NISTIR 6527

Measurement Needs for Fire Safety: Proceedings of an International Workshop

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U.S. Department of Commerce
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Temperature Measurements in Fires

William M. Pitts
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FORUM Workshop on Measurement Needs for Fire Safety

April 5, 2000

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WHY MEASURE TEMPERATURE IN FIRES?

- High temperatures are a characteristic of combustion.
- High temperatures can generate large radiative fluxes which support fires (e.g., pyrolysis or vaporization of fuels, flame spread, flashover)
- Temperature is an indicator of the potential for damage.
- Temperature is an indirect indicator of heat release rate.
- Rates of chemical reactions are highly dependent on temperature.
  - e.g., reactions of solids, i.e., pyrolysis
  - gas-phase combustion
  - water-gas shift reaction
- Temperature is viewed as one of the easier to measure fire characteristics.

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WHAT ACCURACY IS "REQUIRED" FOR TEMPERATURE MEASUREMENTS IN FIRES?

- Very little guidance available in the literature.
- Little discussion of effects of uncertainty on models and/or correlations.
- It is clear that required accuracy depends on how the data will be used:
  - Estimate flashover time for compartment fire.
  - Determine air flow rate through doorway to ±10% by measuring velocity and density (ideal gas law) of incoming gas.
  - Validate temperature range where approach to thermodynamic equilibrium leads to a significant increase in carbon monoxide formation in rich high-temperature upper layers.

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WHAT TEMPORAL AND SPATIAL RESOLUTION ARE "REQUIRED" FOR TEMPERATURE MEASUREMENTS IN FIRES?

- Very little guidance available in the literature.
- Requirements depend strongly on fire dynamics and the design goals for the experiment.
- In general, experiments designed to test and/or validate field models should have higher spatial and temporal resolution than required for similar tests of zone models.
- Special measurements such as using two temperature signals for velocity measurement may require quite high temporal and spatial resolution.

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TEMPERATURE MEASUREMENT APPROACHES TO BE DISCUSSED

- Soot temperature based on resolving thermal radiation
- Holographic interferometry
- Infrared imaging of surfaces.
- Thermocouples
    - Bare Bead
    - Aspirated
    - Use of several variable-diameter probes

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SOOT TEMPERATURE MEASUREMENT

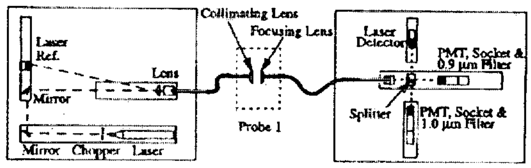

FIGURE 1 Multi-wavelength emission/absorption probe.

- Two-wavelength pyrometry, similar to probe used by Sivathanu and Faeth.
- Measurements recorded inside 6 m x 6 m square pool fire by Gritzo, Sivanthanu and Gill.
- Spectrally resolved thermal radiation at 1.0 and 0.9 µm.
- Two cm long sampling volume, data recorded at 250 Hz.
- Included error analysis, one of largest potential sources was uncertainty for the index of refraction for soot.

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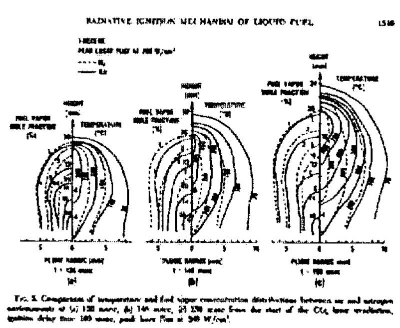
TEMPERATURE MEASUREMENT USING HOLOGRAPHY



- Coherent optical technique
- Used to study fuel vaporization (Kashiwagi et al.) and flame spread over solids (Ito et al.)
- Not widely employed, requires good optical access

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WALL TEMPERATURE MEASUREMENTS USING INFRARED IMAGING

- Technique developed by Arakawa, Saito, and Gruver.
- Records infrared radiation from wall using infrared camera during upward fire spread in a corner.
- Filter to observe radiation in window between 10 μm and 11 μm in order to minimize thermal radiation from heated gases.
- Estimate radiation from soot is much less than that from the walls.
- No detailed uncertainty analysis was provided

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"TYPICAL" THERMOCOUPLE MEASUREMENTS IN REAL-SCALE FIRE ENVIRONMENTS

- By far, the most numerous measurement made in fire tests
- Multiple bare-bead thermocouples positioned throughout test space
- Data recorded digitally with data rates on the order of a few seconds
- Variety of environments
- Generally employ thermocouples with diameters on the order of 0.25 mm
- Usually do not attempt to minimize possible errors in measurements

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WHAT IS THE PROBLEM?

A thermocouple, or any immersion device, can indicate only its own temperature. In general, this will not be equal to the gas temperature unless special precautions are taken. It is the responsibility of the investigator to determine the difference which exists, and to correct for it, or to design the probe such that the difference is acceptably small.

--R. J. Moffat, 1962

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WHY DOES A THERMOCOUPLE JUNCTION TEMPERATURE DIFFER FROM THE LOCAL GAS TEMPERATURE?

Answers

Heating or cooling effects due to:

- Radiation
- Conduction Along Thermocouple Wires
- Catalytic Heating Due to Surface Reaction
- Aerodynamic Heating at High Velocities

Time Response Limitations

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RADIATIVE HEAT TRANSFER TO A THERMOCOUPLE

$$q_{rad} = \sigma\epsilon\left(T_{sur}^4 - T_{tc}^4\right)$$

σ is the Stefan-Boltzmann constant and ϵ is thermocouple emissivity.

THERMOCOUPLE IN STEADY STATE

$$q_{con} = hA(T_g - T_{tc}) = -q_{rad}$$

Substitution gives:

$$T_g - T_{tc} = \frac{\sigma\epsilon\left(T_{tc}^4 - T_{sur}^4\right)}{k_g\left[\frac{0.24 + 0.56\left(\frac{U_o d_o}{\nu}\right)^{0.45}}{d_o}\right]}$$

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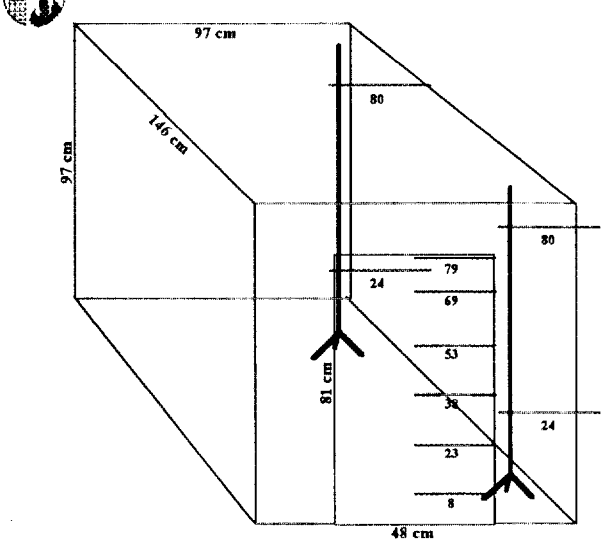

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Picture of Enclosure Fire

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ASPIRATED THERMOCOUPLES

- Adopted design from Glawe, Simmons, and Stickney based on it effectiveness and ease of construction
- Double shield design with flow over inner shield walls
- Both end and side opening versions were constructed
- Also tested much simpler design of Newman and Croce which uses a single shield and is most widely used design in fire testing
- Encountered a paradox: Newman and Croce recommended using an aspiration velocity of 7.7 m/s and claimed "aspirated temperature also appears to approach asymptotically a value which should correspond to the true gas temperature"; earlier literature on aspirated thermocouples indicated that thermocouple "efficiency" increases very slowly with aspiration velocity and recommended use of the highest velocity possible, values up to 150 m/s were employed

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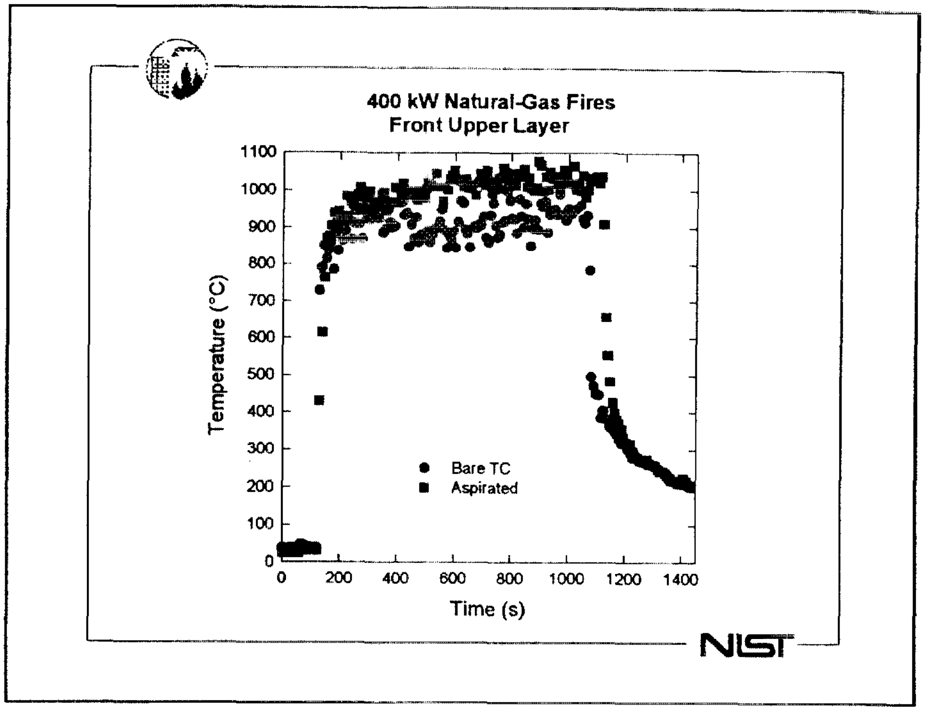
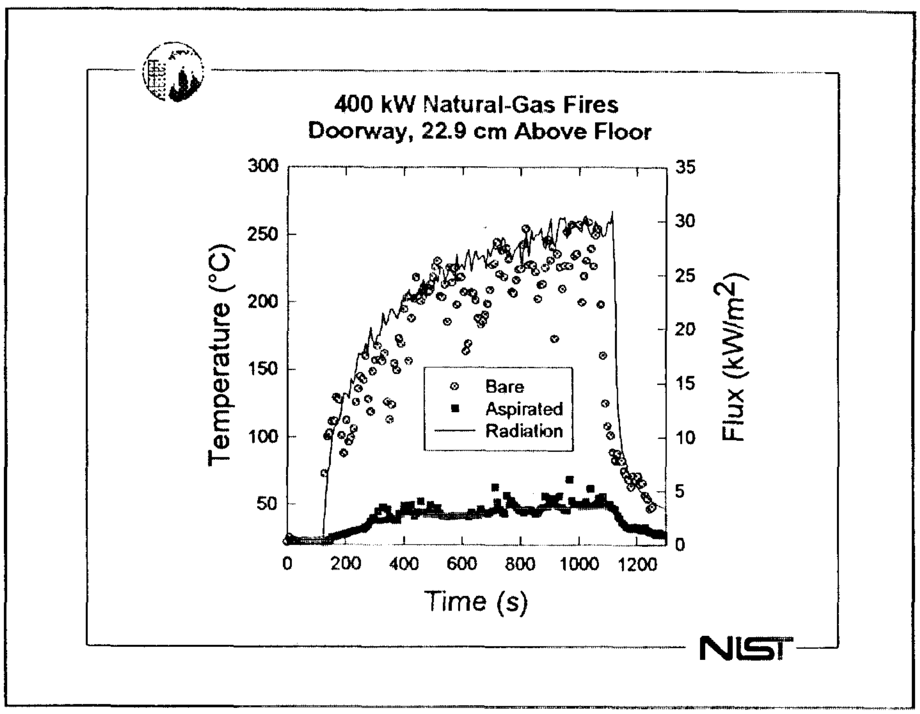
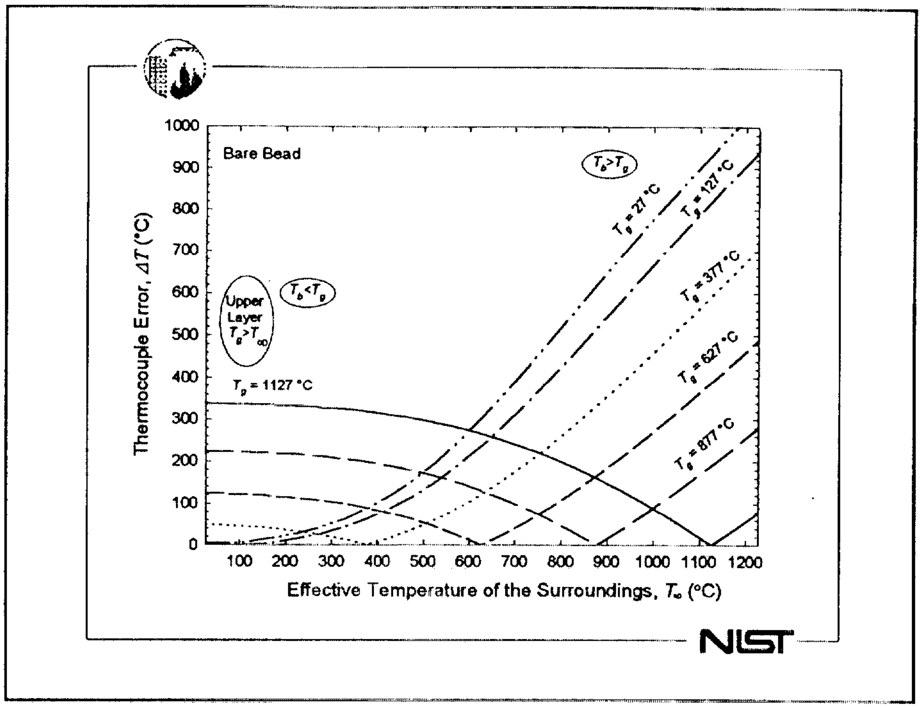

400 kW Natural-Gas Fires
Front Upper Layer
Temperature (°C)
Time (s)
Bare TC
Aspirated
NIST


400 kW Natural-Gas Fires
Doorway, 22.9 cm Above Floor
Temperature (°C)
Flux (kW/m2)
Time (s)
Bare
Aspirated
Radiation
NIST


Bare Bead
Thermocouple Error, ΔT (°C)
Effective Temperature of the Surroundings, T∞ (°C)
Upper Layer
Tg = 1127 °C
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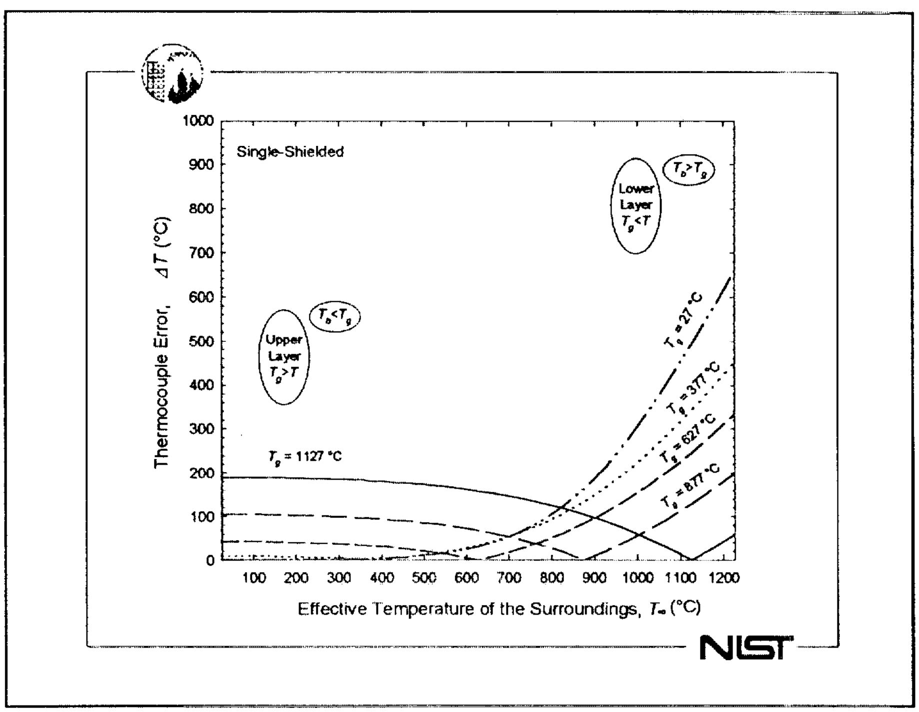
Single-Shielded
Thermocouple Error, ΔT (°C)
Effective Temperature of the Surroundings, T∞ (°C)
Upper Layer
Lower Layer
Tg = 1127 °C
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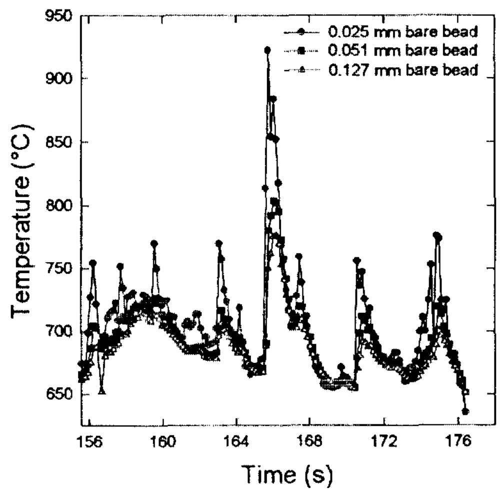
400 kW Natural-Gas Fire
Rear, 80 cm above floor



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THERMOCOUPLE RESPONSE TO A CHANGING TEMPERATURE FIELD

$$T_g - T_{tc} = \tau_{tc}\frac{dT_{tc}}{dt}$$

where τ_{tc} is the time constant for the thermocouple response given by

$$\tau_{tc} = \frac{\rho_{tc}C_{tc}V_{tc}}{h_{tc}A_{tc}}$$

which can be rewritten as

$$\tau_{tc} = \frac{\rho_{tc}C_{tc}V_{tc}d_o}{k_g A_{tc}\left[0.24+0.56\left(\frac{U_o d_o}{\nu}\right)^{0.45}\right]}$$

Note the very strong dependence on the thermocouple diameter. Smaller diamete thermocouples provide much higher time response. The time response also is strongly dependent on local flow velocity, composition, and temperature.

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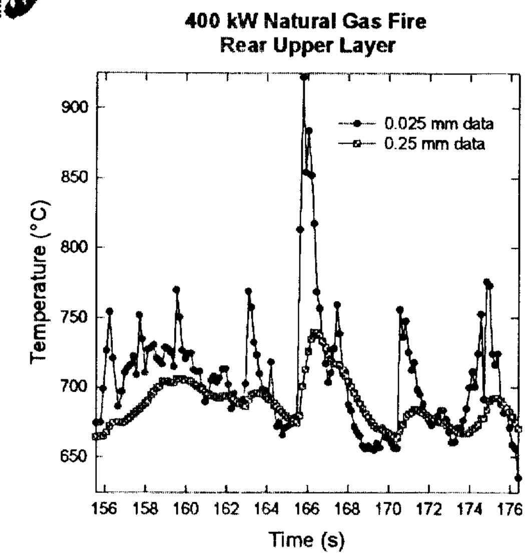

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SPATIAL AND TEMPORAL RESOLUTION FOR THERMOCOUPLE MEASUREMENTS

- Time response for thermocouples typically used in fire experiments vary from few tenths of to greater than one second.
- Is tempting to define the spatial resolution of the probe as the effective size of the sampling area (e.g., bare thermocouple diameter plus boundary layer, volume of gas sampled by aspirated thermocouple).
- Most fire measurements are made in flow field. Effective spatial resolution is most often determined by response time of thermocouple. Consider thermocouple with 0.5 s response time in a flow of 1 m/s. Measurement is made over a length of roughly 0.5 s x 1 m/s = 0.5 m.

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FINAL THOUGHTS

- Approaches need to be developed for estimating errors and uncertainties of temperature measurements in fire environments.
- Effects of spatial and temporal averaging on measured temperatures must be considered.
- Experiments should be designed from the beginning with uncertainty limitations in mind.
- New modeling advances should be used to guide design of experiments and help evaluate uncertainty requirements.

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