Using the National Fire Research Laboratory as a Test Bed for Traceable CO_2 Measurements

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Workshop on Measurement Challenges and Metrology for Monitoring CO_2 Emissions from Smokestacks

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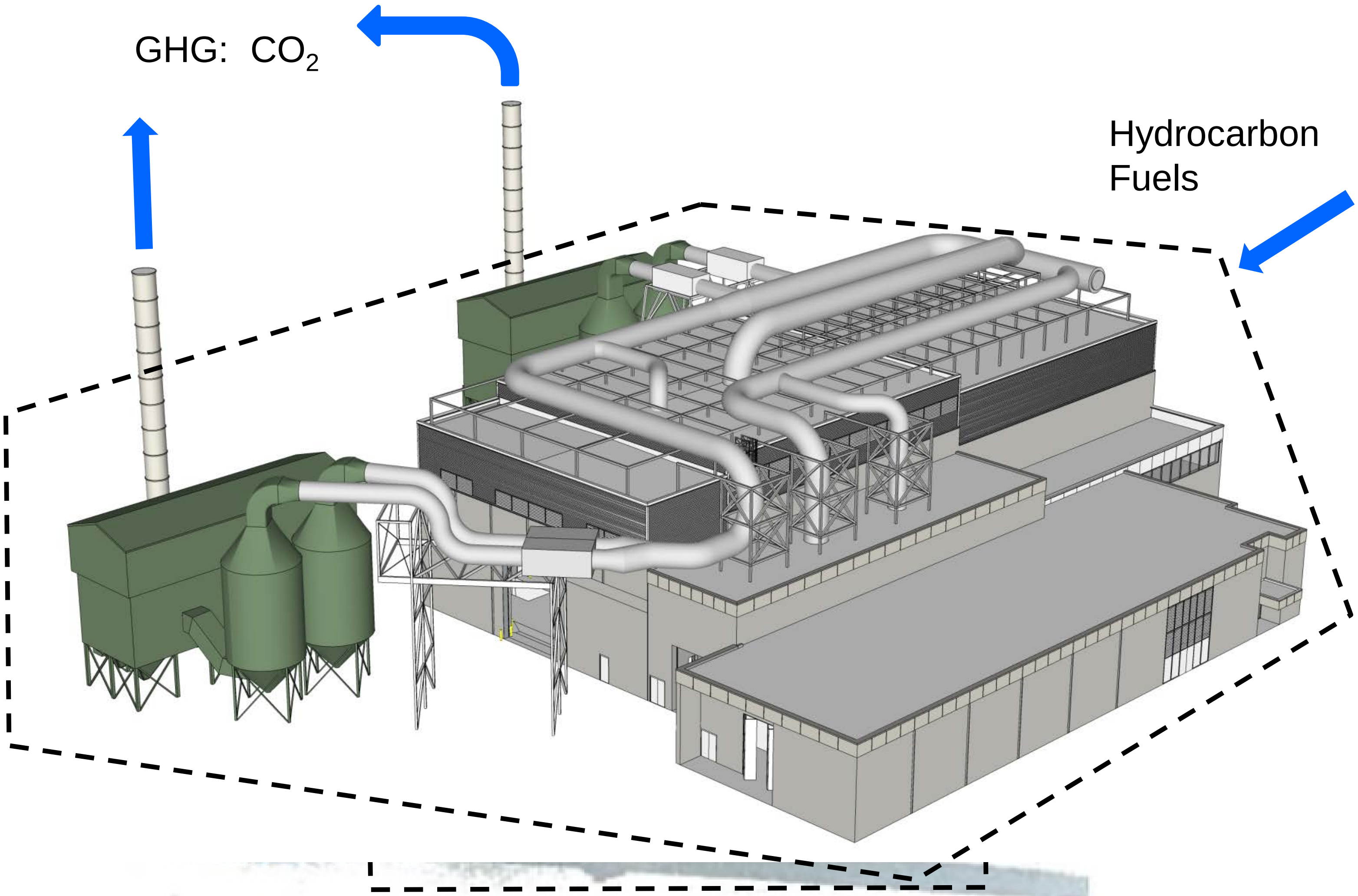
Project Objective: To create a well-characterized and highly accurate reference measurement system at near industrial scale to serve as a test bed for carbon dioxide emissions measurements.

- Scale-Model Smokestack Simulator
- National Fire Research Laboratory
- Goal: Measure CO_2 emissions with ±1% uncertainty
- Reconcile the carbon mass balance at the source
  - Predicted Emissions vs Direct Emissions

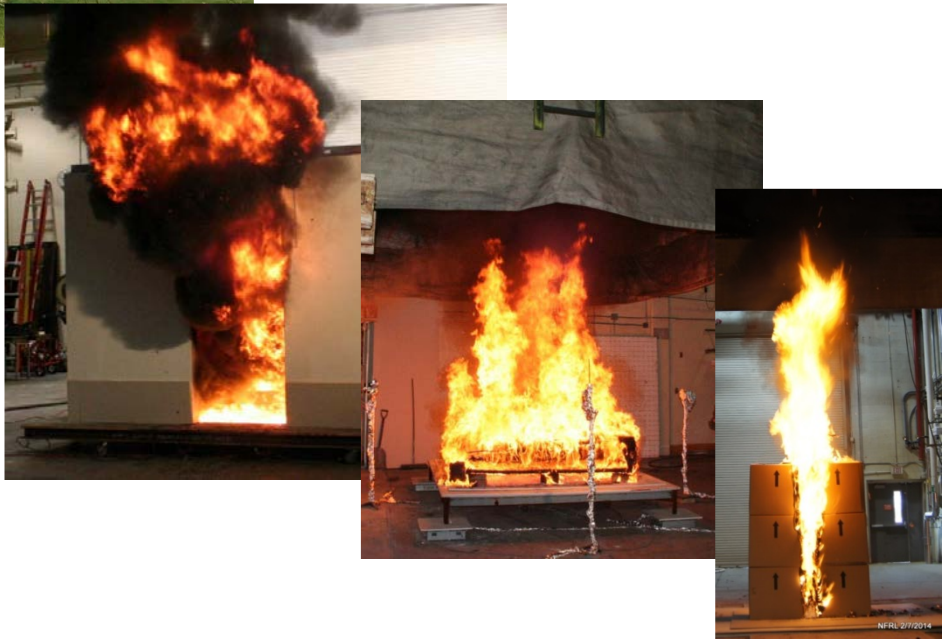
The National Fire Research Laboratory (NFRL) is analogous to a stationary source, only smaller.



Graphics courtesy of: N. Pearson, “The Carbon Numbers Game”, Bloomberg Markets, v42, Jan 2011

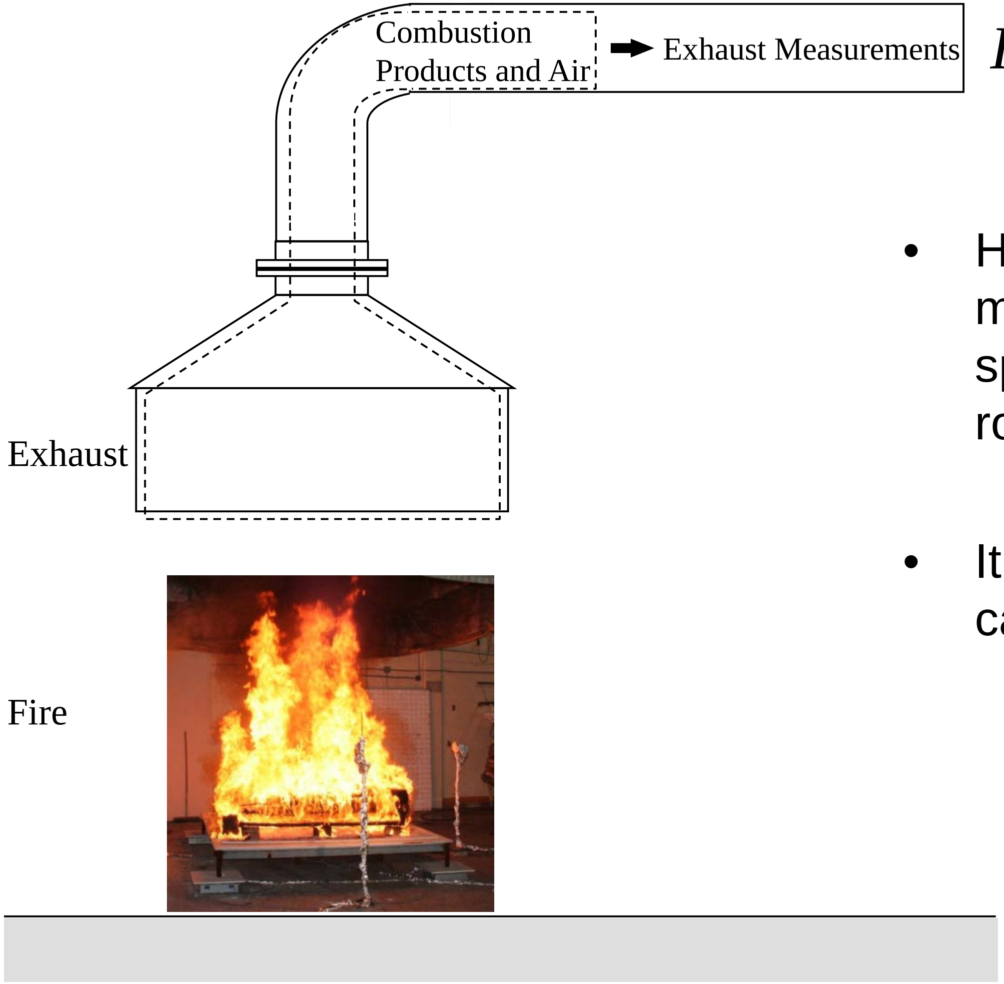
NFRL is a unique facility that provides large-scale fire and structural measurements to fire and building researchers.

- Support fire model validation studies
- Enable fire investigations
- Support post disaster and failure studies
- Enable advances in fire measurements, standards, and codes



- Heat released
- Flame spread
- Fire Spread
- Smoke movement and toxicity
- Early detection and abatement

The rate of heat released by a burning material is the primary measurement of the NFRL.



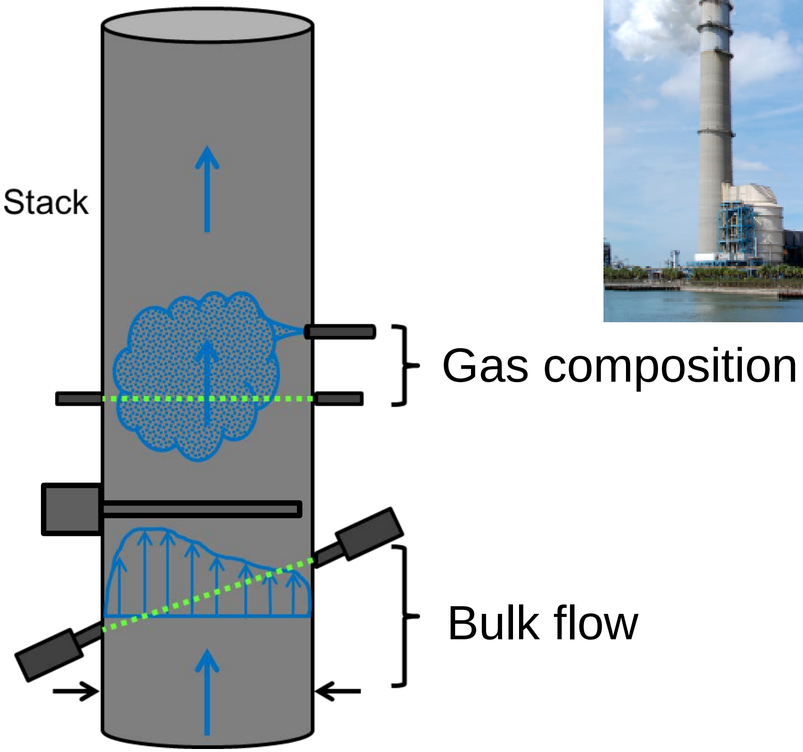
$$HRR = (\Delta H_C)_{Mass\_O2}(\dot{m}^o_{O2} - \dot{m}_{O2})$$

- Heat Release Rate (HRR) is a measure of the potential for a fire to spread to other objects and beyond the room of origin

- It is derived from oxygen consumption calorimetry

Fire research and the emissions industry share a common problem: accurate characterization of flow and concentration in an industrial scale flue gas.

$$\dot{m}_i = Y_i \, \rho \, u \, A$$

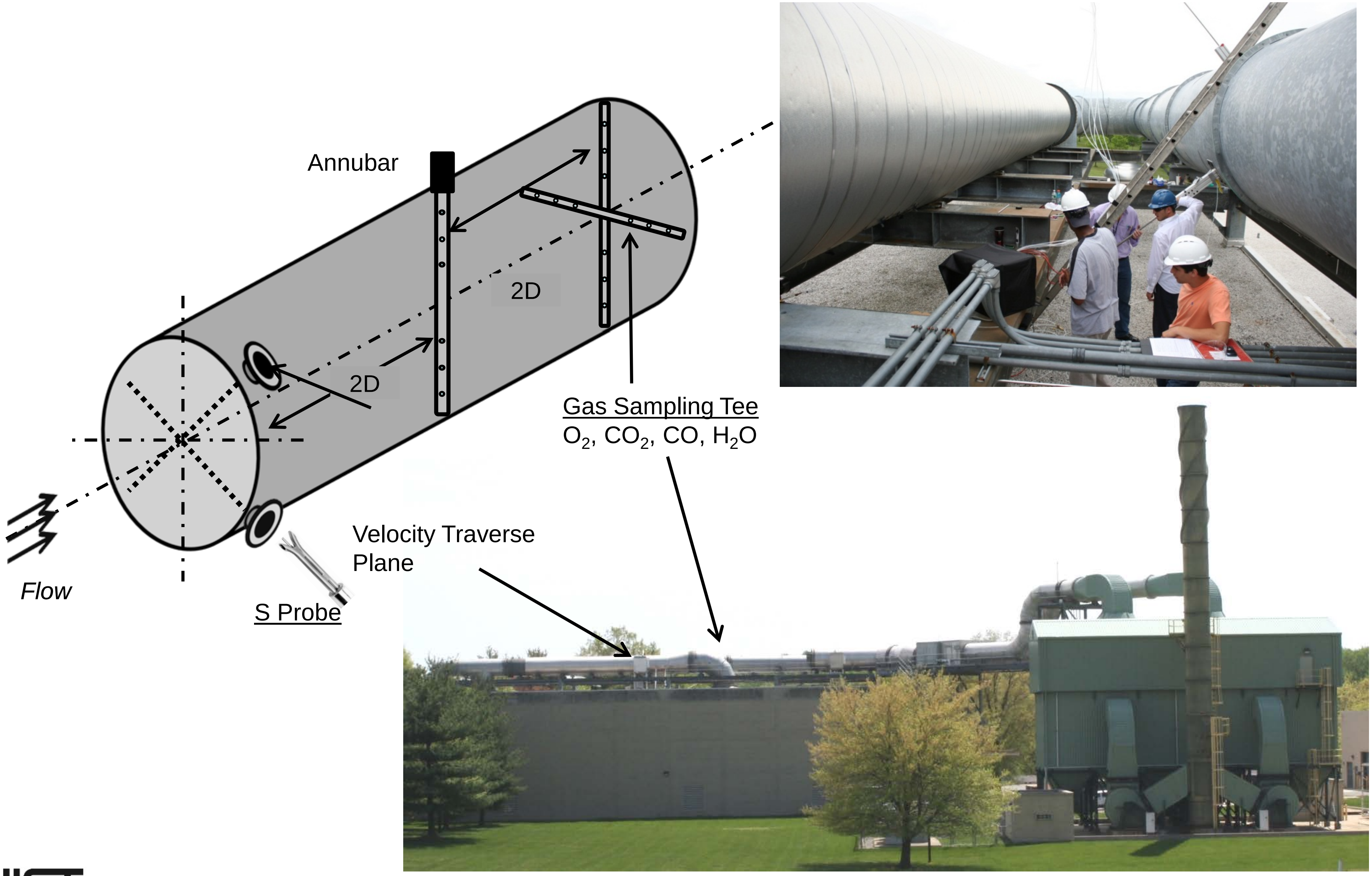



Source: North American Carbon Storage Atlas Partnership, http://gis.netl.doe.gov/NACAP/

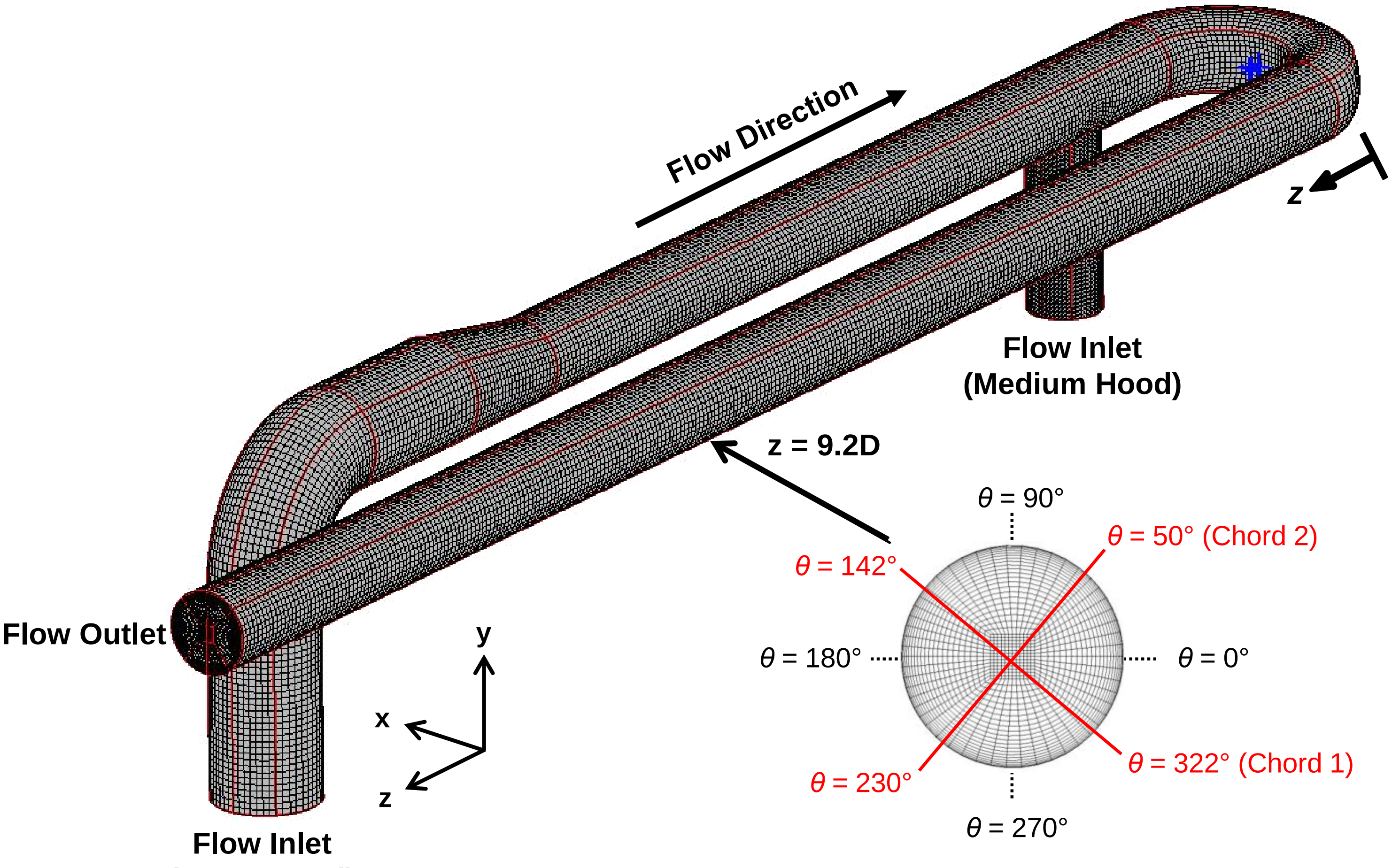
$$HRR = (\Delta H_C)_{Mass\_O2} \left(\dot{m}^{o}_{O2} - \dot{m}_{O2} \right)$$

Flow and Concentration

Routine emissions measurements are conducted in the exhaust duct at the roof of the facility.



Flow path



Traversing Plane Meshing
(Looking from upstream
to downstream)

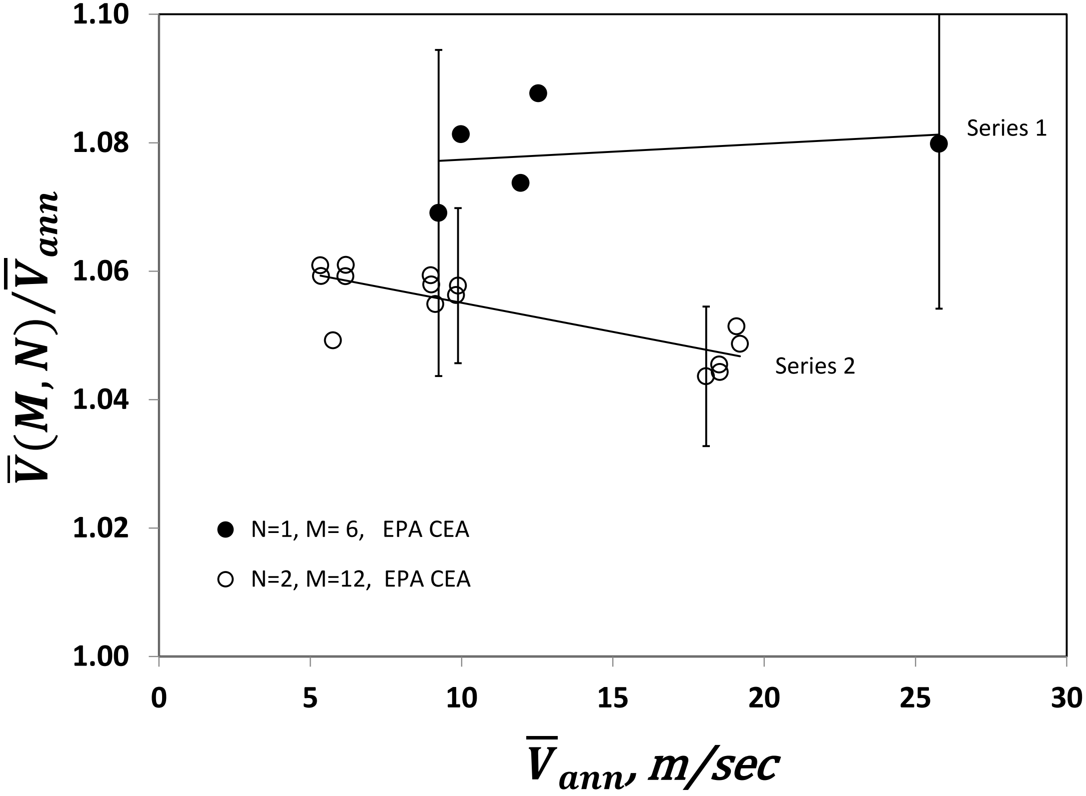
Independent flow RATAs to determine average stack gas velocity agreed to within 4%.

- Followed EPA test methods 1*, 2 and 2G

- Series 1: NIST
  - 1 chord at a time*
  - Scoping measurements*
  - $U_{V(M,N)} = \pm 2.6\%$

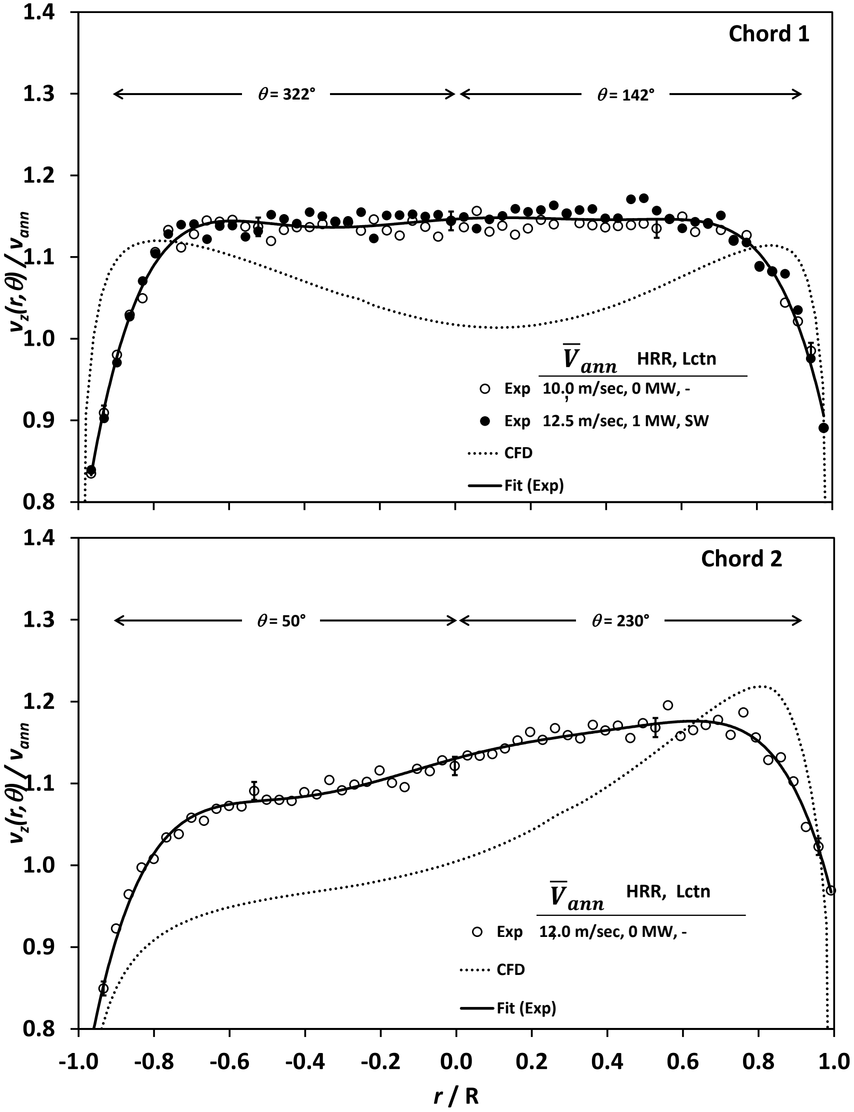
- Series 2: Stack Testing Company (STC)
  - 2 chords simultaneously
  - $U_{V(M,N)} = \pm 1.4\%$

- Annubar provides reference measurement between series 1 and 2

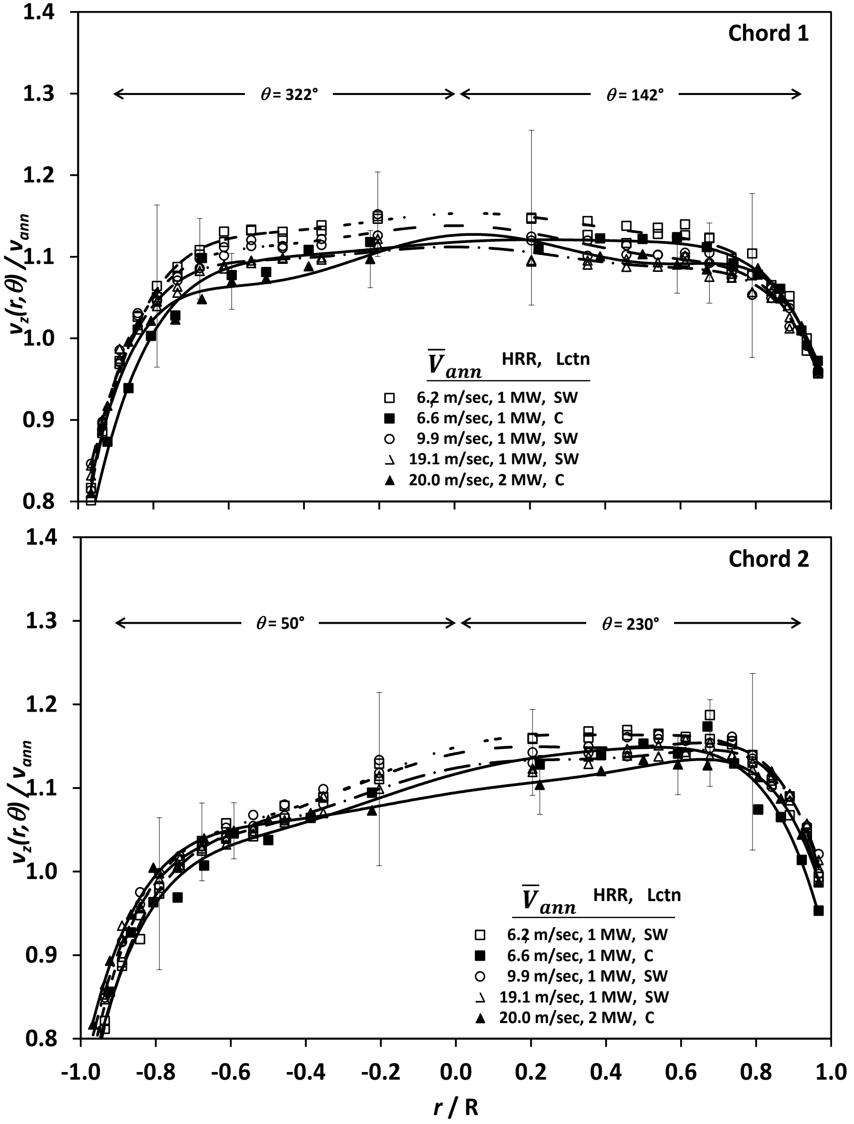


The flow profiles were confirmed with separate experimental trials.

NIST – Series 1



STC – Series 2



Better instrumentation and better calibrations result in lower uncertainty.

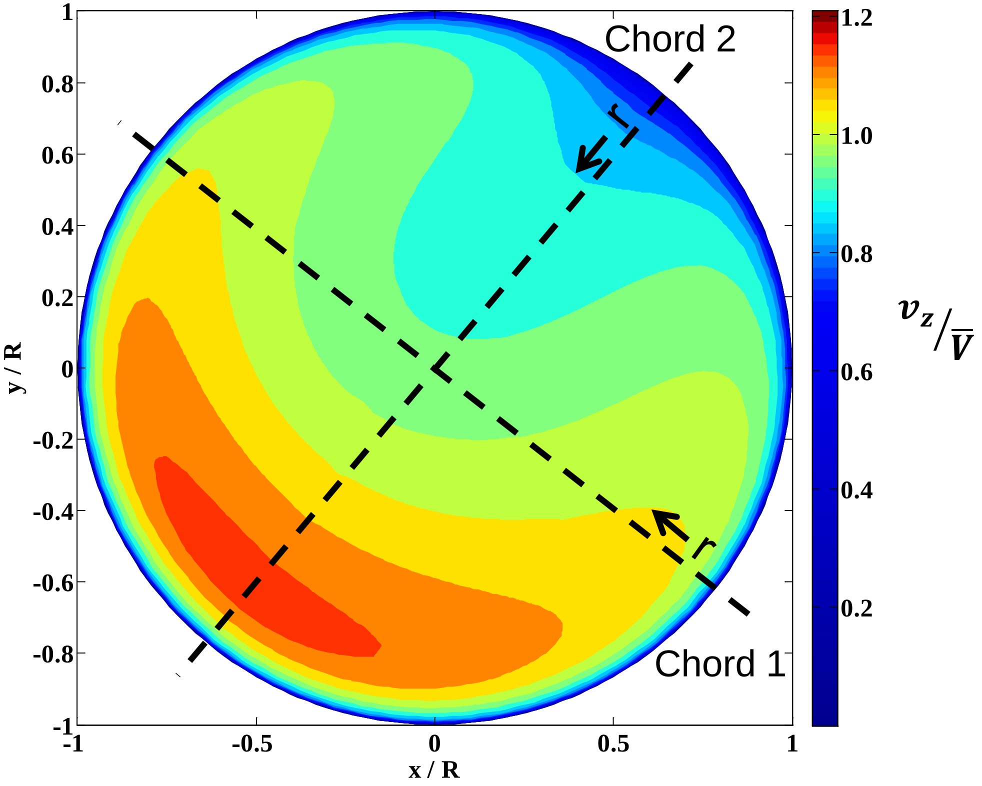
NIST – Series 1

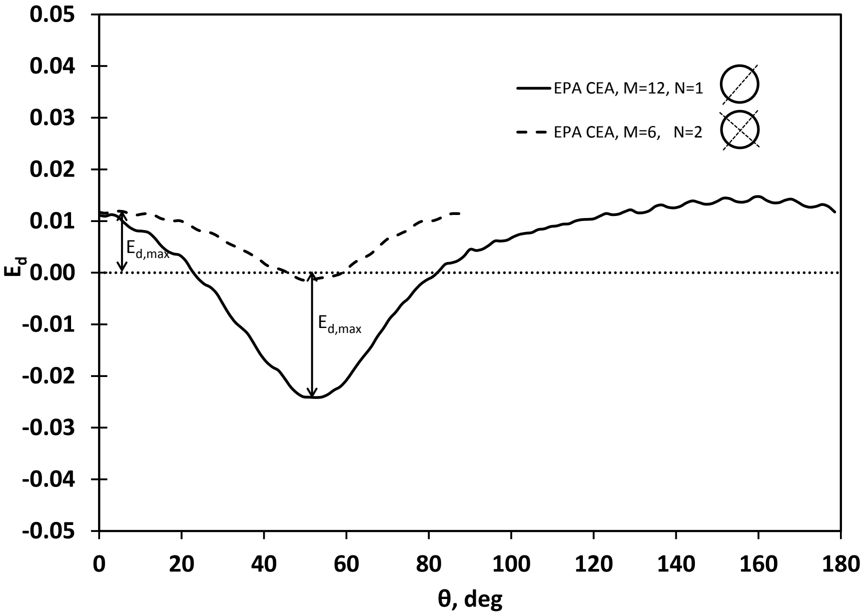
Measurement Component, x_i	**Value**	**Relative Standard Uncertainty, $u(x_i)/x_i$**	**Non Dimensional Sensitivity Coefficient, s_i**	**Percent Contribution, %**
Probe Coefficient, C_p	0.818	0.0048	1.0	86.7
Probe Yaw, ϕ_y (Deg)	2.49	0.0201	0.002	0
Probe Differential Pressure, Δp (Pa)	110.38	0.0008	0.5	0.5
Gas Temperature, T (K)	296	0.0037	0.5	12.8
Duct Static Pressure, P_s (Pa)	100722	0.0001	-0.5	0
Gas Molecular Weight, M_{wet} (kg/kmol)	28.297	0.0001	-0.5	0
Near Axial Velocity, v_z (m/sec)	**11.28**	**0.0052** **(0.0104)**	**Standard Uncertainty** **(Expanded Uncertainty)**	

STC – Series 2

Measurement Component, x_i	**Value**	**Standard Uncertainty, $u(x_i)$**	**Relative Standard Uncertainty, $u(x_i)/x_i$**	**Non Dimensional Sensitivity Coefficient, s_i**	**Percent Contribution, %**
Probe Coefficient, C_p	0.785	0.012	0.0150[b,c]	1.0	88.5
Probe Yaw, ϕ_y (Deg)	2.0	0.5[b]	0.2500	0.002	0
Probe Differential Pressure, Δp (Pa)	403.6	3.1[b]	0.0077	0.5	5.8
Gas Temperature, T (K)	287.3	1.5[b]	0.0052	0.5	2.7
Duct Static Pressure, P_s (Pa)	99193	170[a,b]	0.0017	-0.5	0.3
Gas Molecular Weight, M_{wet} (kg/kmol)	28.73	0.15[c]	0.0052	-0.5	2.7
Gas Velocity, axial, v_z (m/sec)	**20.41**	**0.33** **(0.65)**	**0.0159** **(0.0319)**	**Standard Uncertainty** **(Expanded Uncertainty)**	

The CFD simulation predicted the qualitative features of the flow and was therefore used to estimate the error due to measurement discretization.

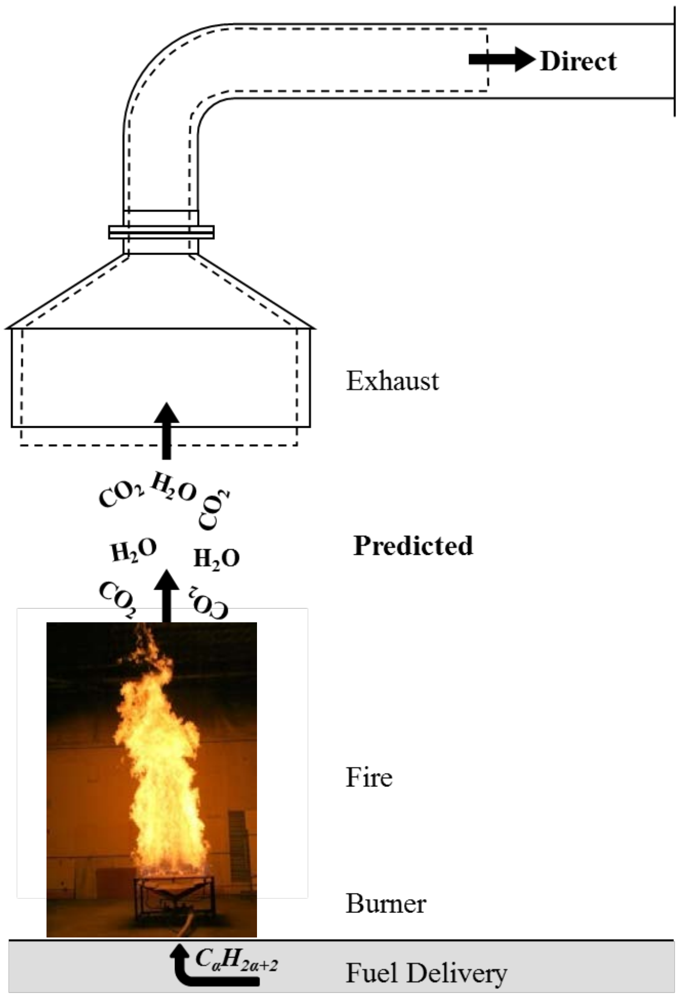




Flow and Concentration

Goal: Use the NFRL to demonstrate best practices for CO_2 emissions measurements with ±1% uncertainty.

CO_2 Mass In (Predicted) = CO_2 Mass Out (Direct)



$$\dot{m}_{CO2} \sim u_e \rho_e A X_{CO2,e}$$

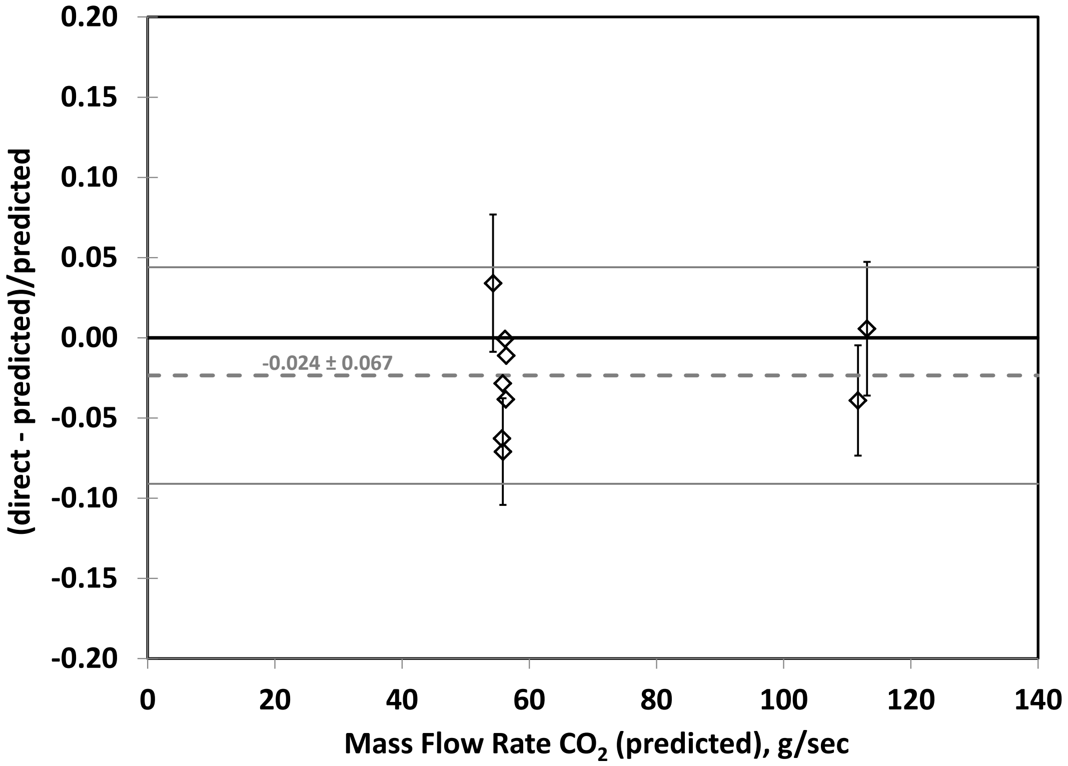
- Mass In = Mass Out
  - Input: metered flow of natural gas (traceable to primary flow standard and gas composition standards), i.e. metered flow of C atoms
  - Assume 100% conversion of C atoms to CO_2
  - Measurement: CO_2 mass flow rate

The distribution of the data from separate experimental trials was within ±7%.

- Many of the point velocity traverse experiments were run with the natural gas fire.

- Direct: Emissions
  - Flue gas measurements of flow and concentration

- Predicted: Fuel
  - Flow and composition measurements of natural gas supply



The natural gas burner system provides a precision source of CO_2; duct/stack diameter measurements are a significant source of uncertainty for flue gas measurements (CEMS).

Predicted (Fuel)

Measurement Component, x_i	**Value**	**Relative Standard Uncertainty, $u(x_i)/x_i$**	**Non Dimensional Sensitivity Coefficient, s_i**	**Percent Contribution, %**
Gas Volume Flow Rate, $\dot{V}_{ng}$ (m^3/sec)	0.02983	0.0019	1.0	22.9
Gas Pressure, P_{ng} (Pa)	197719	0.0016	1.0	16.3
Gas Temperature, T_{ng} (K)	290.65	0.0017	-1.0	19.0
Gas Compressibility, Z_{ng} (-)	0.9958	0.0005	-1.0	1.6
Gas Carbon Fraction, $X_{c,ng}$ (mol/mol)	1.042	0.0020	1.0	26.2
CO_2 Molecular Weight, M_{CO_2} (g/mol)	44.0095	0.0000	1.0	0
Ideal Gas Constant, R (J/mol/K)	8.3144	0.0002	-1.0	0
Burner Conversion Efficiency, η_b (-)	1.0000	0.0015	1.0	14.0
Predicted CO_2 Emissions, $\dot{m}_{CO_2,p}$ (g/sec)	**112.4**	**0.0040** **(0.0080)**	**(Expanded)**	

Direct (Flue)

Measurement Component, x_i	**Value**	**Relative Standard Uncertainty, $u(x_i)/x_i$**	**Non Dimensional Sensitivity Coefficient, s_i**	**Percent Contribution, %**
Exhaust Gas Mean Flow Velocity, V_{exh} (m/sec)	20.91	0.0056	1.0	9.9
Exhaust Duct Diameter, d (m)	1.504	0.0079	2.0	77.6
Exhaust Gas Mean Density, ρ_{exh} (kg/m^3)	1.047	0.0034	1.0	3.6
CO_2 Net Volume Fraction – dry basis, $X_{CO_2,net,dry}$ (m^3/m^3)	0.001819	0.0053	1.0	8.9
Exhaust Gas H_2O Volume Fraction, $X_{H_2O,exh}$ (m^3/m^3)	0.007947	0.0031	0.05	0
Exhaust Gas Molecular Weight, M_{exh} (kg/kmol)	28.7734	0.0001	-1.0	0
CO_2 Molecular Weight, M_{CO_2} (kg/kmol)	44.0095	0.0000	1.0	0
Direct CO_2 Emissions, $\dot{m}_{CO_2,d}$ (g/sec)	**107.3**	**0.0179** **(0.0358)**	**(Expanded)**	

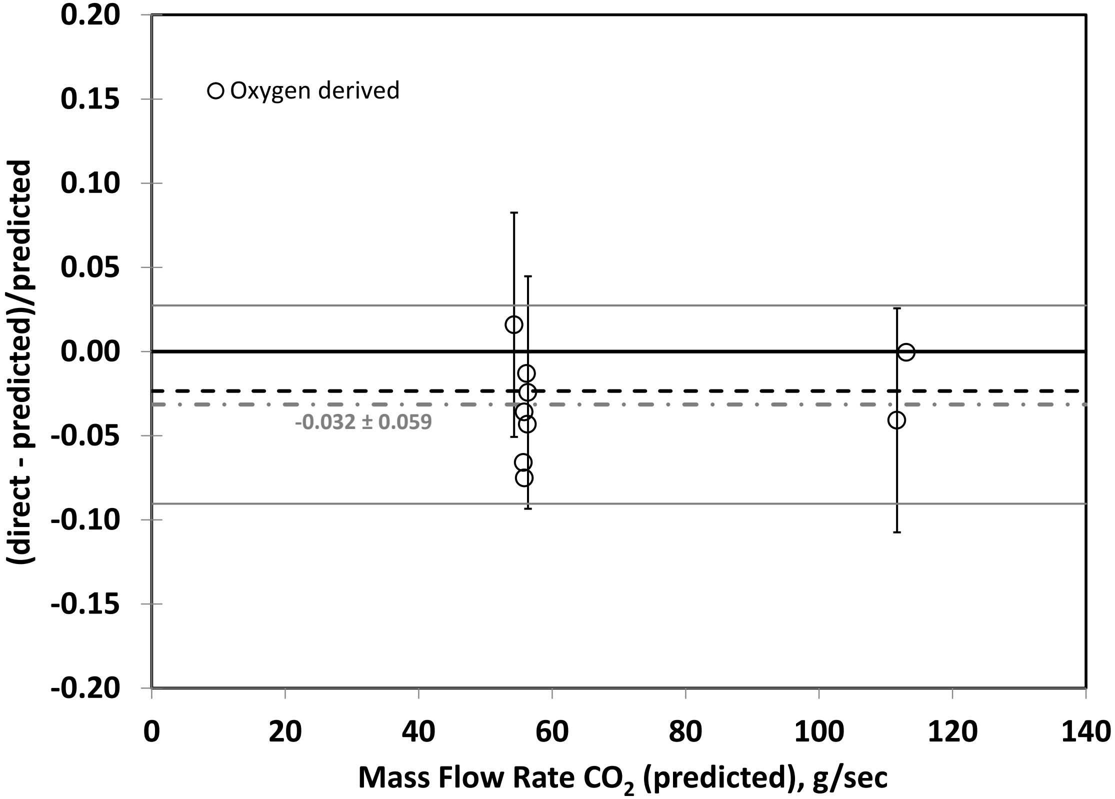
CO_2 emissions derived from O_2 concentration measurements agreed well with direct CO_2 measurements.

- If a CO_2 analyzer is not present, procedures to use O_2 concentration measurements exist

- Based on emission factors for natural gas

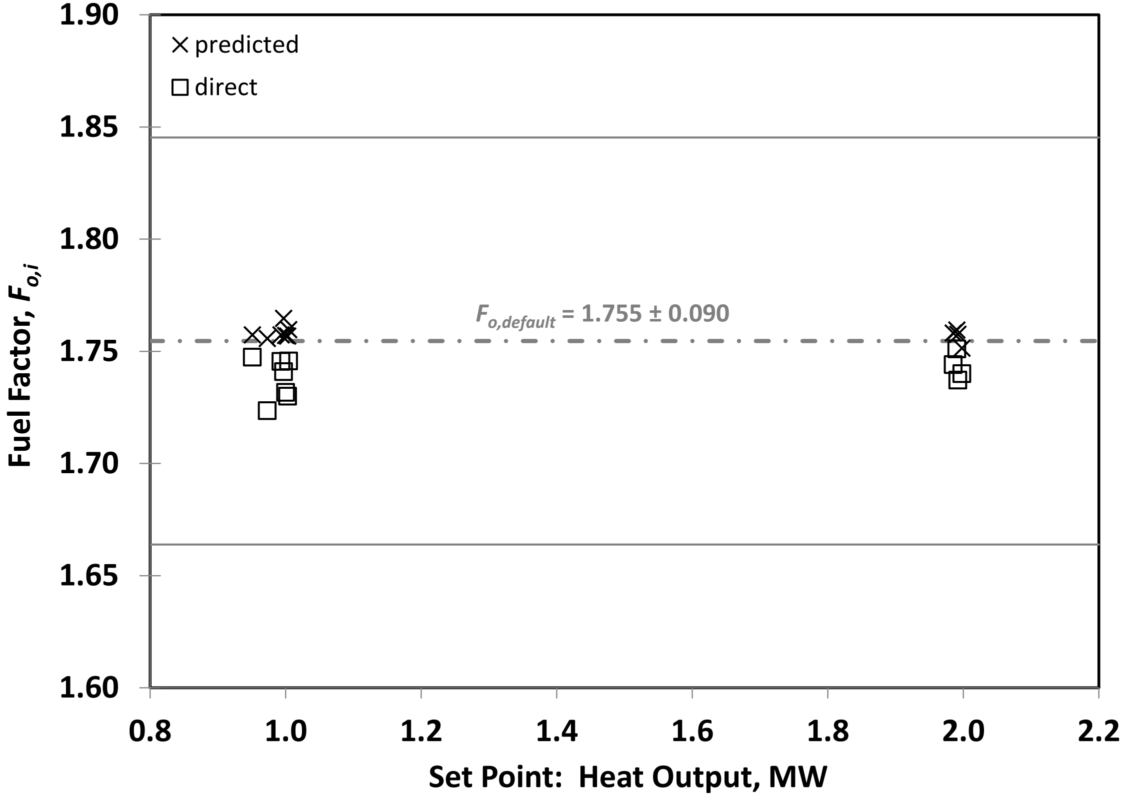
- Larger uncertainty in emission factors

- 40 CFR Pt75 – Appendix F – Conversion Procedures



Fuel Factors computed from the proportions of O_2 and CO_2 agree with the default value, confirming the quality of the gas concentration measurements.

- Predicted: fuel (natural gas) composition measurements
- Direct: flue gas concentration measurements
- EPA Method 3b – Gas Analysis for the Determination of Emission Rate Correction Factor or Excess Air



National Fire Research Laboratory

Summary

- The NFRL has similar measurement systems and functions to a stationary source. It is a near-industrial scale analog of a stationary source – a CO_2 emissions measurement test bed.

- The NFRL has been used to simulate some of the practices of the source emissions measurement industry. The goal is to demonstrate best practices for achieving ±1% uncertainty CO_2 emissions measurements.

- Preliminary results demonstrate that the NFRL has the capability to evaluate CO_2 emissions measurements with mass balance experiments.
  - Fuel derived emissions measurements
  - Direct emissions measurements

Thank You!

Questions

References:

- R. Bryant, O. Sanni, E. Moore, M. Bundy, and A. Johnson, An Uncertainty Analysis of Mean Flow Velocity Measurements Used to Quantify Emissions from Stationary Sources, Journal of the Air and Waste Management Association, v64 (6), pp 646-656, (2014)

- R. Bryant, M. Bundy, and R. Zong, Evaluating Measurements of Carbon Dioxide Emissions Using a Precision Source – a Natural Gas Burner, Journal of the Air and Waste Management Association, To Appear, (Accepted 24 March 2015)