Heat Release Uncertainty in the NIST Large Fire Laboratory

NIST/BFRL: Advanced Measurements and Predictive Methods Program

PI: Matthew Bundy

TEAM: Alex Maranghides, Rik Johnsson, Sung Chan Kim, Laurean DeLauter

NIST Annual Fire Conference
Gaithersburg, MD
April 4th and 5th 2007

National Institute of Standards and Technology

In Memory

Jack Lee (1953-2007)

National Institute of Standards and Technology

Large Fire Research Laboratory

- Fire Test Area (high-bay) 37 m x 9.2 m x 11 m
- Flue Gas Cleaning System – Pollution Control (2000)
- 3 Operational Fire Calorimeters
  - 9 m x 12 m hood = 10 MW Calorimeter (2003)
  - 6 m x 6 m hood = 3 MW Calorimeter (2001) NISTIR 7052
  - 3 m x 3 m hood = 500 kW Calorimeter (2005, 2007)

NIST
National Institute of
Standards and Technology

Examples: LFL Heat Release Rate Measurement

Underventilated Compartment fires for FDS validation *(R. Johnsson)*

Hose Stream Effectiveness *(D. Stroup)*

Wildland-Urban Interface Fires *(W. Mell)*

Heat Release Rate Measurement Method

Oxygen Consumption Principle:

$$HRR = (\Delta H_C)_{Mass\_O2}(\dot{m}^o_{O2} - \dot{m}_{O2})$$

Simplifying Assumptions and Physical Measurements:

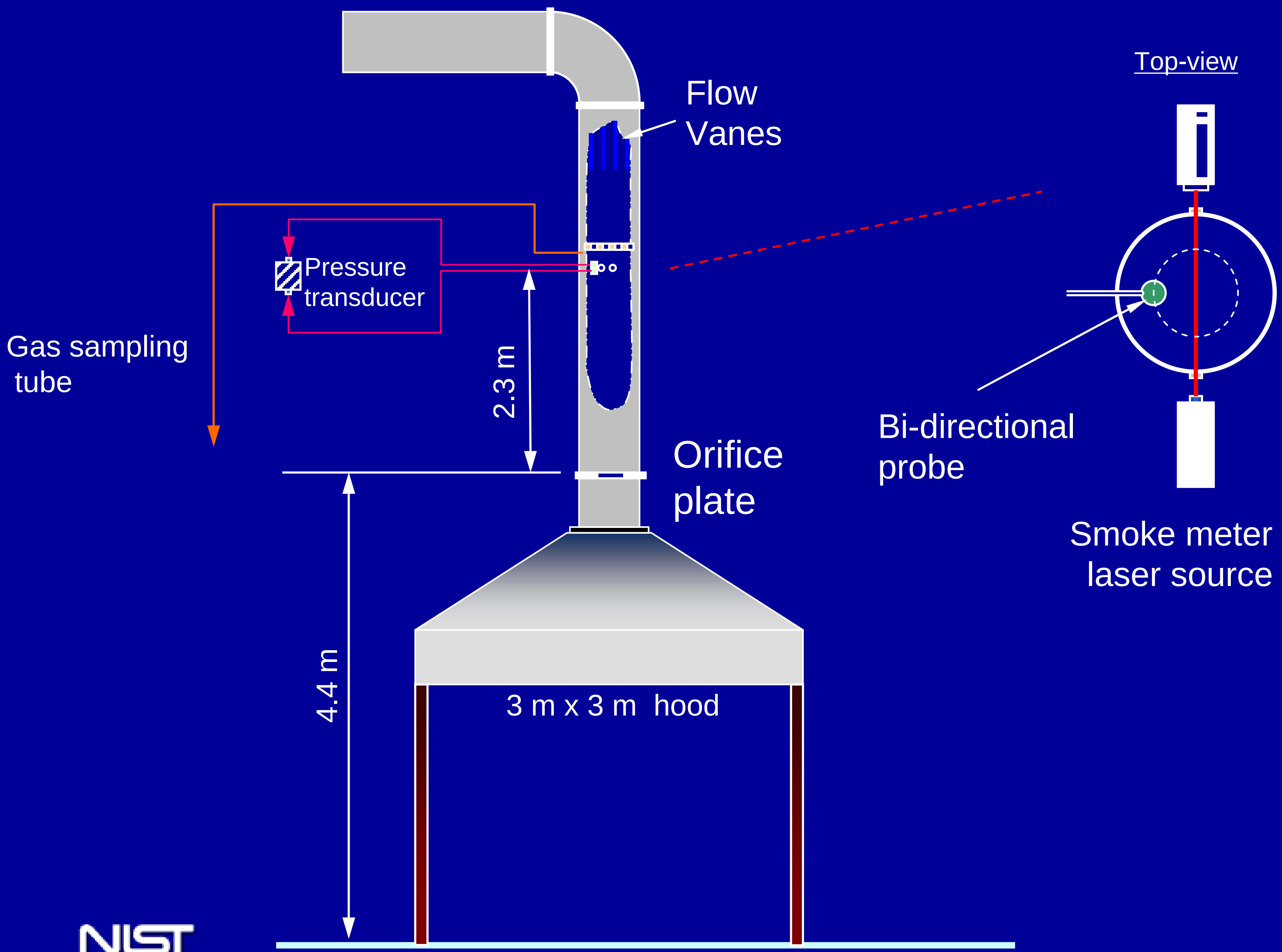
$$\frac{\dot{m}_e}{M_e} = \frac{\dot{m}_{air}}{M_{air}}(1-\phi) + \frac{\dot{m}_{air}}{M_{air}}\phi\alpha \qquad \alpha = 1 + X^o_{O2}(\beta - 1)$$

$$\phi = \frac{\dot{m}^o_{O2} - \dot{m}_{O2}}{\dot{m}^o_{O2}} = \frac{X^o_{O2}(1 - X_{CO2} - X_{CO}) - X_{O2}(1 - X^o_{CO2})}{(1 - X_{O2} - X_{CO2} - X_{CO})X^o_{O2}}$$

$$HRR = (\Delta H_C)_{Mass\_O2}\,\phi\,\frac{\dot{m}_e}{1+\phi(\alpha - 1)}(1 - X^o_{H2O})X^o_{O2}\frac{MW_{O2}}{MW_{air}}$$

National Institute of Standards and Technology

500 kW Calorimeter Exhaust Measurements (2005)



NIST
National Institute of
Standards and Technology

Uncertainty Analysis

Propagation of Uncertainty: $$U_{HRR} = \mathrm{k}\sqrt{\left(\sum_{i=1}^{n} ux_i^{\;2}\left(\frac{\partial HRR}{\partial x_i}\right)^2\right)}$$

x_i = independent variables
ux_i = combined uncertainty of x_i , Type A and B
n = 36 (constants and measured quantities)
k = 2 (95 % confidence level)

Pros:

- Verification of HRR measurement (instead of calibration)
- Prioritize improvements to HRR measurement
- Study general trends and limiting conditions

Cons:

- Correlated variables can lead to over-estimate of uncertainty
- Unidentified physics or measurement processes can produce misleading results

Components of HRR Uncertainty

Table 1. Example of contribution of constant parameters to combined uncertainty in HRR measurement. 500 kW Calorimeter (2005), 180 kW fire.

Variable (x_i)	Units	Value	ux_i (type B)	$2u_c x_i \frac{\partial HRR}{\partial x_i}$ (kW)	Relative Unceratinty
Energy of fuel per O2 (Ef)	kJ/kg O2	13100	350	10.37	5.3%
Energy of CO per O2 (Eco)	kJ/kg CO	17690	10	0.00	0.0%
Expansion Parameter, Alpha (α)	none	1.1	0.048	0.55	0.3%
Molecular Weight dry Air (Mair)	g/mol	28.97	0.1	1.34	0.7%
Molecular Weight Exhaust gas (Me)	g/mol	28.97	0.3	2.01	1.0%
Velocity Shape Factor=Ve/V (Kt)	none	0.85	0.025	11.42	5.9%
Velocity Probe Constant (Kp)	none	1.08	0.05	17.97	9.3%
Ideal Gas Constant (R)	m^3 Pa/K/kmol	8314.47	5.00E-03	0.00	0.0%
Duct Diameter (D)	m	0.4825	2.00E-03	3.22	1.7%
Oxygen Span Gas (O2span)	none	0.2095	5.00E-04	1.16	0.6%
Oxygen Zero Gas (O2zero)	none	0	2.00E-04	0.47	0.2%
CO_2 Span Gas (CO2span)	none	0.02797	2.80E-04	0.51	0.3%
CO_2 Zero Gas (CO2zero)	none	0	2.00E-05	0.51	0.3%
CO Span Gas (COspan)	none	0.0028	2.80E-05	0.00	0.0%
CO Zero Gas (COzero)	none	0	1.00E-06	0.00	0.0%
Velocity Pressure Sensitivity (Pcal)	Pa/V	133.36	5.00E-03	0.01	0.0%

Components of HRR Uncertainty

Table 2. Example of contribution of variable parameters to combined uncertainty in HRR measurement. 500 kW calorimeter (2005), 180 kW fire.

Variable (x_i)	Units	Value	ux_i (type A)	ux_i (type B)	$2u_c x_i \frac{\partial HRR}{\partial x_i}$ (kW)	Relative Unceratinty
Oxygen Zero Voltage (O2zeroV)	V	-3.1E-03	5.0E-05	2.5E-05	0.03	**0.0%**
Oxygen Span Voltage (O2spanV)	V	8.4E-01	5.0E-05	2.5E-05	0.03	**0.0%**
Oxygen Voltage (O2V)	V	8.2E-01	2.2E-04	2.5E-05	4.28	**2.2%**
Ambient Oxygen (O2oV)	V	8.4E-01	2.9E-05	2.5E-05	0.75	**0.4%**
Oxygen Pressure Voltage (O2PCV)	V	7.4E+00	1.7E-04	2.5E-05	0.01	**0.0%**
Press Ref Voltage (O2PCVo)	V	7.4E+00	1.7E-04	2.5E-05	0.01	**0.0%**
CO_2 Zero Voltage (CO2zeroV)	V	-3.6E-04	5.0E-04	2.5E-05	0.01	**0.0%**
CO_2 Span Voltage(CO2spanV)	V	4.6E+00	5.0E-04	2.5E-05	0.01	**0.0%**
Carbon Dioxide Voltage (CO2V)	V	6.0E-01	3.6E-03	2.5E-05	0.35	**0.2%**
Ambient CO_2 (CO2oV)	V	6.9E-02	5.5E-04	2.5E-05	0.05	**0.0%**
CO Span Voltage (COzeroV)	V	3.7E-04	1.0E-03	2.5E-05	0.02	**0.0%**
CO Zero Voltage (COspanV)	V	4.6E+00	1.0E-03	2.5E-05	0.00	**0.0%**
Carbon Monoxide Voltage (COV)	V	1.8E-03	5.6E-04	2.5E-05	0.01	**0.0%**
Exhuast Flow Pressure Voltage (PV)	V	8.8E-01	7.2E-02	2.5E-05	15.71	**8.1%**
Exhuast Flow Zero Voltage (PzeroV)	V	-2.7E-03	5.0E-05	2.5E-05	0.01	**0.0%**
Exhaust Temperature (Te)	K	3.7E+02	8.7E-01	1.3E+00	0.81	**0.4%**
Ambient Pressure (Pamb)	Pa	1.0E+05	2.2E+00	6.7E+02	1.30	**0.7%**
Ambient Relative Humidity (RH)	%	6.3E-01	4.2E-03	2.0E-02	0.00	**0.0%**
Ambient Temperature (Tamb)	C	2.7E+01	1.4E-02	1.3E+00	0.00	**0.0%**

NIST
National Institute of Standards and Technology

Natural Gas Burner HRR Uncertainty

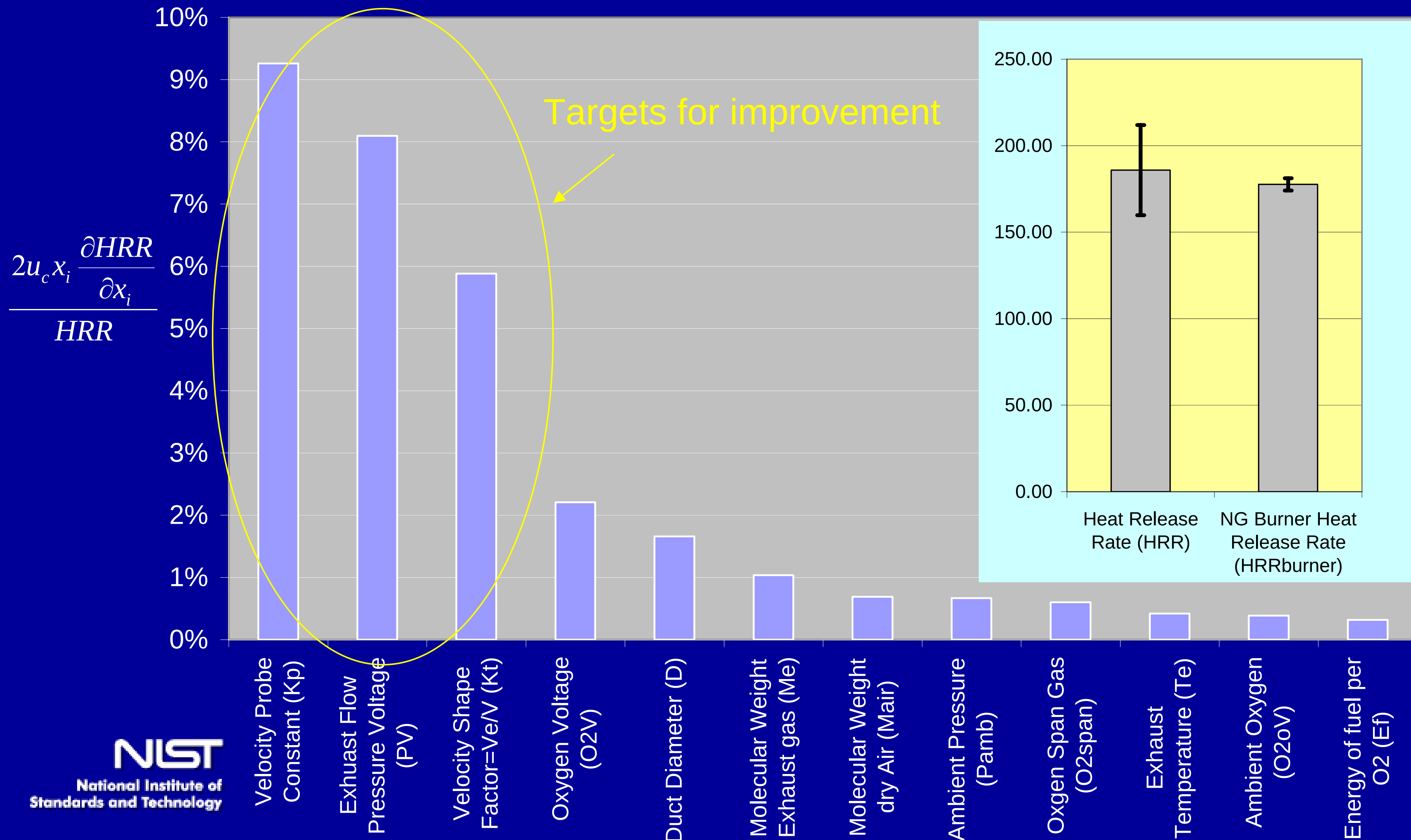
Table 3. Example of components of uncertainty in controlled natural gas fire.

Variable (x_i)	**Units**	**Value**	**ux_i (type A)**	**ux_i (type B)**	$2u_c x_i \frac{\partial HRRburner}{\partial x_i}$ **(kW)**	**Relative Unceratinty**
Natural Gas Energy Value (NGhoc)	MJ/m^3	34.027	1.0E-02	2.55E-01	2.66E+00	**1.500%**
NG Flowmeter Factor (K)	$pulses/cm^3$	0.0005	0.0E+00	3.00E-06	2.10E+00	**1.181%**
Pulse Counter Voltage	V	0.0857	8.3E-05	2.50E-05	3.58E-01	**0.202%**
Pulse Counter Zero Voltage	V	-0.0007	3.7E-05	2.50E-05	1.85E-01	**0.104%**
NG Pressure Voltage	V	0.0170	9.4E-07	2.50E-05	5.24E-01	**0.295%**
NG Pressure Gauge Sensitivity	psia/V	1658.5	0.0E+00	1.50E+00	3.21E-01	**0.181%**
NG Temperature	K	300.8	1.2E-02	6.40E-01	7.56E-01	**0.426%**
NG Burner Heat Release Rate (HRRburner)	kW	**177.63**			**3.55**	**2.00%**

Example: Uncertainty Results – Verification

180 kW steady natural gas fire, 3 m x 3 m hood, 2 kg/s (2005 config.)

U_{HRR} =14% (known fuel), U_{HRR} =15% (unknown fuel),
U_{HRR}=20% (unknown fuel and variable fire position)

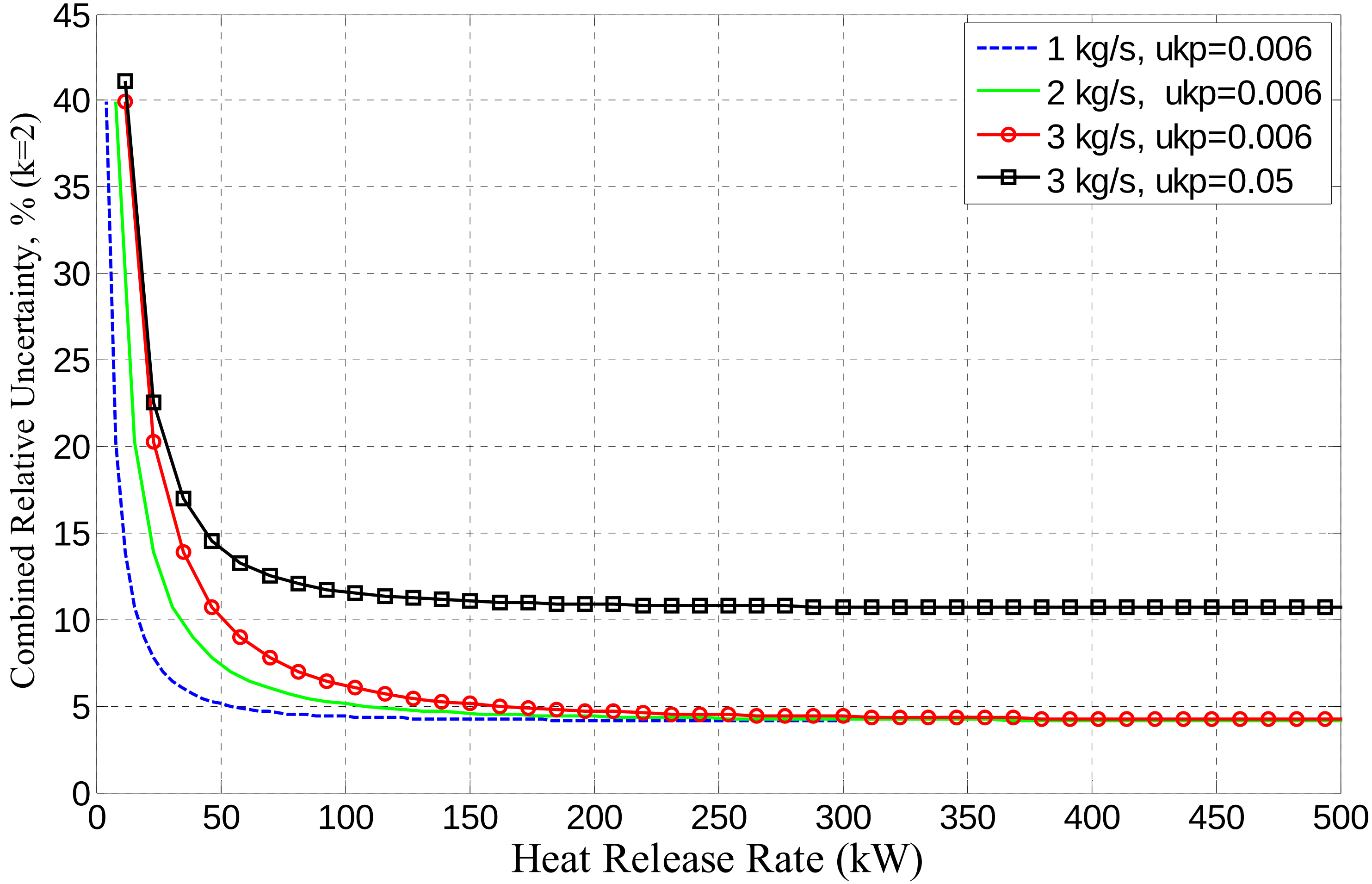


NIST
National Institute of Standards and Technology

Parametric Study of HRR Uncertainty , 500 kW Calorimeter

Assume only Type B uncertainties (ideal case), Methane Fire

Observe effects of probe constant and exhaust flow rate on U_{HRR}



NIST

National Institute of Standards and Technology

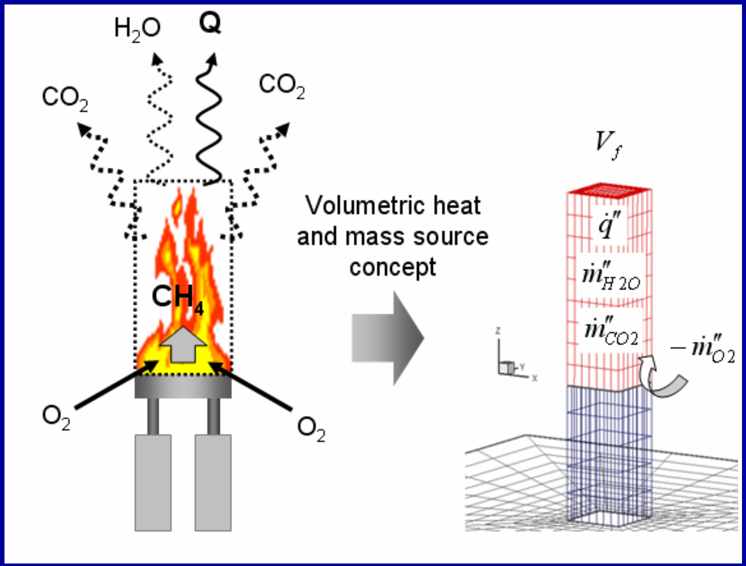
CFD model of HRR measurement

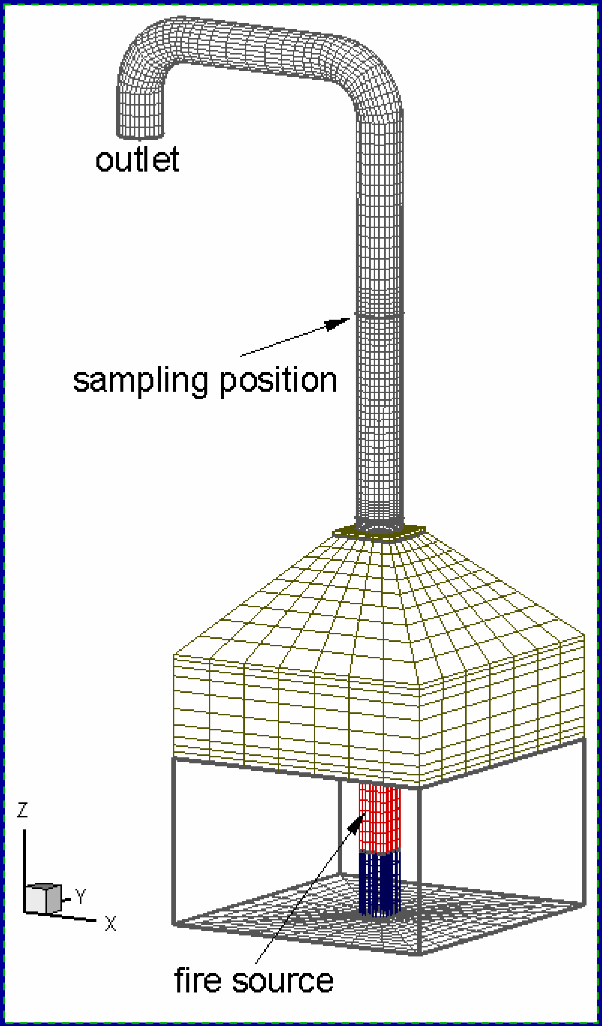
CFD Solver : FLUENT v.6.0

- ✓ Turbulent model : Std. k-ε model with buoyancy modification
- ✓ Density : Incompressible ideal gas
- ✓ Pressure-velocity coupling : SIMPLE algorithm
- ✓ Differential scheme : 2nd order upwind scheme

Fire Source Model:

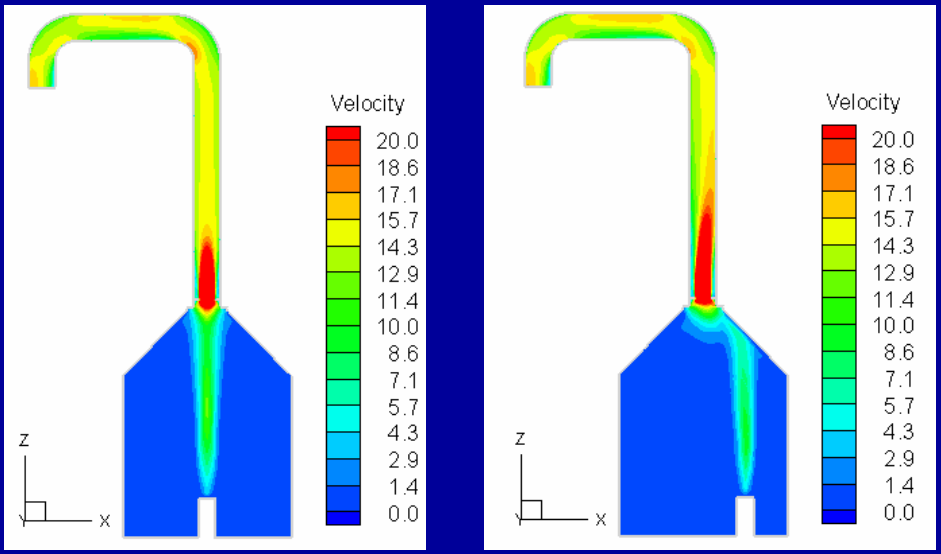
Volumetric heat and mass source model (VHMS)



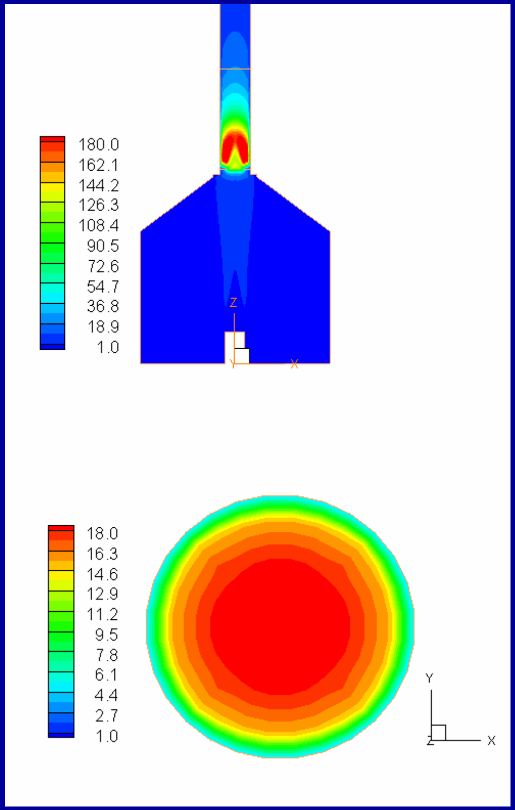


National Institute of Standards and Technology

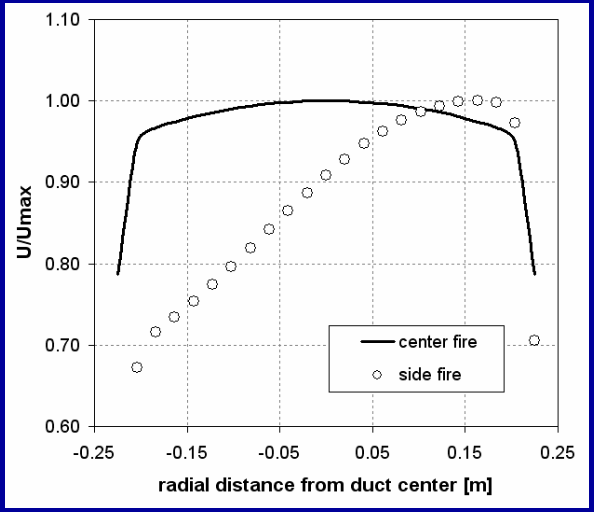
CFD modeling results
200 kW methane fire, 3 m Hood



Velocity Fields



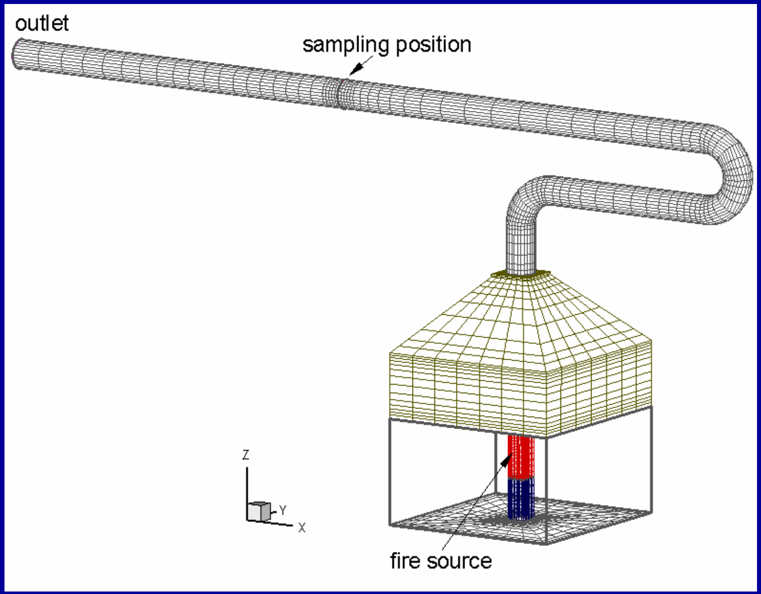
Turbulent Kinetic Energy



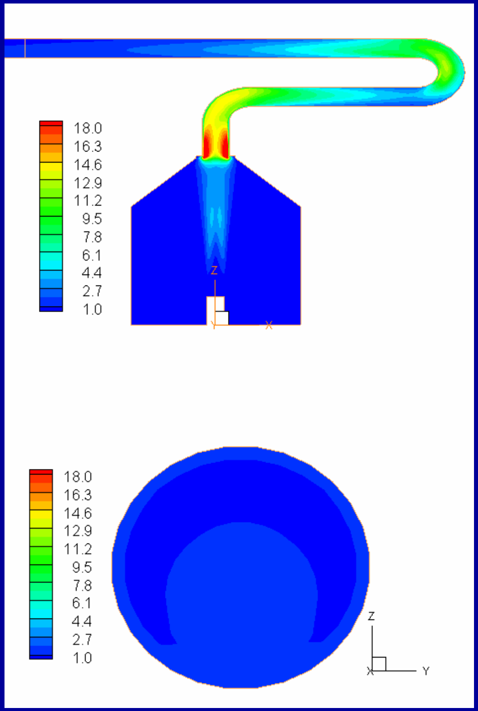
Velocity Profiles

National Institute of Standards and Technology

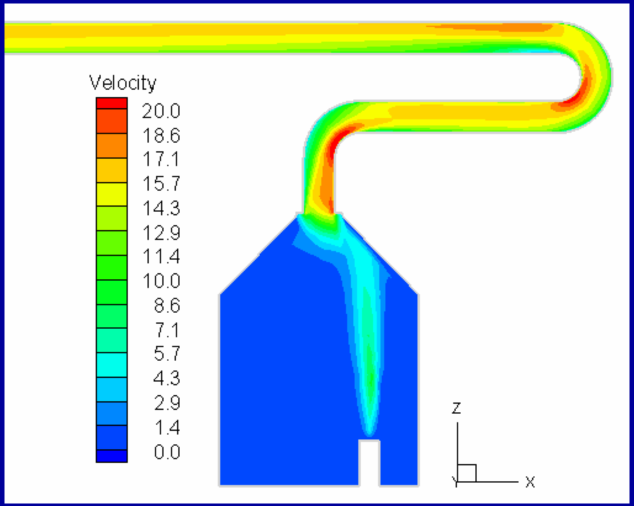
CFD modeling results



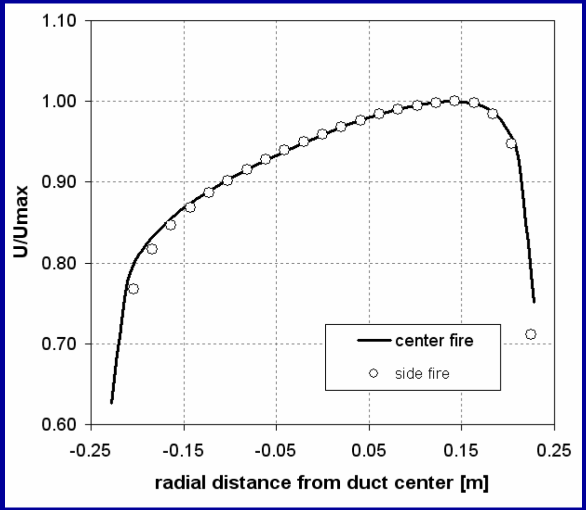
New design for exhaust duct geometry



Turbulent kinetic energy



Velocity field



Velocity profile

NIST National Institute of Standards and Technology

New Exhaust Flow Rate Measurement
500 kW Calorimeter

Reconfigured Exhaust Duct Configuration (Jan 2007)
- 50 feet of new ductwork added
- Instrumentation now on horizontal section of duct

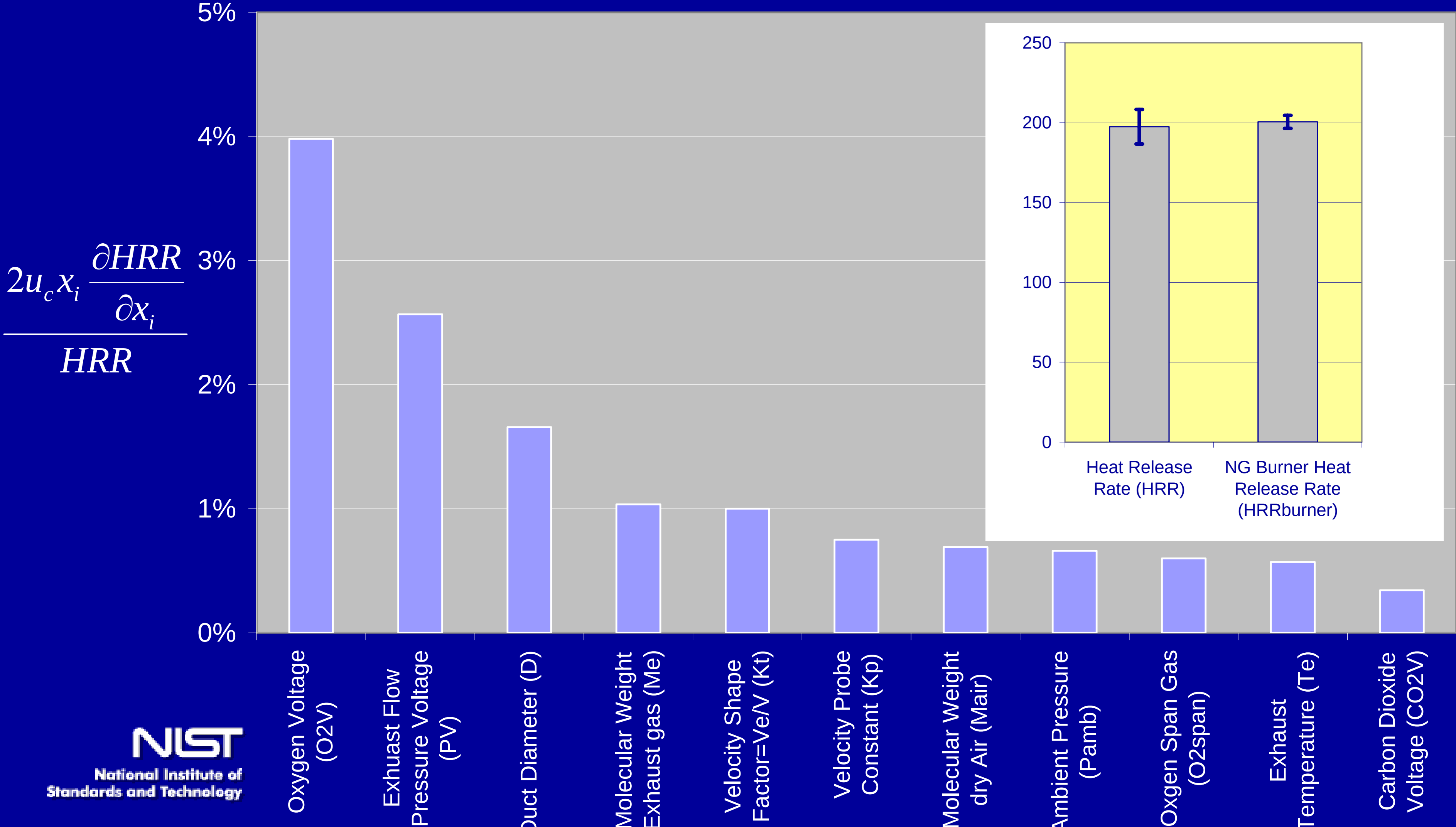
Averaging Pitot Tube:
- Insensitive to small changes in velocity profile shape
- Probe constant uncertainty = 0.75 %
- Needs to be tested with highly sooting fires

National Institute of Standards and Technology

Example: Uncertainty Results – Verification

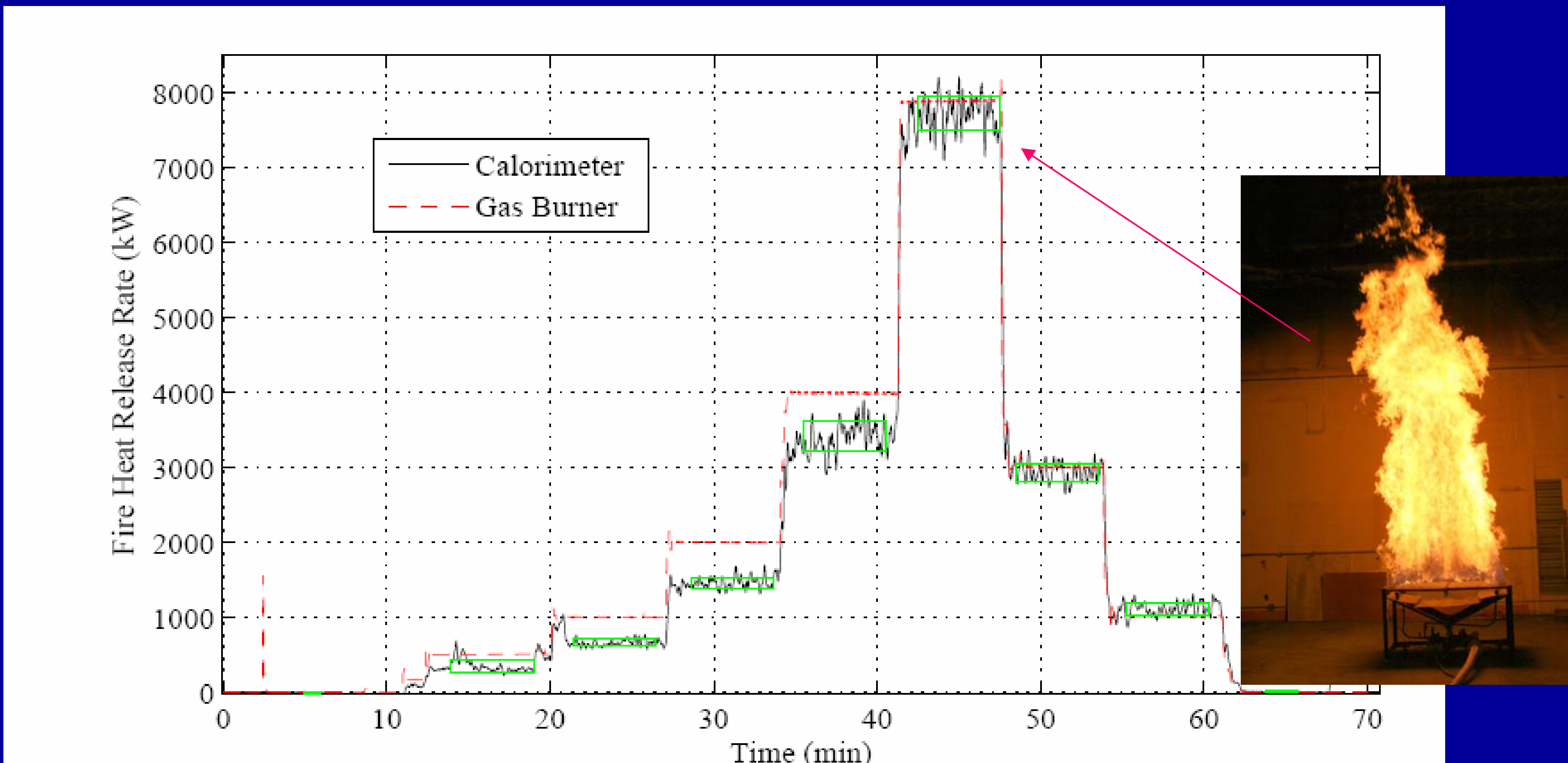
200 kW steady natural gas fire, 3 m x 3 m hood, 2 kg/s (2007 config.)

U_{HRR} =5.5% (known fuel), U_{HRR} = 8 % (unknown fuel),
U_{HRR}= 8 % (unknown fuel and fire position)



National Institute of Standards and Technology

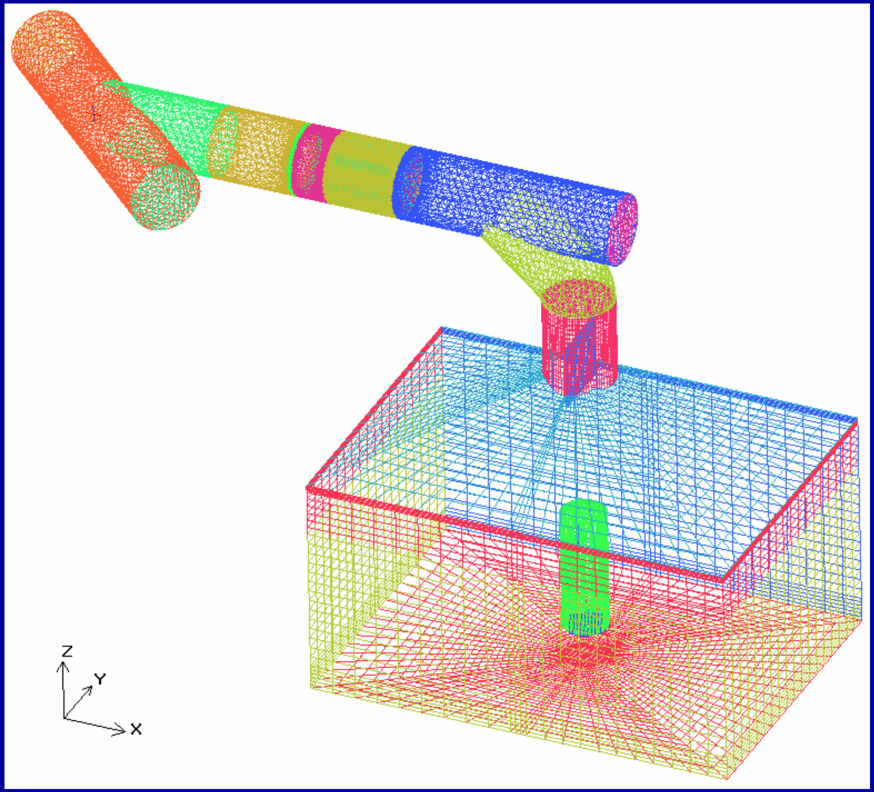
10 MW Calorimeter,
Natural Gas Verification Fire Test

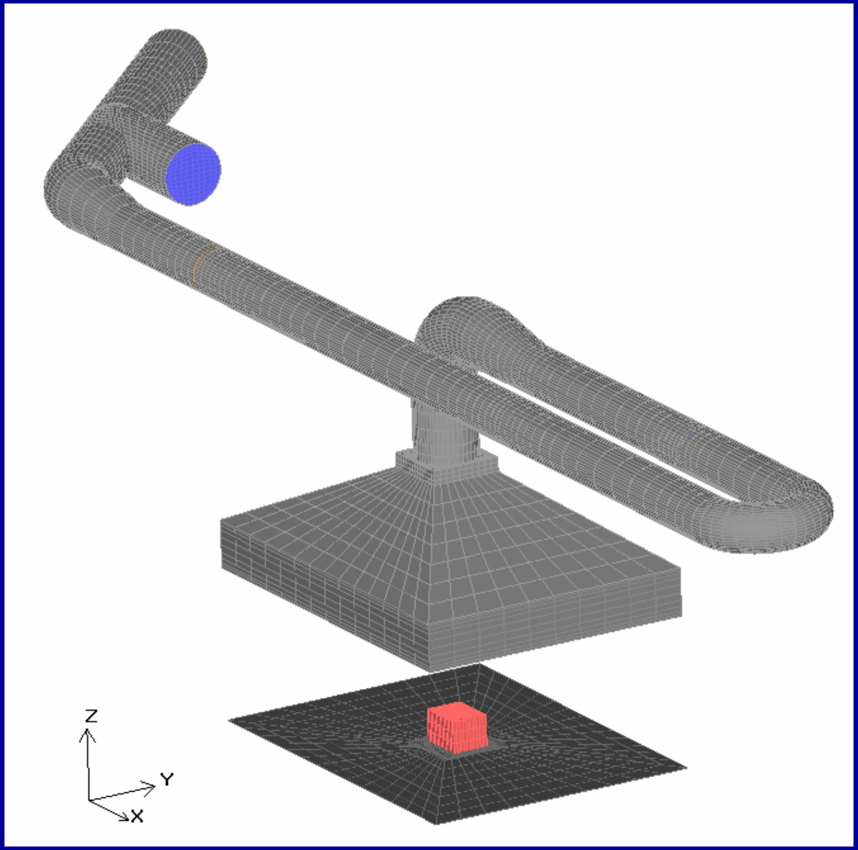


NIST
National Institute of
Standards and Technology

Future Plans

- Proposed modification to 10 MW calorimeter





Summary

- Completed new design and installation of the 500 kW calorimeter (3 m x 3 m hood) exhaust duct

- A new method for exhaust flow measurement has been implemented in the 500 kW calorimeter

- Recent changes in the 500 kW calorimeter have significantly reduced the uncertainty in the HRR measurement

- A plan for reducing the uncertainty in the 10 MW calorimeter (9 m x 12 m hood) has been developed