temperature mapping by Cr:GAP phosphor thermometry with high resolution (temperature, spatial, but not temporal) in presence of strong background radiation associated with combustor burner flame.
  - Robust, operator independent, automated analysis
- Can be used as new tool for studying/optimizing non-additive interplay of cooling mechanisms for TBC-coated components.
  - TBC
  - Air film
  - Through-hole convection
  - Backside impingement
- TBC affects other cooling mechanisms
  - Degrades air film cooling effectiveness
  - Enhances through-hole convection cooling
- Improved TBCs will reduce air film cooling requirements for higher engine efficiency, but combined TBC + air film cooling will not be effective substitute for CMC + EBC development.