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The Uncertainty of Temperature and Heat Flux Calibration for FAA Fire Test

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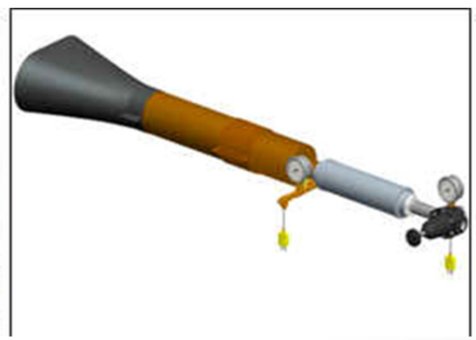
Background and Scope of Presentation

In current FAA fire test guidance, *<u>the flame temperature and heat flux calibration is required</u>* to ensure that the flame is qualified to simulate the possible real-life severe conditions happened inside an aircraft or a powerplant environment.

In this work, the discrepancy between Gardon and Schmidt-Boelter gauges will be discussed. Several suggested cases should be taken when selecting a Gardon or Schmidt-Boelter gauge for use as a calibration standard in fire test equipment.

The uncertainty of thermocouple (TC) measurement in a high temperature environment (fire test) and the effects of convective velocity, TC size, TC location will be presented.



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Heat Flux

- Quantification of the flow of heat from a region of high temperature to a region of low temperature
- Heat transfer occurs by three modes
  - Conduction
  - Convection
  - Radiation
- Heat flux a critical fundamental parameter in assessing flame spread behavior of materials

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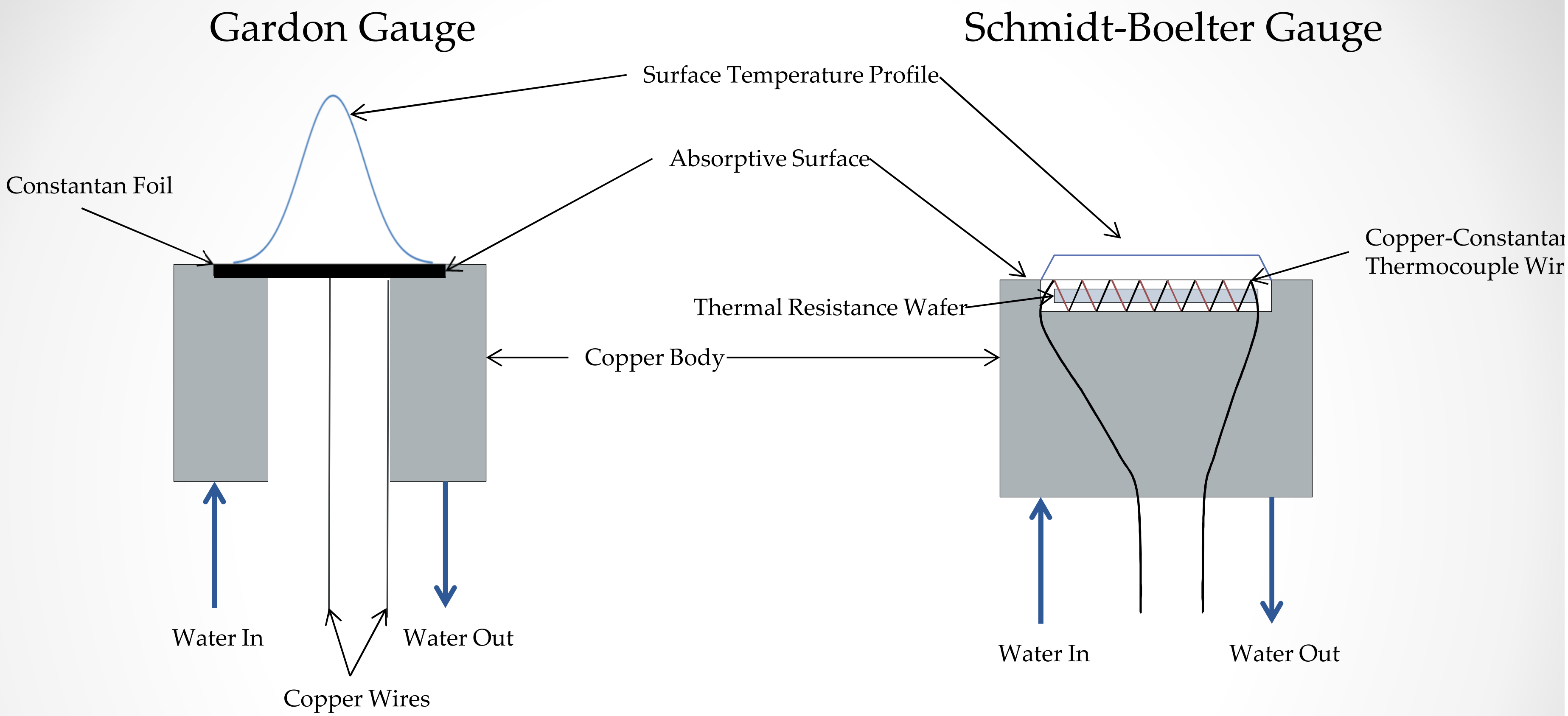
Heat Flux Measurement



- Constant Temperature Copper Body (~cooling water temp)
- Two thermocouple junctions created at the copper wire-constantan foil connections
- Radial temperature gradient exists if temperature at center of foil is not equal to the body temperature

- Multiple TC junctions created on top and bottom of thermal resistance layer (Anodized Aluminum)
- Signal is electrically isolated from gauge body
- Signal is greater in magnitude than Gardon gauge due to multiple thermocouple junctions, hence smaller ΔT required for similar voltage output

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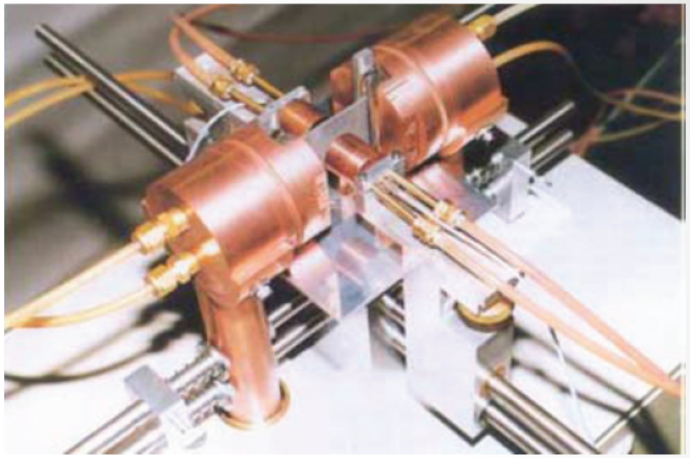
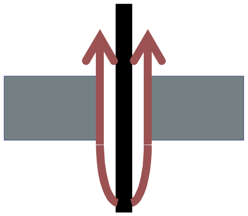
Transfer Calibration

- A NIST-traceable HFG is used to transfer calibration to other gauges
- Electrically heated graphite plate is the radiation source
- Gauges are placed on either side of the plate and mV signals are recorded
- Calibration factor is developed for gauge based on the reference HFG's heat flux readings and the other gauge mV output





- No surround board is used for gauges
- A convective boundary layer flow develops on both sides of graphite plate, should be equal
- Resulting incident flux should be equal for both gauges

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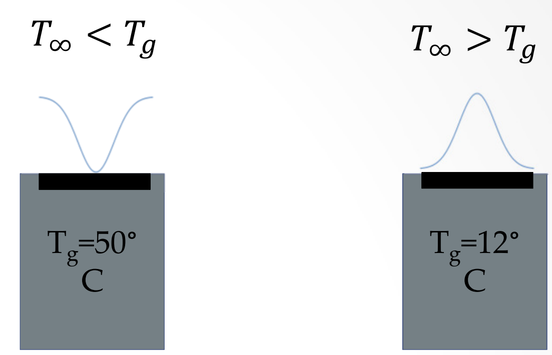
Low Heat Flux Measurement: Some Precaution[1]

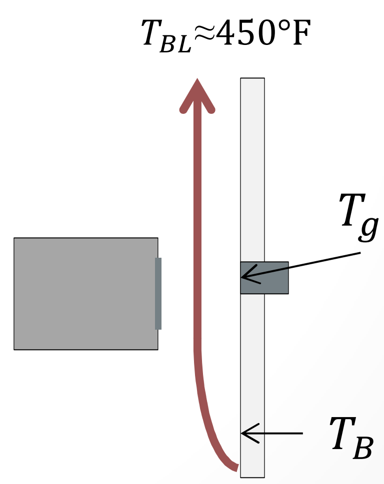
[1] Robertson & Ohlemiller, Fire Safety Journal **25** (1995) 109-124

- **Low Heat Flux at or below 15 kW/m² (1.2 BTU/ft²s)**
- **Errors arise from temperature difference between gauge body and its surroundings**
  - If the cooling water temperature is different from the surrounding temperature, a bias error signal will be measured
  - Experiments with 12° and 50°C water resulted in bias errors of +4.3% and -8.5%, respectively under a 5.9 kW/m² flux
- **Mounting the gauge body in a board was found to increase the flux measurement**
  - Board absorbs radiant heat from furnace
  - Board temperature increases, heats air near the surface
  - Buoyant boundary layer develops with $T_{board}>T_{BL}>T_{gauge}$
  - Heat is transferred from the BL to the gauge
  - This is contrary to what would occur if the board and gauge were at the same temperature
    - BL flow would be lower in temperature than the board, would convect heat *away* from the board
  - Measurement error of approximately 13% higher was obtained with a surround as opposed to bare gauge under 5.9 kW/m² flux.



Heat flows from the gauge to the surroundings

Heat flows from the Surroundings to the gauge



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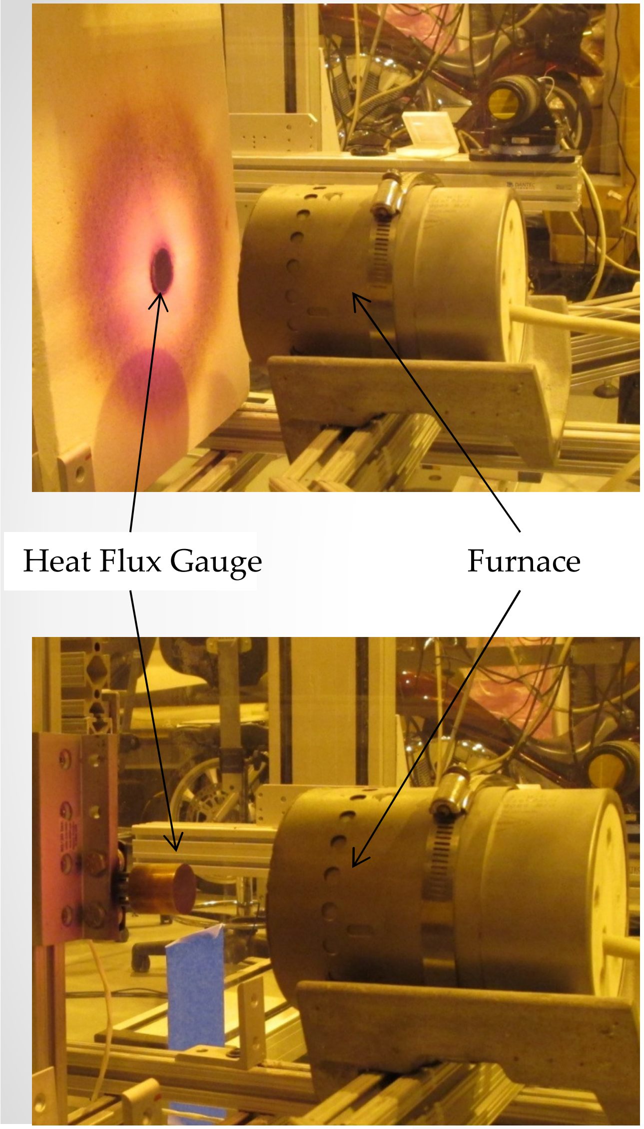
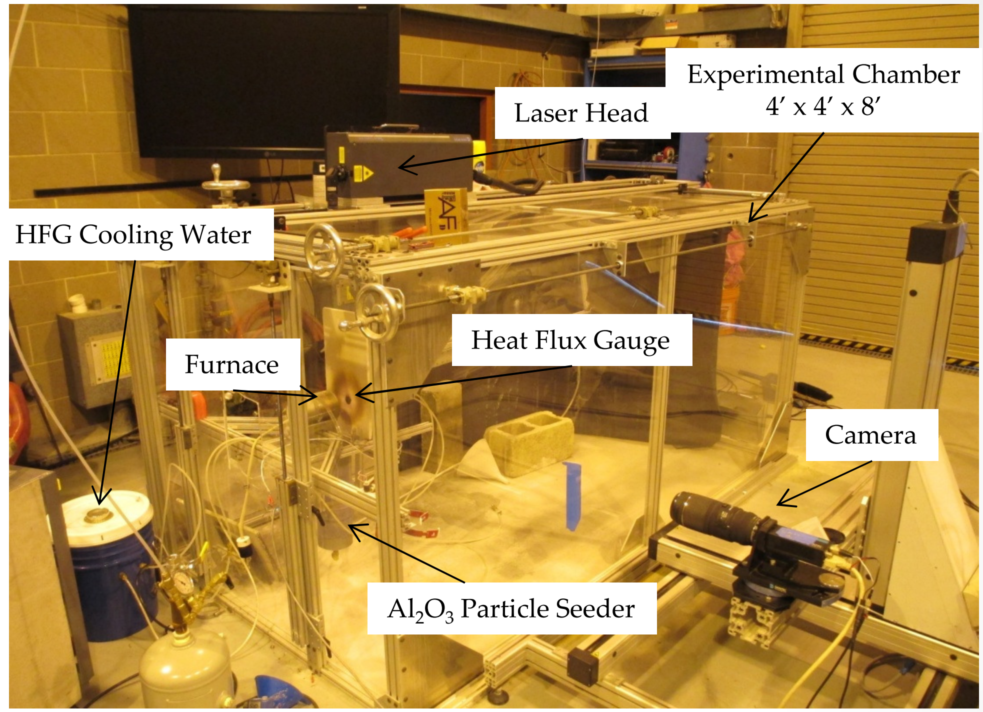
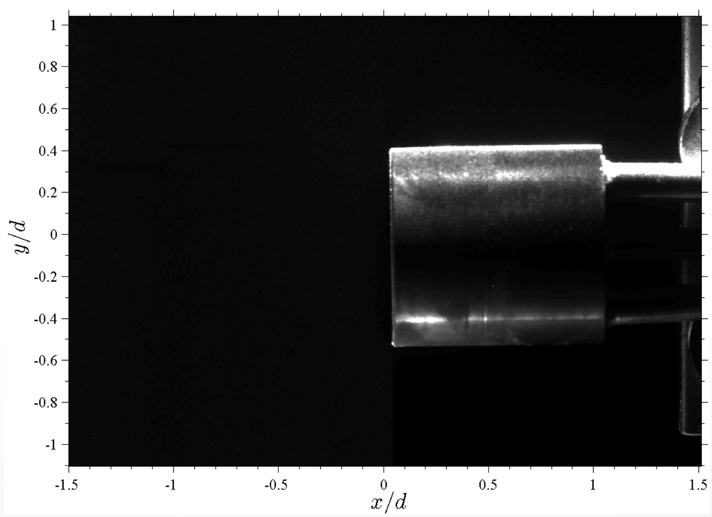
Experimental Setup: Heat Flux & PIV Measurements







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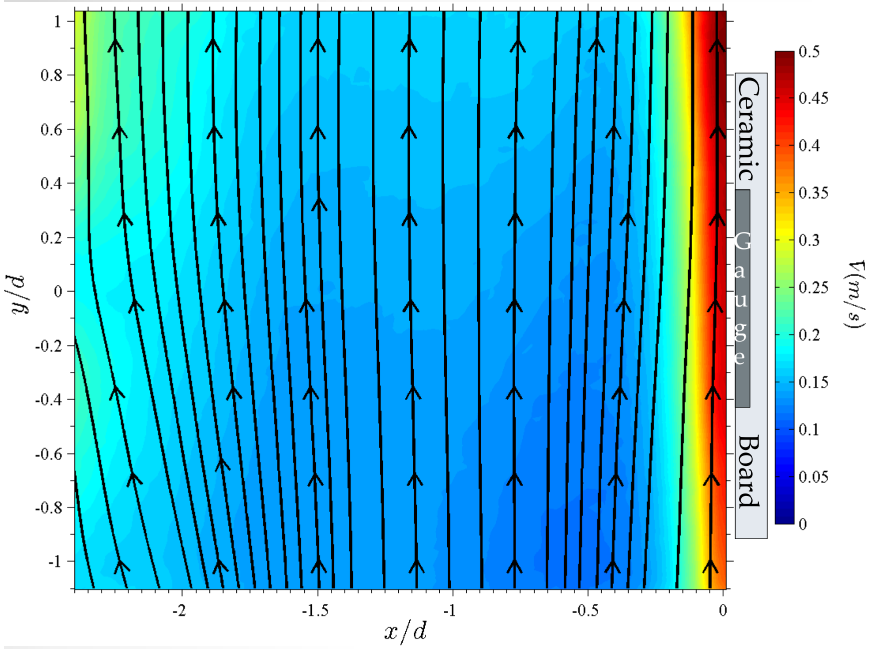
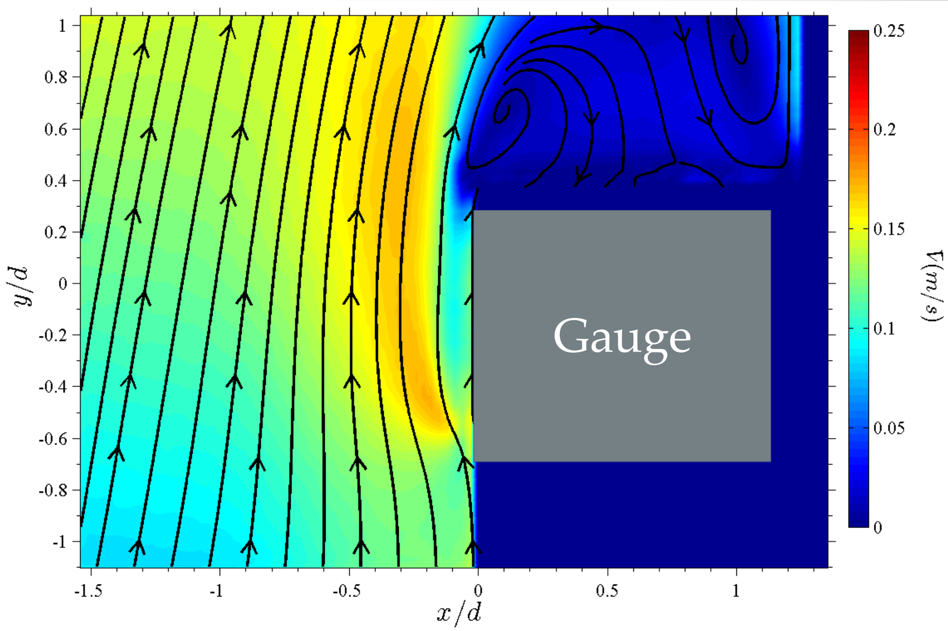
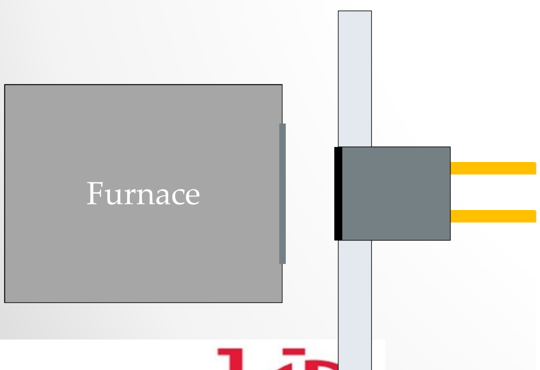
Gauge Flush with Surround Board

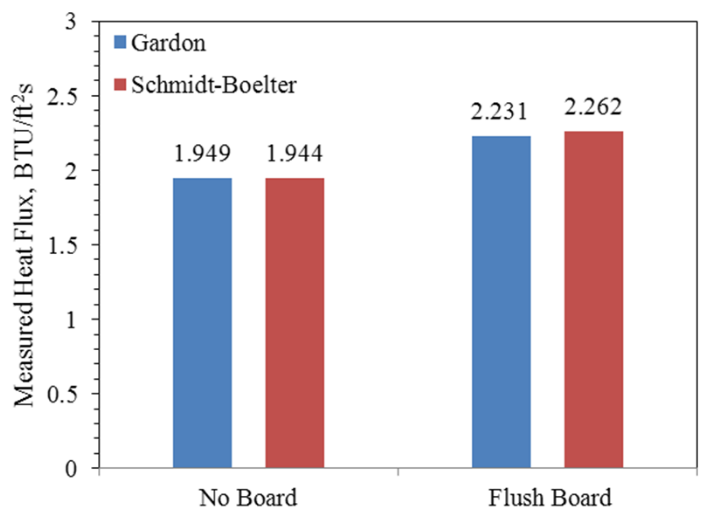


Gauge Only No Surround Board

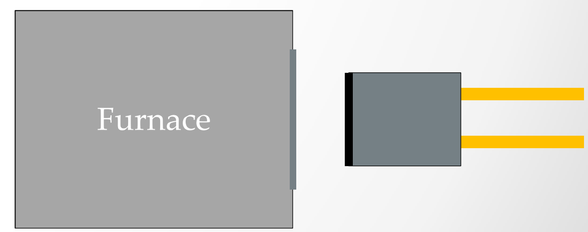


d=1.0 inch, gauge diameter





Board increases signal by approx. 15% due to convective heating from the BL to the gauge surface



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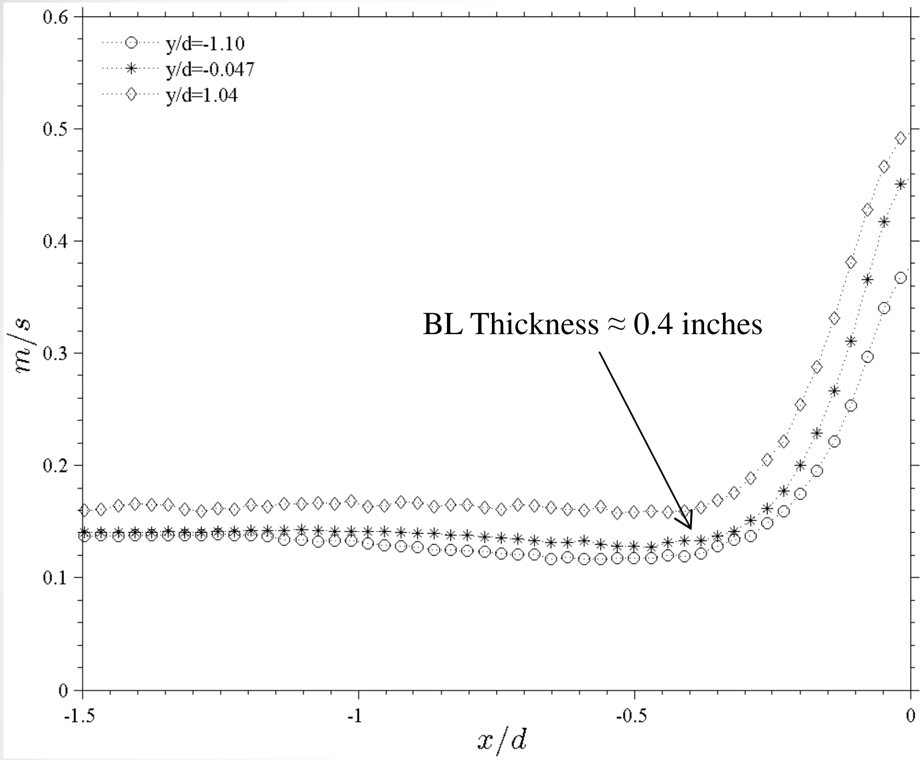
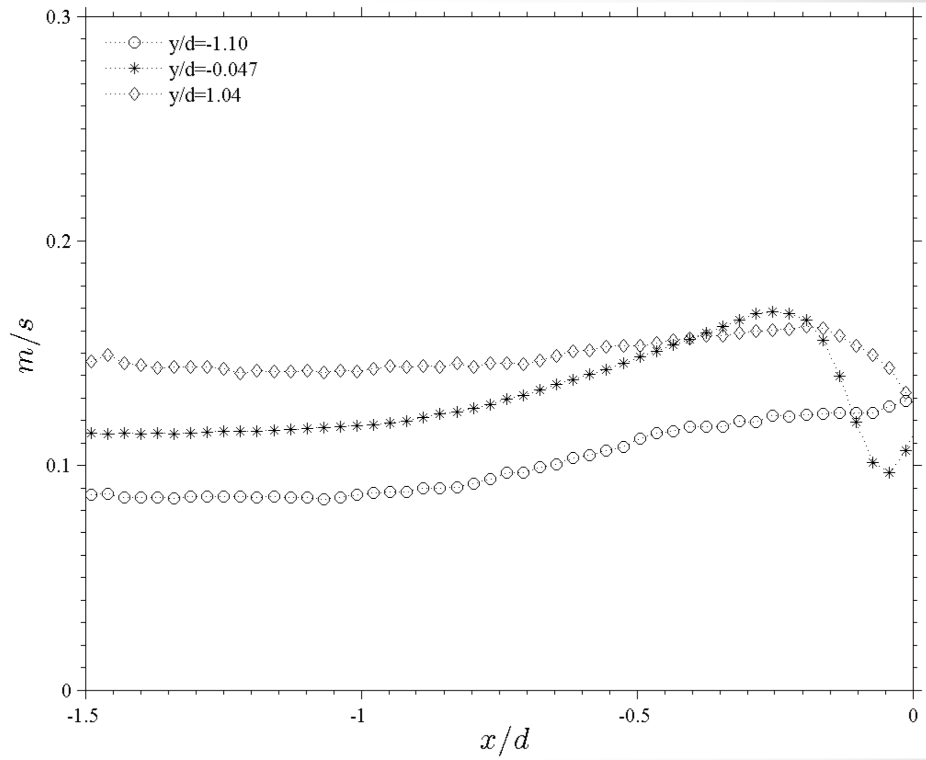
Flush with Board



Center of Gauge, V=0.46 m/s

No Surround



Center of Gauge, V=0.1 m/s

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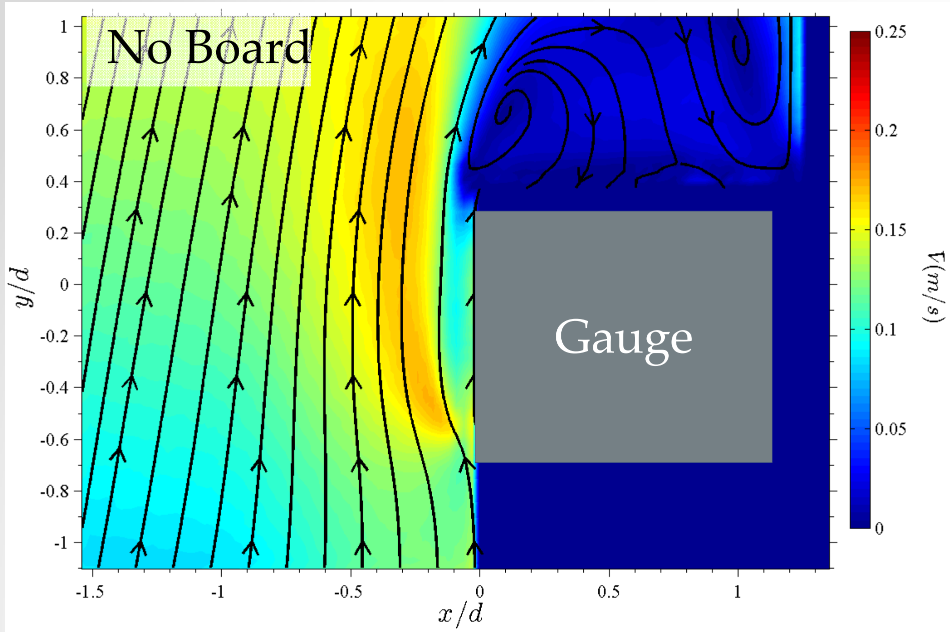
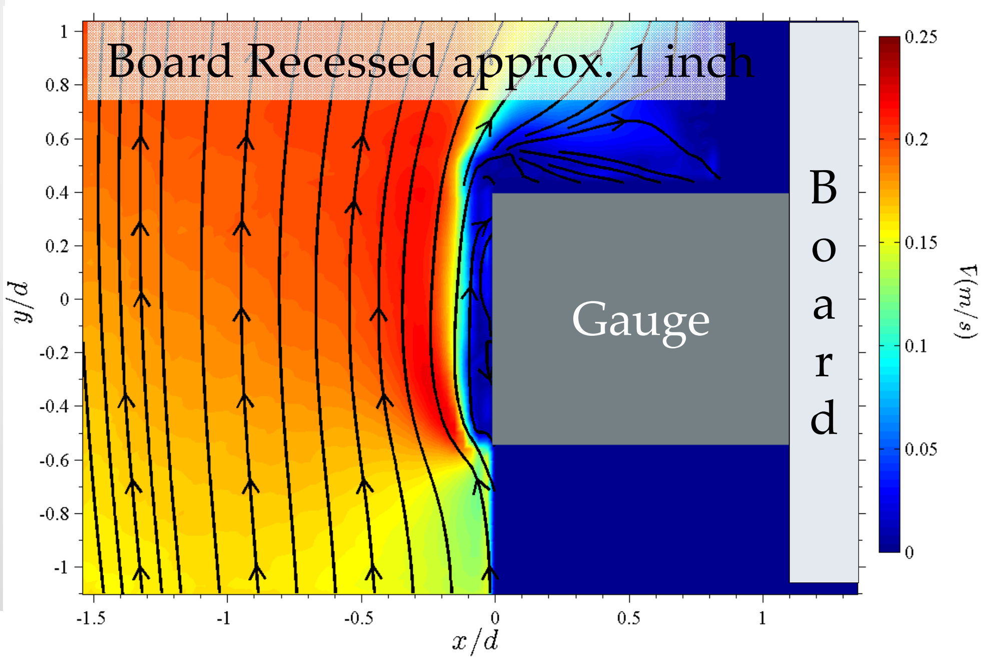
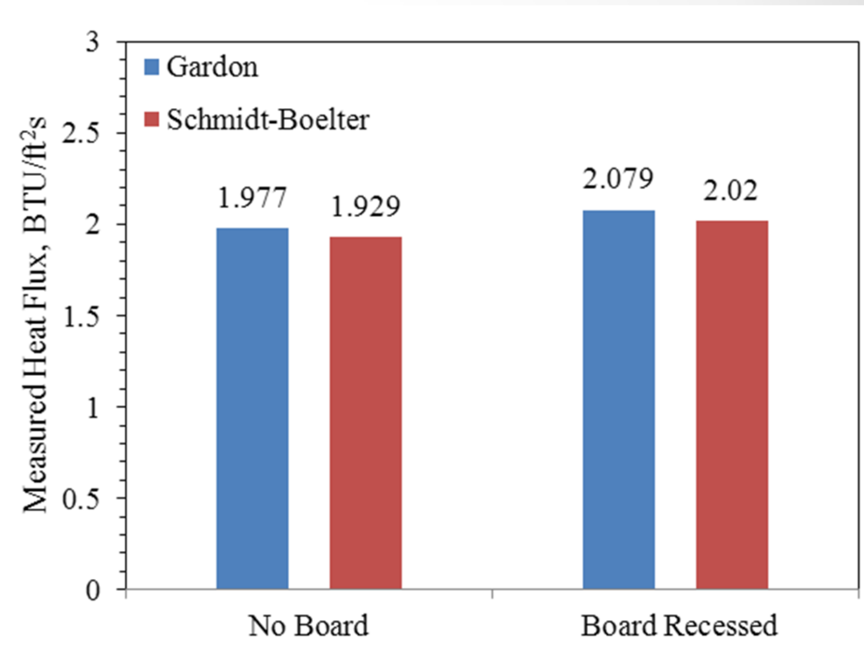




Attempt to reduce convective error by recessing board, placing the sensing surface beyond the boundary layer flow



Recessed board increases signal by approximately 5%

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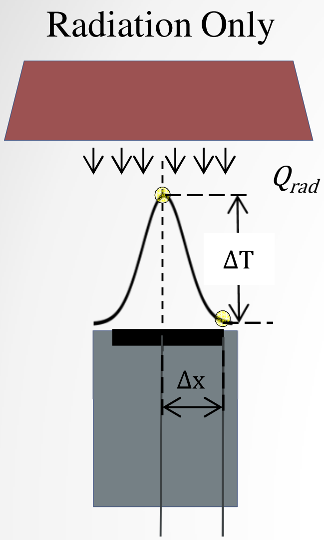
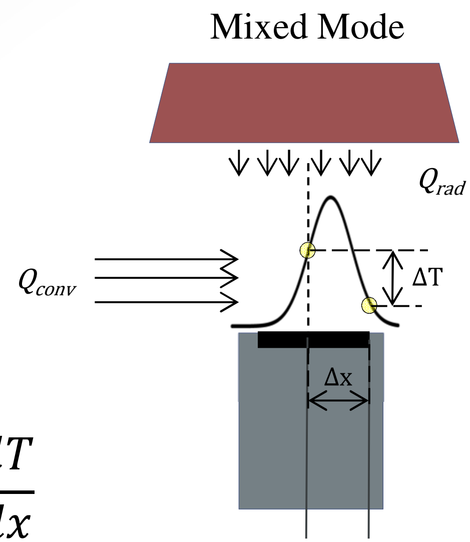
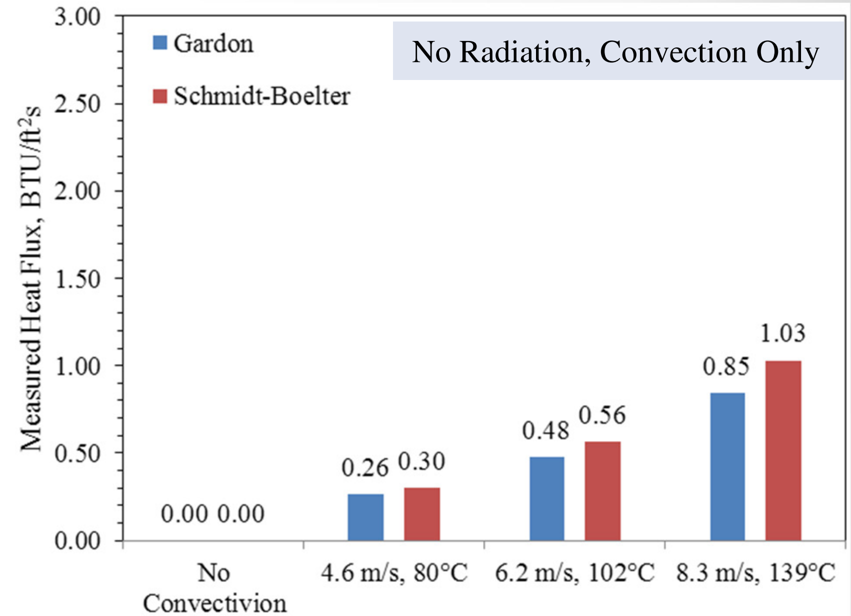
Heat Flux Measurement in Mixed Mode Environment[2]

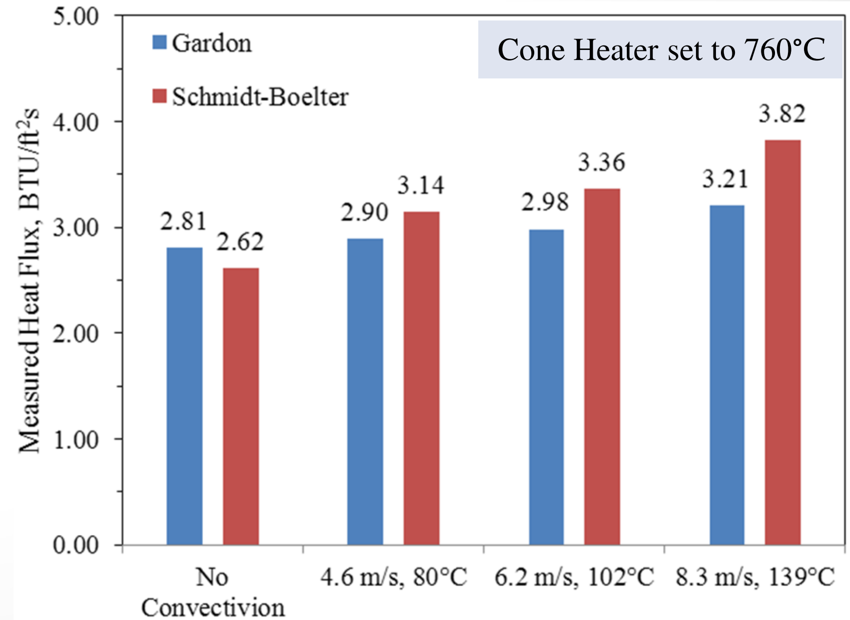
[2]Lam and Weckman, Fire and Materials, Volume 33 Issue 7, November 2009



$$Q \propto \frac{dT}{dx}$$







- **Mixed mode (convection + radiation) measurements were made with Gardon & SB gauges**
- **Hot air gun used for convective source**
- **Cone heater used for radiative source**
- **Gardon gauge 7-8% higher for pure radiation**
- **Gardon gauge 8-18% lower for mixed mode**
  - Discrepancy increased as radiative fraction of total heat flux decreased and convective fraction incrased
  - Convective flow shifts peak temperature away from center of Gardon gauge foil

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Summary

- Care should be taken when selecting a Gardon or Schmidt-Boelter gauge for use as a calibration standard in fire test equipment
  - Bias errors
  - Unknown convective portion of total flux
  - Mismatched calibration and use conditions

- Measurement of relatively low heat flux levels will be more impacted by errors

- Awareness of the situational specific heat transfer modes and the sources of error can lead to the correct choice for heat flux measurement

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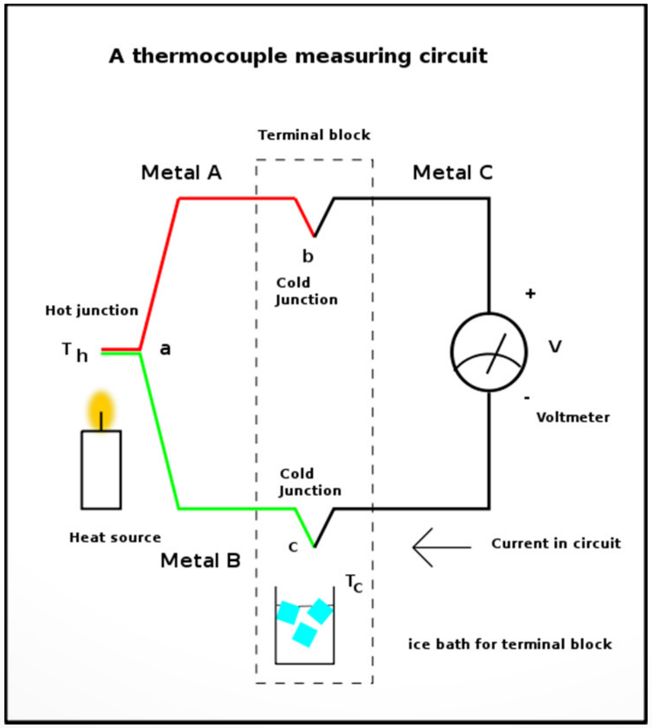
Temperature and Thermocouple

Temperature:
a numerical scale represents the intensity of heat (energy) present in a substance or object

Thermocouple (TC):
a thermoelectric device for measuring temperature, consisting of two wires of different metals connected at two points. It produces a voltage between the two junctions in proportion to the temperature difference.



source: www.wikipedia.com

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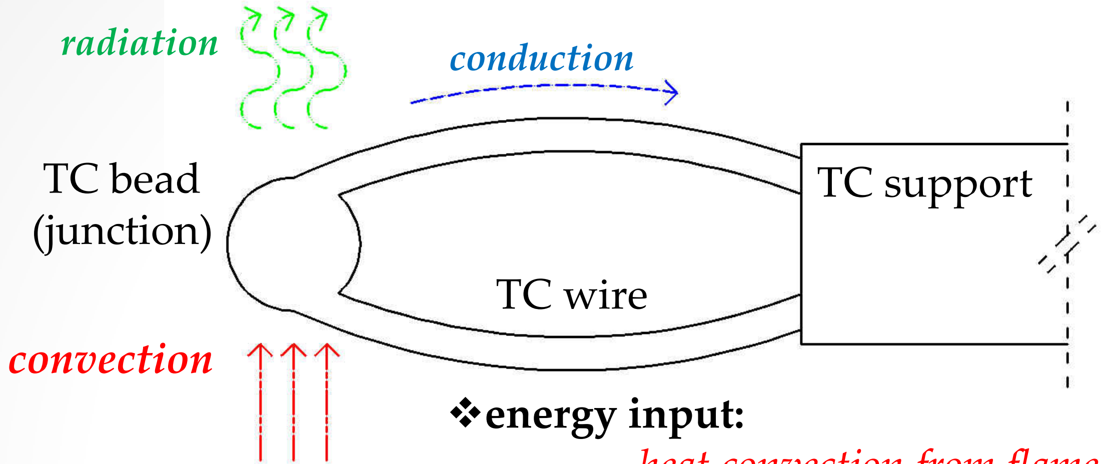
Energy Balance of Thermocouple



❖**energy input:**

heat convection from flame to TC bead
heat radiation from flame to TC bead

❖**energy output:**

heat radiation from TC bead to ambient
heat conduction from TC bead to TC wire or support

$$\frac{4\sigma}{D}\left(\varepsilon_g T_g^4 - \alpha T_{TC}^4\right) + \frac{4h}{D}\left(T_g - T_{TC}\right) = \frac{d}{dx}\left(k\frac{dT_{TC}}{dx}\right) + \frac{4\sigma}{D}\left(\varepsilon_{TC} T_{TC}^4 - \alpha_w T_w^4\right)$$

0 ($\varepsilon_g T_g^4$ term): **very hard to evaluate ε_g & smaller than the other radiation and convection terms**

0 (conduction term): **much smaller as compared to other terms**

0 ($\alpha_w T_w^4$ term): $T_w <<< T_{TC}$

$$\Delta T = T_g - T_{TC} = \sigma\varepsilon_{TC}T_{TC}^4/h$$

(simplified 1D Eq.)

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Assumptions for Analysis

$$\Delta T = T_g - T_{TC} = \sigma \varepsilon_{TC} T_{TC}^4 / h$$ **(simplified 1D Eq.)**

$h = Nu * k / D$

$Nu = Nu(Re)$

$h = h(Re)$

$Re = Re(V)$

$Re = Re(D)$

$\Delta T = \Delta T(V)$

$\Delta T = \Delta T(D)$

Temperature gap strongly depends on the convective velocity and the TC size.

- ***Assumptions for the following theoretical calculation:***
  - TC bead is spherical shape
  - The flame is uniform, and all TCs have the same reading temp.
  - The emissivity of K-type TC (ε_{TC}) is around 0.8.

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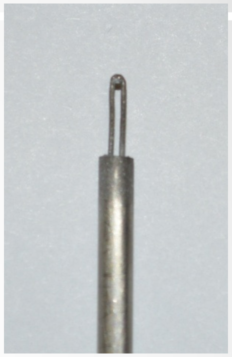
Estimated Temperature Error

fuel	air
2.25 GPH	67.6 SCFM

calibration flame temp. (TC reading temp.)
1920 ^{o}F (1322 K)

measured by K-type TC with 1/8" SS sheath, exposed bead



Calculation Process:

$$\dot{m}_{total} = 0.0403\ kg/s$$

$$V_{gas} = \frac{\dot{m}_{total}}{\rho_{gas} A_{burner}} = 5.22\ m/s$$

$$Re = \frac{\rho_{gas} V_{gas} D_{TC}}{\mu_{gas}} = 14.7$$

$$Nu = 0.42Pr^{0.2} + 0.57Re^{0.5}Pr^{0.33} = 2.33$$

$$h = \frac{Nu * k_{gas}}{D_{TC}} = 313\ {}^{W}/_{m^2 * K}$$

$$\Delta T = \frac{\varepsilon * \sigma * T_{TC}^4}{h} = 443\ K$$

$$T_g = T_{TC} + \Delta T = 1765\ K = 2717\ ^{\circ}F$$

estimated real flame temp.
800^{o}F hotter !!!

- **There is a huge temperature gap around *800 ^{o}F* between thermocouple reading temperature and estimated flame temperature.**
- **The estimated flame temperature is much higher than the TC reading temperature.**

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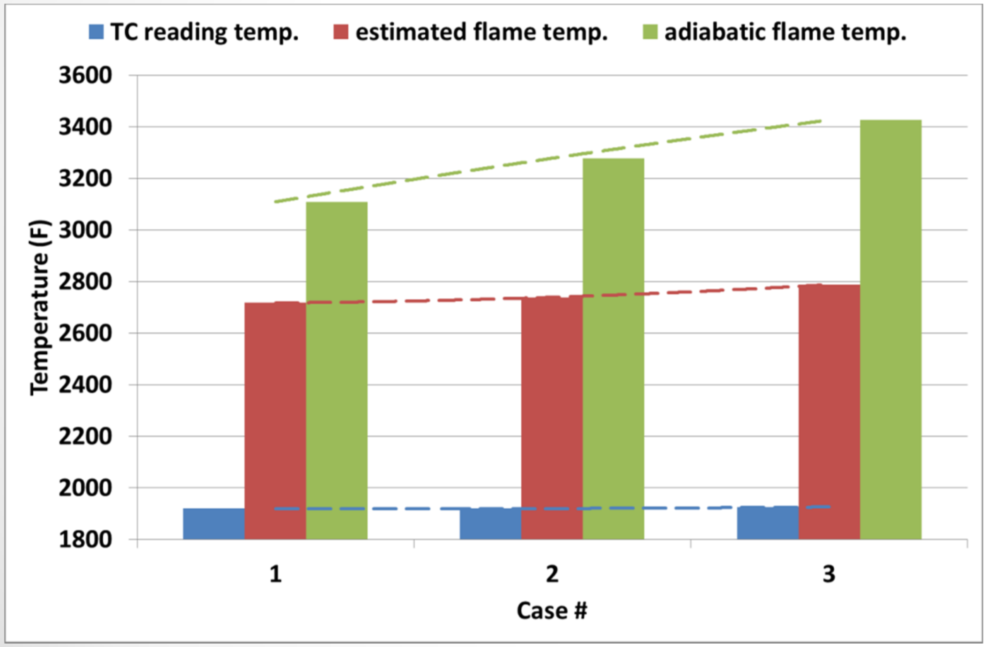
Effect of Convective (Air) Velocity

	test conditions		calibration data				
	fuel (GPH)	air (SCFM)	temp. (°F)	heat flux (BTU/ft^2-s)	**estimated flame temp. (°F)**	**temperature gap, ΔT, (°F)**	**adiabatic flame temp. (°F)**
Case #1	2.25	**67.6**	1920	9.4	**2717**	**797**	**3109**
Case #2	2.25	**62.2**	1920	9.4	**2739**	**819**	**3278**
Case #3	2.25	**57.7**	1926	9.5	**2788**	**862**	**3426**



- **The estimated flame temperature increases with decreasing air flow rate and follows the trend of adiabatic temperature, even though the TC reading temperatures are almost identical among three cases.**

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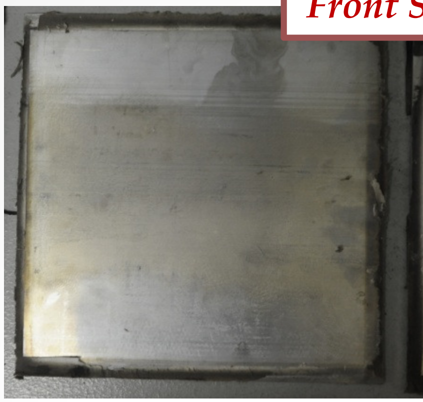
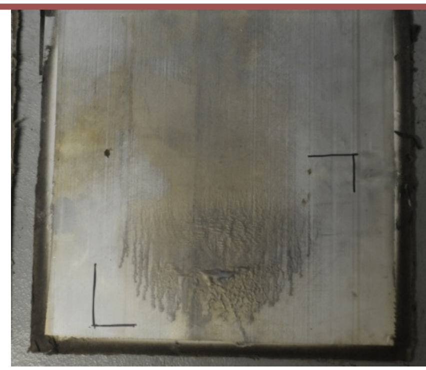
Effect of Convective (Air) Velocity …cont'd

Front Side of Test Panel (after 10 mins)

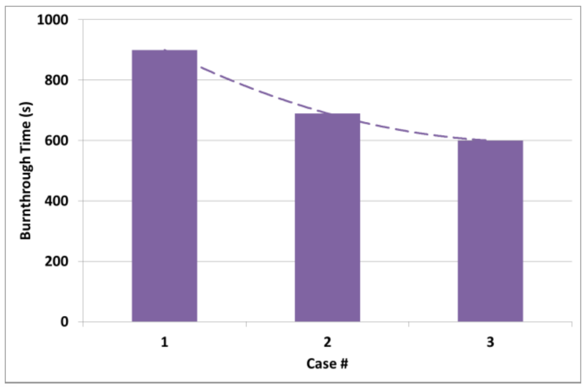


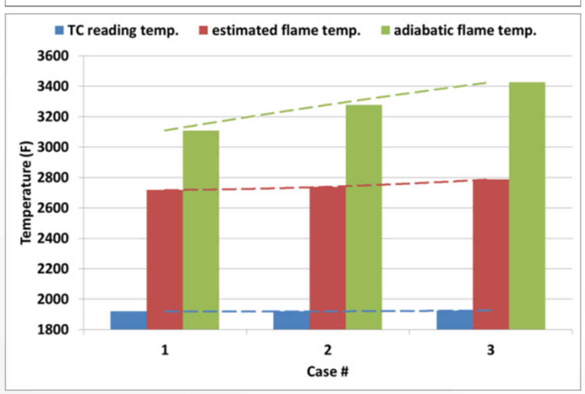
Case #1 (intact)
B.T. = 15 mins



Case #2 (melted)
B.T. = 11.5 mins

Case #3 (burnthough)
B.T. =10 mins





- **The burnthrough time from fire test result shows an inversely proportional relationship with the estimated flame temperature or adiabatic flame temperature.**

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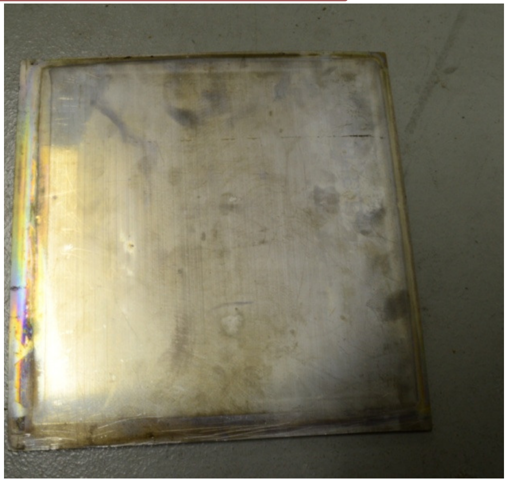
Effect of Thermocouple Size

	test conditions		calibration data			
	fuel (GPH)	air (SCFM)	temp. (F)	heat flux (BTU/ft^2-s)	**estimated flame temp. (ºF)**	**temperature gap, ΔT, (ºF)**
small TCs	2.14	60.4	1919	9.0	**2535**	**616**
big TCs	2.25	62.2	1920	9.4	**2739**	**819**

Front Side of Test Panel (after 10 mins)

big TCs, (melted)
B.T. = 11.5 mins



small TCs, (intact)
B. T. = 15 mins

- **The smaller temperature gap obtained by small TC results in that the small TC could reach the identical reading temperature.**
- **The fire test result shows that the burnthrough time depends on the estimated (real) flame temperature instead of the TC reading temperature.**

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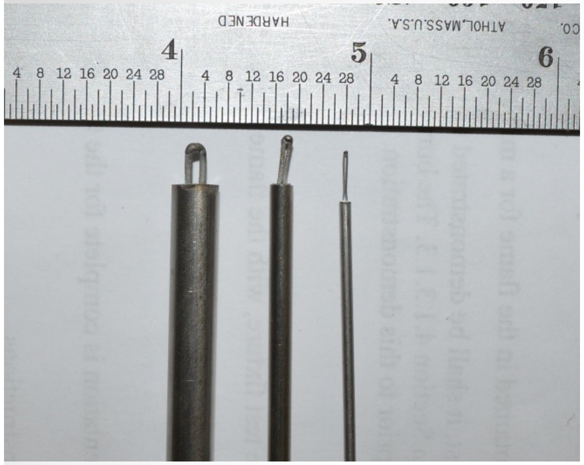
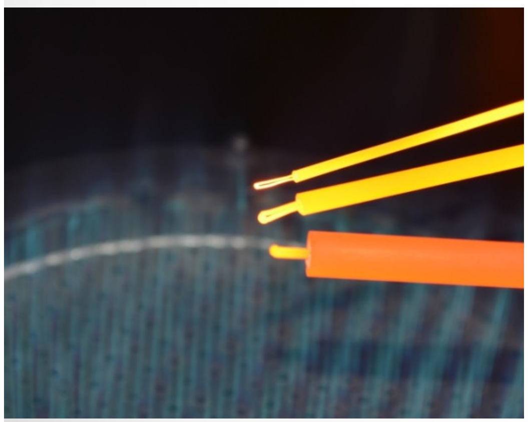
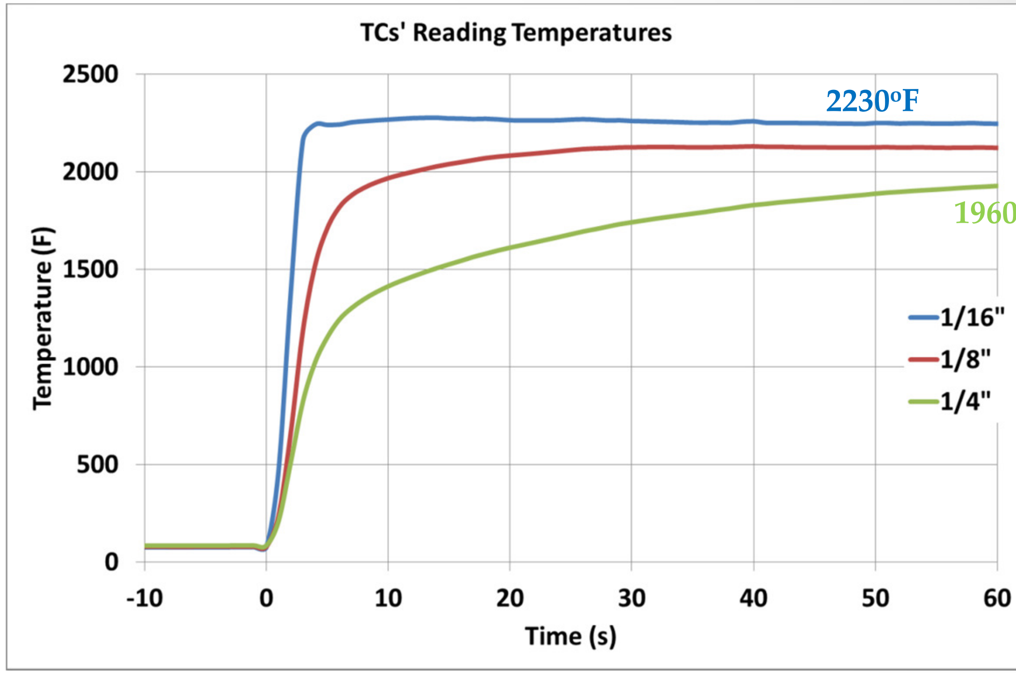
Effect of Thermocouple Size …cont'd



LEFT to RIGHT:
1/4″ SS sheath TC;
1/8″ SS sheath TC;
1/16″ SS sheath TC





	1/16″ TC	1/8″ TC	1/4″ TC
wire size	0.012 inch	0.020 inch	0.039 inch
bead size	0.020 inch	0.033 inch	0.064 inch
AWG	28	24	19

- **The smaller TC could reach higher reading temperature and have faster response time than the bigger TC in the identical fire environment.**

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Literature Review About TC Measurement

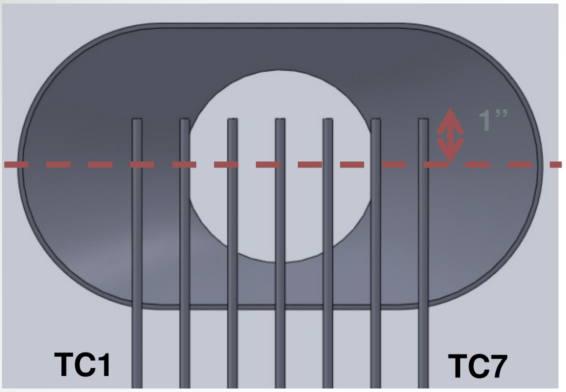
•*According to Blevins' model in 1999, the error of a* ***bare bead thermocouple with diameter*** D_b***=1mm, emissivity ε=0.8, and external convective flow velocity U=0.5m/s*** *could be up to 20%* ***while gas temperature*** T_g***=1400K and ambient temperature*** T_∞***=300 K.*** ***→20% error,*** T_{error}***=280K***

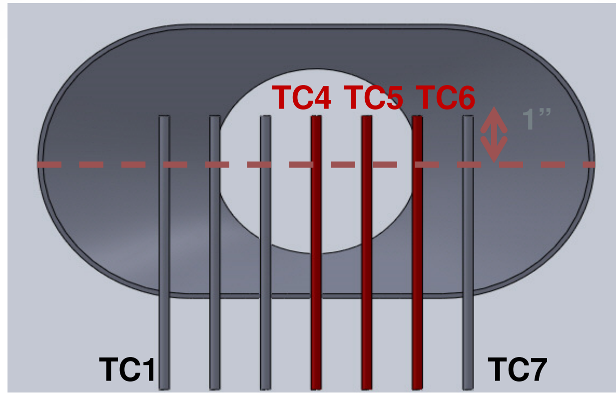
•*If the* ***thermocouple diameter was changed to 1.5mm****, and the remaining rest of properties were kept the same. The error could be up to 340K.* ***→24% error,*** T_{error}***=340K***

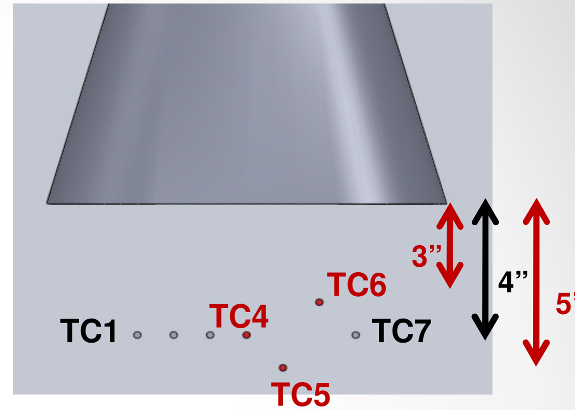
Ref.:

1. Linda G. Blevins, Behavior of Bare and Aspirated Thermocouples in Compartment Fires, Proceedings of the 33rd National Heat Transfer Conference ,Albuquerque, New Mexico, August 15~17, 1999
2. Linda G. Blevins, William M. Pitts, Modeling of Bare and Aspirated Thermocouples in Compartment Fires, Fire Safety Journal, 33 (1999), 239~259

Temperature Distribution Comparison





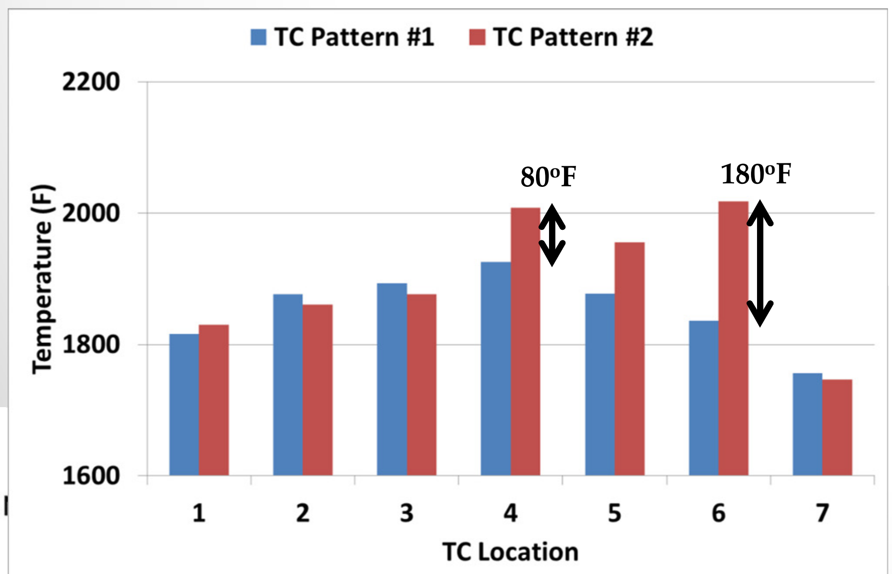


TC Pattern #1

- TC1 – TC7 are identical
- TC size: 1/8″ SS sheathed
- 4″ away from burner exit
- 1″ above the centerline of burner

TC Pattern #2

- TC1 – TC3&TC7:1/8″ SS sheathed
- TC4 – TC6: 1/16″ SS sheathed
- TC1 – TC4&TC7: 4″ away from burner exit
- TC5/ TC6: 5″/ 3″ away from burner exit
- 1″ above the centerline of burner



- **1/16″ TC could get around 100°F higher reading temperature than 1/8″ TC.**
- **The location of TC also shows an impact on the temperature measurement.**

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Summary

- Because of the heat radiation loss, the thermocouple reading temperature is significant lower than the theoretical gas (flame) temperature in the high temperature environment.
- The smaller TC indicates the higher TC temperature and provides quicker response time than the bigger TC.
- The fire test results have been shown to follow the trend of the "adiabatic flame temperature" instead of the "TC reading temperature".
- The location of TC could also have impact on the TC reading temperature.

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