Laboratory Services
Fire Research Laboratory

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Bureau of Alcohol, Tobacco, Firearms and Explosives
Laboratory Services - Fire Research Laboratory
Policies and Procedures Guidelines
ATF-LS-FRL Codes and Standards

1. **Title:** Procedure for use of Codes and Standards

2. **Scope:**

2.1 This procedure provides the approach accepted by the Fire Research Laboratory (FRL) for the use of Codes, including but not limited to Building Codes, Electrical Codes, Fire Protection Codes and Life Safety Codes.

3. **Description:**

3.1 Codes may be used for a variety of applications in the FRL including checking the codes to determine whether a building or item met applicable regulations when it was built/manufactured, providing guidance to CFI agents that have code-related questions and using prescriptive codes to help provide input to calculations and computer models when a generic value representative of something that may be expected to be found in the field is required.

3.2 While the use of prescriptive codes will at times present an engineer with several options, they are generally fairly specific in their requirements and require very little in the way of decisions that may affect an analysis. At times when the information prescribed by the code is either open-ended or vague the engineer should check with the authority having jurisdiction to determine whether or not there have been interpretations or clarifications of the issue. These are often available either via the jurisdictions website or in handbooks for the model codes.

3.3 For each application of codes the engineer should verify that they have obtained the appropriate code for the particular case. While many jurisdictions have similar codes, most have their own amendments that need to be incorporated into any analysis; in addition the relevant edition of the code should be verified, as it is not always appropriate to default to the most recent edition of the code. When codes are used the name of the code and the year of its publication should be noted, as well as the presence (or lack thereof) of any local amendments.

4. **Uncertainty:**
Due to the nature of prescriptive code analysis there is generally not a way in which uncertainty can be measured in a quantitative fashion. Where code-related decisions are made that are unclear or could be interpreted in several ways an appropriate reference or explanation for the decision should be provided in the documentation.

5. **Procedure:**

5.1 The procedure for the use of codes is as indicated in the flow chart below.

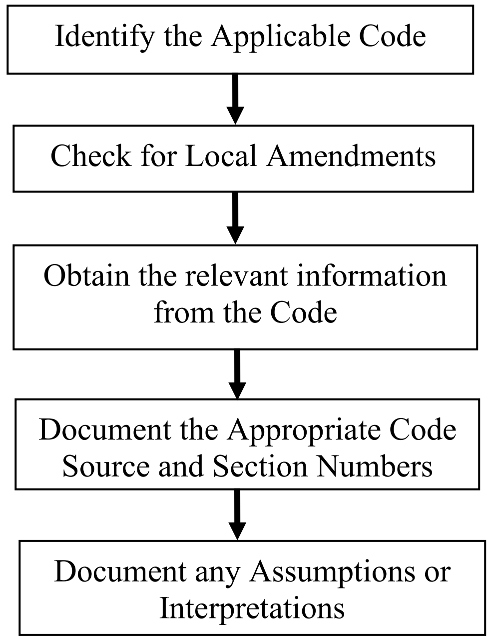


Figure 1. Procedure for the use of codes

5.2 The procedural steps for the use of Codes (as illustrated in the flow chart above) are as follows:

Step 1 – Identify the Applicable Code:
To determine the current applicable version of the code and to find local amendments the local jurisdiction should be contacted. Contact information for jurisdictions within the United States can be found online at:

http://www.reedconstructiondata.com/building-codes/

Often the FRL will need to reference older editions of codes for existing buildings or products. Information regarding which codes were applicable at earlier dates are often available from the local jurisdiction.

Step 2 – Check for Local Amendments:
Although many jurisdictions use similar codes, most have local amendments to these codes that should be referenced. Different cities or towns within the same state may have different code requirements; in addition federal agencies and transportation agencies often have their own code requirements in addition to the local requirements.

Step 3 – Obtain Information:
Once the relevant code is obtained the information should be obtained from within the code should be looked up by an engineer who is familiar with the structure of prescriptive codes. Care should be taken that all of the applicable sections within a single code are reviewed for the item in question.

Step 4 – Document Code Source and Relevant Sections:
Documentation will be provided that identifies the name of the code, the year of the code and any local amendments that have been reviewed. In addition, any piece of code that is referenced should also have its Section Number indicated to facilitate review of the code analysis.

Step 5 – Document Assumptions or Interpretations:
If there are relevant areas where the prescriptive code requirements are unclear or give several options the assumptions and interpretations will be documented. Published handbooks or interpretations should be referenced for these areas if available from the publisher of the code.

6. Documentation:

Documentation of code analysis will be in accordance with the FRL procedure for Technical Research and will provide sufficient information that another engineer with a similar level of training can easily find the applicable code sections and arrive at the same conclusion.

6.1 The documentation shall include a reference to the applicable version of the code used, to include any local amendments or jurisdictional modifications, and the specific code sections(s).

6.2 The documentation shall include a synopsis of the rationale used in making a decision of compliance/non-compliance. This should include the pertinent details of the building/system/product/etc. as well as any assumptions or interpretations made to arrive at the conclusion.

1 Scope

This document covers the Standard Operating Procedures for the CWD 2000 Combustion Calorimeter from Union Instruments. The Combustion Calorimeter is used to measure the heat content and specific gravity of natural gas that is used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL) experiments.

2 Required Materials

a) Ultra High Purity (UHP) Methane calibration gas.

3 Initial Setup

a) The combustion calorimeter is located on the south side of the mezzanine level in the Combustion Calorimeter Shed. It is mounted on the east wall of the shed as shown in Figure 1.

Figure 1. Combustion Calorimeter.

b) Connect the combustion calorimeter to the natural gas supply.

c) Connect the combustion calorimeter to Ultra High Purity (UHP) Methane calibration gas.

4 Start-Up

a) Turn the red valve to the "ON" position where the gas sampling line meets the building main supply (Figure 2).

Figure 2. Combustion Calorimeter Connection to the Natural Gas Supply Line; Red Valve Shown in the "ON" Position.

b) Turn the power switch on the combustion calorimeter to the "ON" position as shown in Figure 3. The power switch is located in the lower right hand corner of the unit.

Figure 3. Combustion Calorimeter Power Switch, Shown in "ON" Position.

c) If proper gas flow is being provided to the combustion calorimeter, activating the power switch should fire a spark that lights the pilot flame.

   i) When the pilot is lit, the red “Flame” light should be active (Figure 4).

Figure 4. Pilot Flame Indicator Light and View Port.

   ii) The pilot flame can be viewed through the viewport next to the “Flame” light. The pilot should be approximately ¼” high.

      (1) If the flame is not present or too short, it may indicate a lack of sample line pressure or a problem with the ignition system.

      (2) If the pilot is too high, it may indicate too much pressure in the sample line.

d) After the pilot is ignited, check the pressure gauges on the right side of the panel (Figure 5). All of the gauges should read between 3.5 and 4.5 mbar. The top gauge shows differential pressure across the specific gravity cell, the middle gauge shows differential air pressure, and the bottom gauge shows gas pressure at the Wobbe jet.

Figure 5. Combustion Calorimeter Pressure Gauges.

i) If the pressure is low for the top or bottom gauges, adjust the regulators for the sample or calibration gasses, as shown in Figure 6.

ii) Use very small adjustments to avoid adding too much pressure.

Figure 6. Combustion Calorimeter Sample Gas (bottom) and Calibration Gas (top) Pressure Regulators.

e) Check the UHP methane tank to ensure that the valves are open and that there is sufficient gas in the tank to perform calibrations.

f) Verify that the data cables are correctly plugged into the Data Acquisition System (DAQ). The dry (superior) specific heat (CV_s), the saturated (inferior) specific heat (CV_i) and the specific gravity (SG) are currently recorded by the Historian via Allen Bradley PLC Modules under the channels "AB183_AI04_08", "AB183_AI04_10" and "AB183_AI04_09", respectively.

NOTE: The combustion calorimeter is left in the "ON" position at all times in order to provide a continuous measurement of the natural gas entering the building. Only turn the combustion calorimeter "OFF" when performing maintenance.

5 During Use

a) The specific gravity cell within the combustion calorimeter is highly sensitive to vibrations. When entering and leaving the Combustion Calorimeter Shed the door should be opened and closed gently. When opening and closing the combustion calorimeter front panel care should be taken to move the panel slowly and minimize vibration and air flows reaching the specific gravity panel.

b) The combustion calorimeter's signal stability is indicated by the "Stab." label in the upper right corner of the main display screen. When the value is > 0.15 the unit will not provide accurate readings or complete a calibration.

c) The combustion calorimeter should be maintained in an environment in which the temperature does not vary by more than ± 7 °C from the temperature at which calibration was performed. It should not be subjected to temperature gradients exceeding 2 °C / hour. If using the combustion calorimeter with a calibration burner, the warning light on the burner control iFix screen will alert that the temperature variation is outside of tolerance.

6 Shut-Down

a) Turn off the power switch located on the bottom right hand corner of the unit.

b) Close the red valve on the natural gas sampling line.

c) Close the UHP Methane calibration gas tank.

7 Calibration

a) The combustion calorimeter is calibrated with UHP Methane.

b) The combustion calorimeter automatically performs calibration Monday-Friday at 07:00.

c) Additional calibration can be initiated at any time using the combustion calorimeter on-screen menu.

Options
ÄCalibration
ÄCalibrate

d) Calibration takes approximately 10 minutes. During this time, the “Operation” light will stop blinking green. The “Operation” light will begin blinking again once the calibration has finished.

e) Calibration records are recorded and stored within the calorimeter.

f) Calibration constants specific to the individual calibration gas are entered into the combustion calorimeter. These constants are calculated using a software program from the manufacturer.

i) The values calculated for UHP Methane (assuming 100% methane and negligible traces of other gasses) are shown in Table 1. The values highlighted in Table 1 are the values that need to be entered into the Combustion Calorimeter “Configuration of Calibration Gases” Page. Figure 7 shows a screen shot of the values entered into the Combustion Calorimeter.

Table 1. Calibration Constants for UHP Methane.

COMPRESSIBILITY (Z)	0.9981		
SPECIFIC GRAVITY (S.G.)	0.5547		
CALORIFIC VALUE	**BTU/SCF**	**KCAL/NM^3**	**KJ/NM^3**
Net, Dry	913.2	8570	35865
Gross, Dry	1014.3	9519	39834
Net, Saturated	897.3	8421	35241
Gross, Saturated	996.6	9353	39141
WOBBE INDEX			
Net, Dry	1226.1	11507	48154
Gross, Dry (W.I.$_s$)	1361.8	12780	53483
Net, Saturated	1204.8	11307	47317
Gross, Saturated (W.I.$_i$)	1338.1	12558	52554
OFFSET FROM CV NET TO VE GROSS	1.1107		

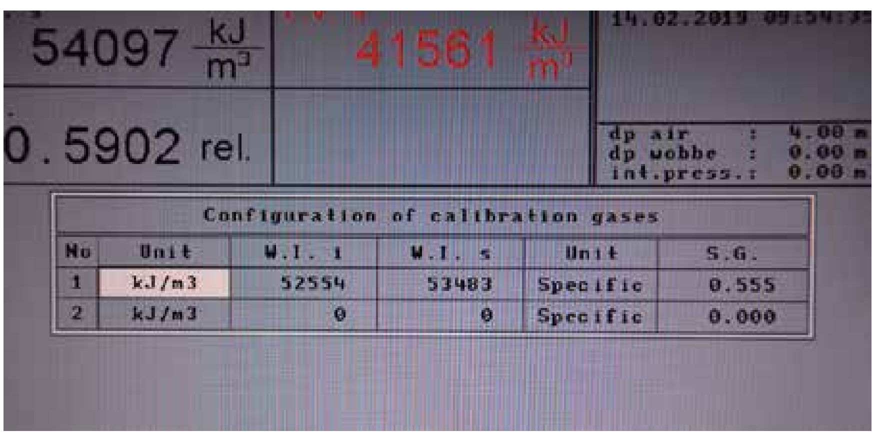


Figure 7. Combustion Calorimeter Calibration Constant Screenshot.

ii) If a calibration gas other than UHP Methane is used the calibration values will need to be recalculated. In this case, contact Delta Instruments to have one of their representatives perform the calculations.

8 Maintenance

a) Turn off the combustion calorimeter and close ALL gas lines before performing any maintenance. This system involves natural gas under pressure and should only be operated by those with proper training.

b) Periodic maintenance checks should be performed to identify any potential problems with the equipment. Delta Instruments recommends that these checks be performed every six months.

   i) All hose connections to the gauges, pressure sensors, specific gravity cell and the primary air connection to the burner should be checked and changed if necessary.

   ii) The gas pressure regulator diaphragm should be checked; if this has become hardened or brittle, it should be replaced.

   iii) The rubber connections on the Wobbe jets and air jets should be checked for any leakage.

   iv) The calibration gas should be checked to ensure an adequate supply and for expiration date of the gas calibration certification. The combustion calorimeter requires 5-10 liters of calibration gas per calibration cycle, which occurs five times per week.

c) If any problems are noted when performing maintenance, the following troubleshooting steps can be taken.

   i) Specific gravity or gas pressure cannot be adjusted to within 3.5 – 4.5 mbar:

      If the gas or specific gravity cell pressures are outside the 3.5-4.5 mbar range and slight changes to the external pressure regulators (see Startup procedure) do not solve the problem, an engineer may adjust the weight on the internal gas sample regulator.

      To adjust the gas sample regulator, unscrew the silver metal cap (Figure 8) and add/remove weights as necessary to achieve the required pressure. Note that this will adjust both the specific gravity and gas sample pressures, and it is best to avoid changes to this regulator if possible

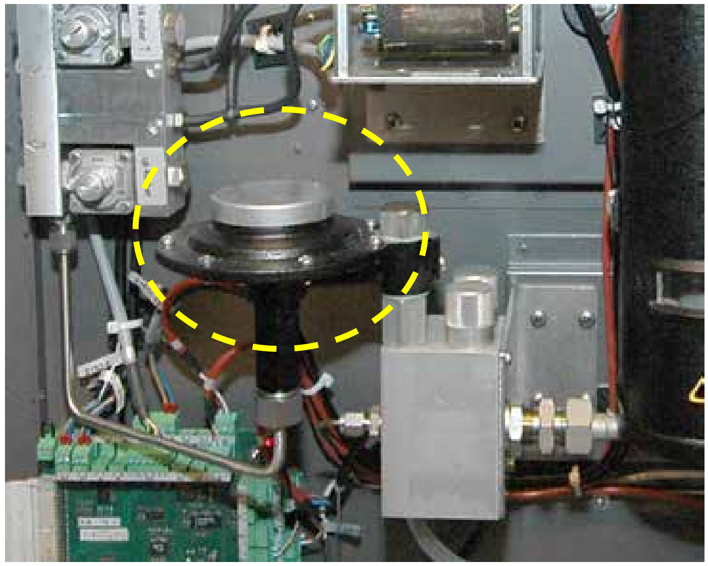


Figure 8. Combustion Calorimeter Internal Gas Sample Regulator.

ii) Air flow pressure reading is less than 3.5 mbar

Either the air filter needs to be cleaned/replaced, or the fan unit needs to be replaced.

iii) Unstable readings

Unstable readings may result from rapid temperature fluctuations. If this becomes a problem it may be necessary to provide a more stable temperature control system in the Combustion Calorimeter Shed.

iv) Drift in readings

If readings drift upwards in one direction and are not corrected by calibration the air filter must be replaced.

If readings drift downwards it is likely that the heat exchanger is worn out. Remove and wash the heat exchanger with warm water and remove any deposits with a brush. The heat exchanger should be dried with compressed air before reinstallation.

v) Incomplete/no ignition

The pilot flame will not ignite if the door to the unit is open. Close and lock the door in place before attempting to turn on the combustion calorimeter.

It is possible that the ignition electrode is corroded and needs to be replaced.

Insufficient gas pressure can lead to lack of ignition. Check that the gas line is intact, all valves are open, and pressure regulators are set correctly.

vi) Fault Light

If the Fault Light comes on, the system will need to be rebooted. The issues is most likely due to a power outage and the unit did not reboot properly.

vii) Product Manual

The display panel for the CWD 2000 was replaced in September of 2018 with a modern day panel. The replacement display panel is nominally the same as the original panel but the menus are different. When referring to the product manual, refer to the product manual for CWD 2005 for the display panel and refer to the product manual for the CWD 2000 for all other components.

viii) Software problems

The combustion calorimeter is currently running version 4.42 of the required software. Updates can be made using factory software installed via a floppy drive on the inside of the door of the combustion calorimeter (underneath the monitor).

All other software problems should be directed to Delta Instruments.

PROTECTING THE PUBLIC
SERVING OUR NATION

Scope

This document lists the commissioning documentation requirements for commissioning an instrument or piece of equipment that will be used for casework testing by the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), Fire Research Laboratory (FRL). A list of instrument and equipment used by the ATF FRL and the documents required to commission those instruments and equipment shall be maintained by the FRL Laboratory Section Chief (LSC). The terms instrument and equipment will be used interchangeably throughout this document.

Laboratory Instructions

The Laboratory Instruction (LI) is a document which provides the reader with a general understanding of the instrument. The LI is not intended to serve as a user's manual. The LI at a minimum shall provide the following information;

A general description of the instrument which describes the type of measurement the instrument records and the scientific principles that it uses to make those measurements.

The uncertainty and/or accuracy associated with the instrument type.

The general operating requirements and procedures.

The information that is required to be documented while using the instrument.

This document is required to be uploaded to Qualtrax. The document file name shall be structured as follows;

FRL LIXXX – Instrument Name.doc

where XXX represents the Laboratory Instruction Number assigned to that instrument and Instrument Name shall be replaced with the actual Instrument Name.

Technical References

A Technical Reference (TR) should be written to act as supplemental document to the LI when two or more instruments of different types are used to record the same type of measurement. A TR is required for each type of instrument recording the same measurement. The TR should give a physical description of the instrument, state the instruments operating principal, measurement range, measurement output and accuracy.

This document is required to be uploaded to Qualtrax. The document file name shall be structured as follows;

FRL TRXXXy - Instrument Name.doc

where XXX represents the LI Number that the TR was written to supplement and y is a sub letter which starts with a, then b, then c, etc. For example, two TRs are written for LI001, then the two TR document file names would be FRL TR001a – Instrument Name.doc and FRL TR001b – Instrument Name.doc, respectively. The Instrument Name shall be replaced with the actual Instrument Name.

Standard Operating Procedures

A Standard Operating Procedures (SOP) document shall be written to serve as the Fire Research Laboratory (FRL) user's manual for the instrument. Upon reading the SOP the user should have a good working knowledge of how the instrument is to be used during a FRL experiment. The following information shall be included in the SOP if deemed necessary during the commissioning process.

Required Supplies – The SOP shall list all supplies required to use the instrument.
Start UP Procedures – The SOP shall list all the necessary procedures required to use the instrument prior to the start experiment.
Experiment Procedures – The SOP shall list all of the necessary procedures required to use the instrument during the experiment.
Shut Down Procedures – The SOP shall list all of the necessary procedures required to use the instrument after the experiment.
Maintenance Procedures – The SOP shall list all of the maintenance procedures require to use the instrument. The procedures can be both preventative and repair procedures if necessary.
Calibration or Functional Verification Procedures – The SOP shall list all calibration requirements or functional verification procedures required to use the instrument.

This document is required to be uploaded to Qualtrax. The document file name shall be structured as follows;

Instrument Name – Standard Operating Procedures.doc

where Instrument Name shall be replaced with the actual instrument name.

Instrumentation Work Order

The Instrumentation Work Order is a document that is used during the planning stages of a test series to specify the types and quantities of the different instruments that will be required for a particular test series. This document contains a section for each commissioned instrument. When a new instrument is commissioned, a section shall be added to this document which will allow a user to specify the type, quantity and any specialized information particular to that instrument. The Instrumentation Work Order does not need to be uploaded to Qualtrax.

Data Sheet

A Data Sheet is a document which is used to record specific data and/or parameters about a particular instrument. All recorded instrument data and/or parameters are maintained using the FireTOSS secured data base and a hard copy is not required. The Data Sheet does not need to be uploaded to Qualtrax.

FireTOSS Report Template

A FireTOSS report template shall be written if an instrument description is required to be inserted into the experiment report generated by the FireTOSS Print Reports Program. The report template at a minimum shall give a description of the instrument, list the limits or operating range of the instrument, the accuracy and/or uncertainty of the instrument and if necessary, the signal output of the instrument measured by the data acquisition system. The FireTOSS Report Template does not need to be uploaded to Qualtrax.

List of Standards

If an instrument is constructed to conform to one or more listed standard such as an International Standard Organization (ISO) standard or an American Society for Testing and Materials (ASTM) standard, then a list of those standards shall be included within the LI or TR, whichever is more appropriate.

Manufacturers Documentation

If an instrument has documentation such as a user manual that comes from the manufacturer when purchased, then a copy of that documentation shall be maintained by the FRL Calibration Technician.

Training

A training presentation shall be assembled which can be used to teach FRL staff how to use the instrument in accordance with FRL policy. The training presentation shall contain at a minimum the following information;

A list of materials required to complete the training exercise.
A description of the instrument and the instrument's operating principle.
List the factors which could affect the results of the instrument.
List the calibration and/or functional verification requirements.
Explain how and where the calibration records are maintained.
List the FireTOSS parameters associated with the instrument.
If necessary, list the calculations performed using the data collected by the instrument.
If necessary, provided an example of the instrument's Test Record.

If necessary, show an example of the instrument's Work Order.
Provided a list of the Manufacturers documentation that would be helpful to read or use as a reference or troubleshooting guide.
If necessary, provide Hands on Training
List the "Best Practices" or methods when using the instrument.

The Training Presentation does not need to be uploaded to Qualtrax.

List of Examiners

A list of Examiners shall be maintained by the LSC. An Examiner understands the scientific principles which the instrument uses to make measurements and has the hands-on technical skills to install and operate the instrument in accordance with FRL procedures. The Examiner can determine if the instrument failed and whether that failure has an impact on the results of the experiment and to determine if that instrument must be taken out of service until it can be verified that the instrument operating properly.

List of Operators

A list of Operators shall be maintained by the LSC. An operator has the general knowledge of the instrument's operating scientific principles and has the hands-on technical skills to install and operate the instrument in accordance with FRL procedures. The Operator can determine if the instrument failed but must consult with an Examiner to determine if the failure has an impact on the results of the experiment and whether the instrument must be taken out of service.

1. **Title:** Procedure for use of Computer Modeling

2. **Scope:**
2.1 This procedure provides the approach accepted by the Fire Research Laboratory (FRL) for use of computer models in conjunction with an engineering analysis. This procedure applies to all types of deterministic computer models used by the FRL, including but not limited to zone models, field models and egress models.

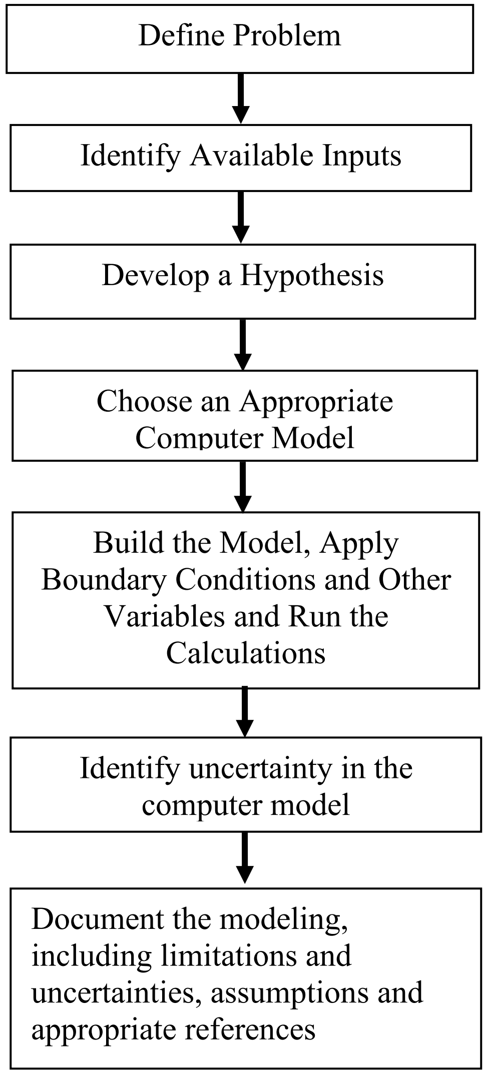
2.2 This procedure is not meant to restrict the methods of analysis available to the engineers, nor does it forbid the use of any specific models.

3. **Description:**
3.1 Activities covered by this procedure include any computer-aided calculations used to model the effects of fire or to simulate emergency evacuation scenarios.
3.2 Computer models can be used to assist with a wide variety of problems; for a given problem there may be one or more models that can provide an appropriate solution, as well as models that are not appropriate for the given scenario. The engineer must be familiar with the assumptions and limitations inherent in the chosen computer model, as well as with the uncertainty involved in the boundary conditions and other variables that are applied by the model-user.
3.3 When applicable, the default procedure for the use of deterministic fire models is to follow the guidelines provided in ASTM E 1355 "Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models". The recommended procedure for the use of computer egress models is to follow the recommendations contained within Appendix A of NIST GCR 06-886 "Guide for Evaluating the Predictive Capabilities of Computer Egress Models".

4. **Uncertainty:**
There is a level of uncertainty involved in all Computer modeling analyses. The uncertainty associated with a given computer modeling analysis should be quantified by the engineer using the methods detailed in the documents referenced in Section 3.3 of this procedure, or by employing another method of uncertainty analysis that is widely accepted in the field of Fire Protection Engineering.

5. **Procedure:**

5.1 The procedure for the use of Computer Modeling is as indicated in the flow chart below.



5.2 The procedural steps for the use of Computer Models (as illustrated in the flow chart above) are as follows:

Step 1 - Define the Problem: Identify the problem by establishing the goals of the Fire Dynamics calculations and determining the desired output from the analysis.

Step 2 - Identify Available Inputs: Gather all of the relevant input variables that are available and determine whether there is enough information to proceed with an analysis. If there is not enough information available for a Computer Model than an evaluation should be made as to whether laboratory testing will be required to solve the problem.

Step 3 - Develop a Hypothesis: Use engineering judgment and other available resources to develop a hypothesis.

Step 4 - Choose an Appropriate Computer Model: Choose an appropriate computer model to perform the analysis. An effort should be made to use existing models that have been validated through published literature. If a pre-existing validated computer model is not available, changes to existing models can be made or new computer models can be built to use in the analysis if proper uncertainty analysis and model validation are completed and documented as a part of the analysis.

Step 5 – Perform the Modeling: Data files and model inputs should be constructed in a way that can be recorded and reviewed by another engineer. When possible, OUT files should be used to record the iterative steps performed by the computer model. Technical reviews of both input and output files should be carried out by a competent peer reviewer.

Step 6 - Identify Uncertainty: Identify/quantify the uncertainty involved in the calculations in accordance with Section 4 of this procedure.

Step 7 – Documentation: Documentation shall be in accordance with the FRL procedure for “Technical Research” and Section 6 below.

6. Documentation:

Documentation of computer fire modeling analyses will be in accordance with the FRL procedure for Technical Research and will provide sufficient information that another engineer with a similar level of training can review and/or recreate the computer fire modeling work.

Several items specific to computer modeling should be documented:

- The model name and publisher
- The version number of the model
- Any changes or re-compilations that are made to the model during the course of the analysis
- A description of the computer that was used to run the simulations (processor type and speed, operating system, available memory, etc.)

I. Scope

This document contains the Standard Operating Procedure (SOP) for the Fire Testing Technology (FTT) Cone Calorimeter located in the Pyrometrics Laboratory (Pyro Lab) at the ATF Fire Research Laboratory. These procedures were developed based on the FTT SOP [1], which conform to *ASTM E1354* [2], and was modified accordingly for use at the ATF Pyro Lab.

II. Required Supplies

A. Sample

Conditioned sample

Sample holder, edge frame and wire grid (if needed)

Ceramic fiber blanket to be placed in sample holder

Heavy-duty aluminum foil to wrap sample

Scale to measure sample mass

Calipers to measure sample thickness

B. Reference Bar to Set Cone Height

25 mm bar if edge frame not used

23 mm bar if edge frame is used

C. Calibration Gases

Nitrogen (Zero Grade)

CO/CO_2 span gas - 0.8% CO, 8% CO_2, balance N_2 (Primary Standard)

Methane gas (Chemically pure)

D. Drying Agent

Indicating drying agent/desiccant to remove moisture from gas samples

E. Filter Elements

Course and fine paper elements for soot filters

Micro-filter (located in line with the pressure gauges just upstream of the gas analyzers)

F. Calibrated Weights

Range applicable to items being tested (approximately 25-50 grams heavier than items being tested)

G. Smoke Calibration Card

Black block labeled "Zero"

H. Water

Water source required for heat flux gauge

III. Sample Preparation

Prior to testing, each sample should be conditioned to moisture equilibrium (constant mass) in a conditioning chamber, according to ISO 5660-1 [3]. *The ISO standard states that constant mass is achieved when the mass of the sample does not differ by more than 0.1% or 0.1 g, whichever is greater, in two successive measurements in a 24 hour period.*

A. Sample Fabrication

Standard sample size is 100 mm x 100 mm (3.9 inch x 3.9 inch).

Samples can be up to 50 mm (2 inch) thick. If the sample is nominally thicker than 50 mm, the sample will need to be cut from the unexposed surface to achieve a thickness of 50 mm or less.

B. Sample Documentation

Each sample requires a sample conditioning sheet.

The individual who is recording the mass measurement will date and initial each measurement.

Sample dimensions (length, width, thickness, exposed surface area) will be documented on the sample conditioning sheet.

Initial sample mass will be recorded.

C. Sample Conditioning

Fabricated samples will be placed in a conditioning chamber capable of controlling the temperature and humidity within an enclosed environment.

The conditioning chamber should typically be set to a temperature of 23°C (73°F) and a relative humidity of 50%.

Sample mass will be recorded until constant mass is achieved, which occurs when the mass of the sample does not differ by more than 0.1% or 0.1 g, whichever is greater, in two successive measurements in a 24 hour period. [3]

IV. Start Up Procedures

A. Verify Instruments are Calibrated

At the start of each test day, document the FRL ID numbers for the following instruments and verify that each instrument is calibrated.

Data Logger

Gas Analyzer

Load Cell

Methane Mass Flow Meter

Heat Flux Gauge

Differential Pressure Transducer

Atmospheric Pressure Transducer (if installed)

B. Pre-Test Initialization Procedure

Turn on Instruments

a. Turn on the power to the data logger.

b. Verify that the gas analyzer is on (*Analyzer* button).

Note: The gas analyzers take several hours to warm up. Therefore, it should be left on permanently.

c. Verify that the laser is on (*Smoke* button).

Note: The laser takes several hours to warm up. Therefore, it should be left on permanently.

d. Turn on the main power to the cone calorimeter (*Power* button).

Cold Trap

a. The cold trap valve must be closed during testing and opened after testing is completed to drain away any water that has accumulated (to prevent corrosion).

If cold trap valve is closed at the start of a test day, open the valve at the bottom of the cold trap and allow any water to drain. Close valve when finished.

If the cold trap valve is open at the start of the test day, close the valve prior to testing.

b. Turn on the power to cold trap (*Cold Trap* button). Allow cold trap to run for approximately 15 minutes prior to turning on sample pump.

c. Ensure that the cold trap temperature has reached 0°C (32°F) prior to testing. The temperature can be checked any time in the *Status* section of the *ConeCalc* software.

ConeCalc Software

a. Start the *ConeCalc* software program on computer.

Check Filters and Drying Agents

a. Check that the indicating drying agent/desiccant is in good condition. Change if necessary.

b. Check that the primary (course) filter and secondary (fine) filter are clean. Change if necessary.

C. Pre-Test Calibration Procedures

Zero Methane Mass Flow Meter

a. Ensure that the *Methane On/Off valve* on the cone calorimeter is set to **OFF**.

b. Using the *ConeCa*lc software, select *Calibrations/Zero MFMs* and press the **Zero** button to zero the methane flow meter in the *ConeCalc* software.

c. Check that the display for voltage (V), flow (slpm), and heat output (kW) all read 0.00.

d. Then press **OK**.

Set Exhaust Duct Flow

a. Verify that the *Exhaust Control On/Off switch* is set to **OFF** and *the speed controlle*r is set to 0%.

b. Turn the *Differential Pressure Transducer (DPT) valve* to the **OFF** position.

c. In the *ConeCalc* software, select *Calibrations/DPT & Flow*.

d. Press the **Zero** button. After several seconds of collecting data, the pressure should read approximately 0.00 Pa.

e. Press **OK** to record the zero point of the DPT calibration.

f. You will then be promoted to set the exhaust flow. Enter in the required flow rate of **24 l/sec**.

g. Turn the *DPT valve* to the **ON** position.

h. Turn the *Exhaust Control switch* to the **ON** position.

i. Slowly adjust the fan speed controller from zero to the required volume flow rate of 24 1/s, which is approximately **47%** on the exhaust speed controller.

j. Click **OK** on the computer. The measured flow rate will then be displayed on the screen.

k. When 15 consecutive readings have been measured that are within 2 l/s of the required flow, the software will tell you that the flow is correctly set. **Do not adjust the fan speed once the flow has been set.**

l. Press **OK** to return to the calibrations panel in the software.

D. Calibrate Gas Analyzers

1. In *ConeCalc* software, select the software routine *Calibrations/Gas Analyzers*.
2. Open the cylinders for the zero gas (nitrogen) and the span gas (CO/CO_2), which are located in the gas cylinder closet (Closet A) across from the Pyro Lab. Also, open the cylinder for the methane gas, which is located in the adjacent closet (Closet B).
3. In the Pyro Lab, there is a gas manifold located above the front of the cone calorimeter. Open the valve tagged "N_2".
4. On the cone calorimeter, switch both gas analyzer valves to the *Nitrogen* position.
5. Adjust the gas pressure to 5 psi for each gas analyzer. **THIS IS VERY IMPORTANT.**

   There are three ways to adjust the gas pressure, of which the first one is the preferred method:

   a. Adjust the valve labeled "nitrogen", which is located below the load cell area of the cone calorimeter.

   b. Adjust the gas regulator positioned near the pressure gauges upstream of the gas analyzers (only use this method to make minor changes to the pressure).

   c. Adjust the nitrogen tank output pressure using the tank regulator.
6. Wait at least 5 minutes until the O_2, CO, and CO_2 readings stabilize at approximately 0.0%.
7. Zero the CO on the gas analyzer, using the menu system (Menu|Calibrate|Password 4000|Manual Cal|▲|▲CO|Low Cal|0.0000%|Yes). When the CO reading has stabilized at 0.000%, press **Quit** twice.
8. Then press ▼ to select the CO_2 channel. Select **Low Cal** and ensure the display says 0.000% and select **Yes** to perform the calibration. Then press **Quit** twice.
9. Then press ▼ to select the Oxygen channel. Select **Low Cal** and ensure the display says 0.000% and select **Yes** to perform the calibration. Then press **Measure** to exit the calibration screens on the gas analyzer.
10. In the *Gas Analyzers Transducer Calibration* panel press the **Zero** button in the Oxygen Cell section. After the routine has finished (the progress bar has reached the top) check that the Oxygen reads 0.000% on the computer screen.
11. Then press the **Zero** buttons in the CO_2 cell and CO cell sections. Check that the CO_2 and CO both read 0.000% on the computer screen. DO NOT press the OK button.
12. Close the valve tagged "N_2" on the gas manifold above the cone calorimeter.
13. On the cone calorimeter, turn the valve for the O_2 analyzer to *Sample Gas*. DO NOT turn on the sample pump at this time.
14. Open the valve tagged "CO" on the gas manifold above the cone calorimeter.
15. On the cone calorimeter, turn the valve for the CO/CO_2 analyzer to *CO/CO_2 Span Gas*.

14. Set the CO/CO_2 pressure entering the gas analyzer to 5 psi and wait approximately 5 minutes for the CO/CO_2 readings to stabilize. Note that the gas pressure can be adjusted following the steps outlined in Step 5, except that the gas is CO/CO_2 instead of N_2.
15. On the analyzer menu system select Menu|Calibrate|Password 4000|Manual Cal|▲|▲ CO|High Cal| then ensure that the value is that stated on the calibration gas bottle certificate. Then select **Yes** to perform the calibration of the CO cell.
16. When the reading has stabilized press **Quit** twice.
17. Then press ▼ to select the CO_2 channel. Select High Cal and ensure the display shows the value is that stated on the calibration gas bottle certificate and select **Yes** to perform the calibration of the CO_2 cell. Then press **Measure**.
18. Check that the CO and CO_2 Span Values on the computer screen match those on the calibration gas bottle certificate (if not then edit the values). Then press the **Span** buttons for the CO_2 and CO cells. Check that the CO and CO_2 values are adjusted to the correct span concentrations.
19. Close the valve tagged "CO" on the gas manifold above the cone calorimeter.
20. Turn the valve for the CO/CO_2 analyzer to *Sample Gas*.
21. Turn on the sample pump (*Pump* button).
22. Let the oxygen concentration stabilize for at least 5 minutes.
23. On the analyzer menu system select Menu|Calibrate|Password 4000|Manual Cal|Oxygen|High Cal| then ensure that the value is 20.95%. Then select **Yes** to perform the calibration. When the reading has stabilized press **Measure.**
24. Press the **Span** button in the Oxygen section on the computer screen. Check that the Oxygen value on the computer screen is 20.95%.
25. Leave the sample pump on.
26. Then press the **OK** button to accept all the gas analyzer calibrations in ConeCalc.
27. Press **Main** to return to the Main panel in ConeCalc.

E. Perform the C-Factor Calibration

1. Ensure that the sample pump is on and has been running for at least 15 minutes.
2. Open the valve tagged "CH_4" on the gas manifold above the cone calorimeter.
3. Place the calibration burner in position under the cone.
4. Ensure the spark igniter is in the idle position and push the *Ignition button* **ON**.
5. Select **C-factor** from the Main panel in the *ConeCalc* software. The C-factor panel will open and then select **Routine**.
6. Enter the required information for the C-factor test.
   a) Change the *filename* by selecting the **File** button and then select the folder to store the C-factor file.
      i) In general, the C-factor file is stored in the directory of the sample for the first test of that day.
      ii) Use the following filename configuration for a C-factor test: "*CFactor_mmddyy.csv*", where "mm" is the two digit month, "dd" is the two digit day", and "yy" is the last two digits of the year.
   b) The information for the *Apparatus Specifications* does not need to be changed.
   c) Enter in the current temperature, relative humidity, and pressure for the *Atmospheric Conditions*.
   d) Verify the *Carbon dioxide* is set to **Non-scrubbed**.
   e) Verify that the HRR Level for the *Burner* is set to **5 kW**.
7. Press **OK** after all the relevant information has been entered.
8. Verify that the gas analyzers display the following values:
   a) O_2: 20.95 % ± 0.01 %
   b) CO_2: 0.040 % ± 0.005 %
   c) CO: 0.000 % ± 0.003 %

   If any of the gas analyzers are outside of their tolerances, then either a High Cal must be performed for the O_2 analyzer or Low Cal for the CO/CO_2 analyzer.
9. After verifying the readings on the gas analyzers are within tolerance, open the shutters under the Cone heater.
10. Ensure that the *Methane valve* on the cone calorimeter is in the **OFF** position.
11. In the *ConeCalc* software, select **Yes** to perform the pre-run calibrations.
12. Press **Start** in the C-factor Calibration panel to collect the baseline data.

    Note that during the entire C-factor routine, ensure that the sample line pressure for O_2 and CO/CO_2 remain at 5 psi. Adjust the regulators positioned near the pressure *gauges upstream of the gas analyzers as necessary.*

13. Place the igniter over the methane burner and visually verify that it is sparking.
14. Plug power into the mass flow meter for the methane burner and verify/adjust the setpoint to 9.2 slpm.
15. When instructed by the computer program, open the *Methane gas valve* on the cone calorimeter
16. Remove the igniter after the methane gas ignites.
17. Verify the flame is within the opening of the cone heater. If not, adjust the position of the burner and then secure in place.
18. If necessary, adjust the methane flow on the mass flow meter to obtain approximately 5 kW. The HRR is shown in the bottom left graph and display using the ConeCalc software.
19. Allow the data collection part of the routine to complete and close the *Methane gas valve* when instructed. (DO NOT adjust the methane flow valve or the pressure regulator on the bottle during the data collection phase (last 3 minutes of the routine).
20. Press the **Stop** button to finish the routine when instructed.
21. Press **Save Mean** to save the *Mean C-factor*. Press the **Exit** button to return to the C-factor panel.
22. Press the **View Log** button to view a log of the saved C-factors. The acceptable range for the instrument is 0.040 - 0.046. Compare the current C-factor to the previous value. The difference between the two C-factors can be calculated automatically be selecting the current and previous C-factors on the C-factor graph.

    Measurements on two successive test days shall not differ by more than 5%. Such differences indicate malfunctions, which require rectification before testing is continued. Typically, a high C-factor results because of leaks or blockages, a very high C-factor means that the cold trap is still open, a low C-factor may be due to a leak in the methane line or a faulty mass flow meter.
23. Press the **Close** on the C-factor Log Panel to return to the C-Factor panel. Then Press the **Exit** button to return to the Main panel.
24. Remove power from the mass flow meter.
25. Turn the *Ignition* **OFF** and remove the methane burner.
26. If it will be more than 20 minutes before a test is run, turn off the sample pump.
27. Close the valve tagged "CH_4" on the gas manifold above the cone calorimeter.
28. Close all of the gas cylinders located in the gas cylinder closets.

F. Calibrate Smoke System *(this section only applies if smoke measurements are obtained)*

1. Place the "smoke zero blank" (a black metal block for interrupting signal between laser and photodiode) between the laser and the compensating photodiode (next to the laser).
2. Select the software routine *Calibrations/Smoke* and then press the **Zero** button.
3. Check that the Calibrated Main and Compensating signals [PDM(-) and PDC(-)] are 0.000. If not, then press the **Zero** button again.
4. Remove the smoke zero blank and ensure that the blank slot and filter slot is covered.
5. Press the **Balance** button to adjust the input values of each of the photodiodes to give a normalized ratio of 1.000 (this is in the PDC(-) and PDM(-) displays). The Transmission (%) panel should also read approximately 100%. If not, then press the **Balance** button again.
6. Then press the **OK** button.

G. Configure Load Cell

1. Turn on power to the load cell (*Load Cell* button).
2. Check that the range of the load cell is appropriate for the mass of the specimens that will be tested.
   a. From the main menu of the *ConeCalc* software, select *Configuration*.
   b. Verify that the upper range of the load cell (indicated by the "*measured span*" value) is greater than the mass of the specimens to be tested.

      Note that it is very important that the specimen mass does not exceed the upper range of the load cell as specified in the *ConeCalc* software. Although the load cell controller will display the correct mass, the signal sent to the computer will "top out" (i.e., the signal will be greater than 10 V). Therefore, an incorrect mass reading will be recorded and all parameters involving mass calculations will be invalid.

   c. Click the **Cancel** button to return back to the *ConeCalc:Main* screen.
   d. Click the **Status** button to go to the *ConeCalc:Status* screen.
3. If the load cell has already been set to the desired range for a series of tests, then only a 2-point verification is required. **Otherwise, proceed to Step 4 to change the range.**
   a. Add an empty sample holder (with fiber blanket, edge frame, and grid if used) to the load cell.
   b. Push the **Tare** button below the load cell controller. Verify that the load cell controller and the mass on the *Status* screen both show a value of **0**.
   c. Add a weight to the sample holder that is slightly greater than the largest mass to be tested. Verify that the load cell display and the mass on the *Status* screen are both reading the correct weight. **No additional configuration of the load cell is required. Proceed to the *Experimental Procedures* section.**

4. **Perform the following steps, only if a new load cell range is required.** To configure the range of the load cell, both the load cell controller and the load cell settings in the *ConeCalc* software must be adjusted.

   a. Determine the maximum mass (m_{max}) of the samples that will be tested. Choose a range slightly larger than this largest mass. For example, if the samples weigh about 80 g, then select 100 g as a full scale load.

   b. Use the following procedure to set the new range in the load cell controller.

PUSH	DISPLAY	COMMENTS
MENU x 17	OT.SC.OF	
MIN	READl	
MAX/MIN	00000.0	READ1 must be 00000.0
MENU	OUTPT1	
MAX/MIN	00.0000	OUTPTl must be 00.0000
MENU	READ2	
MAX/MIN	MMAX	Enter maximum mass here (e.g., 00100.0)
MENU	OUTPT2	
MAX/MIN	10.0000	OUTPT2 must be 10.0000
MENU	STORED	RESET2

   c. Use the following procedure to set the new range in the *ConeCalc* software.

      i. From the main menu of the *ConeCalc* software, select *Configuration*.

      ii. In the *Transducer Calibrations* window, edit the load cell information as shown below, so that the four numbers match those entered into the load cell controller in Step 4b.

	Output		Measured	
	Zero	Span	Zero	Span
Load Cell	0 V	10 V	0 g	m_{max} g

      iii. After entering the number, press **Accept**.

      iv. Then select **Status** from the main menu.

      v. Add an empty sample holder (with fiber blanket, edge frame, and grid if used) to the load cell.

      vi. Push the **Tare** button below the load cell controller. Verify that the load cell controller and the mass shown in the status window both show a value of **0**.

      vii. Add a weight to the sample holder that is slightly greater than the largest mass to be tested. Verify that the load cell controller and the mass shown in the status window both show the correct value of the weight added.

V. Experiment Procedures

A. Prepare Sample

1. Remove sample from conditioning chamber.
2. Measure and record the sample mass. Verify that the sample has achieved constant mass.

   Constant mass is achieved when the mass of the sample does not differ by more than 0.1% or 0.1 g, whichever is greater, in two successive measurements in a 24 hour period.
3. Wrap the sample in one layer of heavy-duty aluminum foil, shiny side towards the sample, covering the sides and bottom and leaving the testing surface exposed
4. Place sample in a clean horizontal sample holder, which contains a ceramic fiber blanket.

   The ceramic fiber blanket must be dried by heating to 150°C (300°F) for at least 3 hours and then placed in a desiccator containing a drying agent/desiccant to remove any water.
5. If needed, use the optional edge frame and/or wire grid. If a different mounting procedure is to be used, as specified by the test sponsor, take the appropriate steps and document properly for records.

B. Tare Load Cell

1. Remove the sample from the sample holder.
2. Place the empty sample holder (including edge frame and/or wire grid if used) on the load cell.
3. Allow the mass reading to stabilize.
4. Press the **Tare** button on the Mass Loss Calorimeter section of the cone calorimeter.
5. Remove the sample holder from the load cell. **DO NOT PRESS THE TARE BUTTON AGAIN.**

C. Check Height of Cone Heater

1. Ensure that the cone heater is at the proper distance above the sample surface.
   a. Use the 25 mm reference bar if the edge frame is not used. Measure from the top of the sample surface to the bottom of the cone heater.
   b. Use the 23 mm reference spacer if the edge frame is used. Measure from the top of the edge frame to the bottom of the cone heater.

D. Set Heat Flux

1. Ensure that the cooling water to the heat flux meter is flowing.
2. Place a non-combustible cover on the load cell platform.
3. Open the shutters under the cone heater.
4. Remove the red cap from the heat flux meter. **NEVER TOUCH THE BLACK SURFACE ON THE HEAT FLUX METER.**
5. Place the heat flux meter under the cone heater and set it to the desired distance below the cone heater. Use the appropriate reference bar (25 mm or 23 mm) to set the height. Take care to NOT touch the black surface of the heat flux gauge.
6. Turn on the power to the cone heater (*Cone* button)
7. Using the ConeCalc software, select *Heat Flux*.
8. Select the required heat flux from the drop down list and then adjust the temperature controller to give the required heat flux. This is done by pressing the ▼ and ▲ buttons on the temperature controller. If the desired heat flux has been tested previously, the temperature controller set point will be displayed on the ConeCalc screen.
9. When the temperature has stabilized, look at the heat flux meter reading (Irradiance) displayed in the program.
10. Adjust the temperature using the ▼ and ▲ buttons until the irradiance is at the required level (the Irradiance display will be green).
11. When the heat flux is stable, press the **Save & Exit** button.
12. Remove the flux meter.
13. Check that the copper end of the heat flux meter is cold.
14. Place the red cap on the flux meter and store the meter under the load cell platform.
15. Turn on the sample pump (this will allow for adequate warmup time prior to testing).
16. Leave the shutters open. Make sure the non-combustible cover is on the load cell platform.

E. Setup Video Camera *(Optional)*

Recording video during a cone calorimeter experiment is not required. If using a video camera to record the experiment, complete the following steps.

1. Mount the video camera so that it does not obstruct the operator from installing the sample holder on the load cell.
2. Turn the video camera on and adjust the zoom of the lens so that the video camera is focused on the top of the sample. *Typical video camera views include the bottom of the sample holder to the bottom of the hood, which allows the operator to observe relevant testing events.*

3. Ensure that the video camera is routed through the Pyrometrics Lab to a known DVR channel.

F. Pre-Test Final Check

1. Put the specimen in the sample holder. Secure the edge frame to the sample holder, if used.
2. Check the system one more time, as follows:
   a. Ensure that there is sufficient drying agent in the column.
   b. Check that the laser system slots are covered.
   c. Check that the pressure to the oxygen and CO/CO_2 analyzers is the same as it was during the calibration of the analyzer (5 psi).
   d. Check that the volume flow rate through the duct is 24 l/s ± 2 l/s.
   e. Check that the heater temperature is the same as the temperature noted at the time of the heat flux setting.
   f. Ensure that the sample pump has been running for approximately 15 minutes.
   g. Check that the O_2 concentration is approximately 20.95% over a 1 minute period. If not, then perform a high calibration of the O_2 analyzer by using Calibrations/Gas Analyzers and then press **High** in the Oxygen Cell section. Note that you may have to also adjust the high calibration point in the analyzer software.
   h. Ensure the spark electrode is in the idle position and then turn the spark igniter on.
3. Select **Start Test** in ConeCalc and then enter the required information listed below. Remember that your tests are performed **"Non-scrubbed"** and you must enter the correct laboratory conditions (temperature, relative humidity and atmospheric pressure).
   a. The sponsor for the experiment should be the FireTOSS assigned case number, both for research and casework testing.
   b. The sample description should be used to provide a general label for the sample type.
   c. The Sample ID is chosen pre-test by the operator and should be filled into the Material name/ID as well as the Test/report name fill in sections.
   d. Ensure the test time is set to **1 second** intervals.
   e. Ensure the operator is selected from the drop-down menu. If a new operator is running the experiment, their name can be added to the list.

f. If using the edge frame, ensure that the button is checked, and the sample area is set to 88.4 cm^2. If the edge frame is not used, ensure the edge frame button is not checked and the sample area is set to 100 cm^2.

g. If the sample is prepared as exemplar in the laboratory and have specific requirements for completion or assembly, note these items in sample preparation fill in form section

h. If the sample has specific manufacturer information, note in the manufacturer fill in form section

   If there are multiple manufacturers or other notes to describe, provide further detail in the notes fill in form section

i. Set the file name and desired save location prior to testing.

   File names do not have a specific requirement, but in general they are typically saved as the sample name in a folder of the same naming convention, created by the test operator.

   Note that PMMA tests should be saved with the naming convention PMMA – mmddyy_1,2,3,etc. These experiments should be saved with the sponsor for the next upcoming test series. The description should be set as PMMA and the sample ID as PMMA-mmddyy_1,2,3,etc. These experiments are run without the edge frame.

j. Note that sample information can be loaded from previous projects to save time in filling out specific information. However, the following information will still need to be updated prior to testing: Sample ID, mass, dimensions, test number, heat flux, lab conditions, file save name and location.

   Information can be loaded from the last experiment, or from a different experiment (Load Other) that will prompt the user to select a file from a file directory window

Note that changes can be made to the test setup parameters after the experiment is completed. This can be achieved through print reports/edit data/test information.

4. Then press **OK**.
5. Then perform the pre-run calibrations by pressing the **Yes** button.

G. Testing

1. Open up FireTOSS Experiments. Create a new experiment and enter in all relevant sample and project information. *Note that the Laboratory Conditions Object must be removed.*
2. If recording video during the experiment *(optional)*:
   a. Open iFIX and select the created FireTOSS Experiment ID. *This can be easily achieved if the operator clicks the FireTOSS logo on the Experiment Select tab, which automatically selects the current highlighted experiment in FireTOSS. The selected experiment in iFIX will also show at the top left of the program screen.*
   b. Open the Video tab. Select the assigned DVR for the camera, which will assign the DVR to the selected Experiment ID.
   c. Start the test in iFIX (*which will also start recording the video*).
3. Ensure that the shutters are open. DO NOT put the specimen on the load cell at this time.
4. In ConeCalc, press **Start Baseline** and collect at least 60 seconds of data.
5. While the baseline data is being collected, open the time capture program on the desktop, which is named **Timestamper.exe**.
6. When instructed to insert the specimen, close the shutters and remove the non-combustible cover from the load cell.
7. Place the sample holder with the specimen on the load cell and allow the mass to stabilize.
8. If desired, pull down the protection screen on the cone calorimeter.

   Note: if the test is being documented with a video camera and/or photographs, the use of the protection screen is not recommended.
9. Move the spark igniter into position and ensure that the *Igniter* button is **ON**.
10. To start the test, open the shutters, press the "**S**" key on the keyboard or hand set, and click the Record Time on the *Timestamper* program.

    Note: It is suggested that two people run each test, due to the multiple tasks that occur simultaneously. For example, one person will open the shutters, while the other person presses the S key and clicks the Record Time on the Timestamper program. ***If the operator presses <u>the "S"</u> key after the test has been started in ConeCalc, then the test will stop without any option to continue.***
11. When sustained ignition occurs, record the time by pressing the "**I**" key on the keyboard or hand set. Remove the spark igniter.

    *Note: sustained ignition occurs when a flame exists over most of the test specimen surface for at least 4 seconds. Also, if the "**I**" key is pressed multiple times, the program will only keep and record the last time the key is pressed.*

12. Press the "**E**" key on the keyboard or handset to mark an event time. This time will be displayed in the *Comments* dialogue box after the end of the test, where comments about the event can be entered. *(It is important to hand write the event at the time of occurrence to input into ConeCalc at the end of the test.)*
13. When the specimen stops flaming, press "**F**" key on the handset or keyboard (this records the flameout time).

    *Note: If the "**F**" key is pressed multiple times, the program will only keep and record the last time the key is pressed.*
14. Collect data for an additional 2 minutes.
15. Press the "**S**" key on the handset or keyboard to stop the test or press the "**Stop**" button in ConeCalc.
16. If the specimen does not ignite within 30 minutes, terminate the test and discard the sample, unless the specimen is showing signs of heat evolution (HRRPU > 5 kW/m^2) or unless specific alternative instructions have been received from test sponsor. If burning occurs for more than 1 hour, stop test at 1 hour and remove sample.
17. Close the shutters. Remove the specimen and place it under the laboratory fume hood. Place the non-combustible cover on top of the load cell.
18. Open the shutters.
19. Stop the experiment in iFIX *(thus stopping the video)*
20. Turning off the sample pump between experiments can reduce the amount of indicating drying agent/desiccant used during the tests. If the sample pump is shut off between experiments, make sure to turn the sample pump back on at least 10 minutes prior to starting the next experiment.

H. Post Test Procedure

1. In ConeCalc, click on the *Print Report* menu.
   a. When the *Print Test Report* opens, verify that the current sample data has been loaded.
   b. Click *Export Data* to generate a reduced data file.
   c. Save the file with the default naming convention (the program will add a "_red" to the end of the original filename).

2. Check the reduced data file to verify the sample time interval and data generated are correct.

3. Open the raw data file and change the value for the "Time of Test" (B6 in Excel) to the time listed in the time capture program (TimeStamper.exe). ***Make sure that the file format is changed to hh:mm:ss.***

4. Open the Cone Calorimeter Upload Data Program. *This program uploads ConeCalc data into a FireTOSS experiment.*
   a. Add the Experiment ID from FireTOSS.
   b. Find the raw data file associated with the Experiment ID and select it (*the reduced data file is associated with the raw file through the naming convention and will be automatically populated in the upload program*).
   c. Import the data into FireTOSS.

5. Open FireTOSS and verify that the data has been imported correctly.
   a. Select the *Cone Calorimeter* object.
   b. Type "Cone" into the *Description* row. The bar codes for the equipment assigned to the Cone Calorimeter will automatically be populated in the "Cone Calorimeter" object. *Note that the FireTOSS computer must be connected to the calibration database for this to occur.*

6. Upload any test photos into FireTOSS.

7. Attach the C-Factor file to the first test conducted that day.

VI. SHUT-DOWN PROCEDURE

1. Adjust the cone heater temperature to 0°C.
2. Turn the exhaust fan off after cone temperature drops below 250°C.
3. Turn the following buttons OFF:
   a. Pump
   b. Cold Trap
   c. Load Cell
   d. Ignition
   e. Cone
4. Turn off data logger.

Leave the Gas Analyzers and Smoke buttons on all the time.

5. Shut down the ConeCalc application.
6. Ensure that the gas bottles are turned off.
7. Ensure that the cooling water is turned off.
8. Open the Cold Trap drain valve to drain the water. Leave the tap open until the next time the instrument is used.

VII. MAINTENANCE

Periodic maintenance of the cone calorimeter is required. Listed below are items that need to be maintained on a regular basis.

A. Gas Sampling System:

The components of the gas sampling system listed below should be cleaned at the indicated times. The usual indication of clogging of the gas sampling system is the need to re-adjust the bypass valve repeatedly to maintain the proper flow to the analyzers. If clogging occurs, cleaning of the gas sampling system will need to be performed on a more frequent time interval. *Note that any time a change is made to the gas sampling system (e.g., replacing the sample lines), then the gas analyzer time offsets need to be verified* [4].

1. **Sample Ring -** The sample ring should be cleaned once a year, at a minimum. The necessary frequency of cleaning will depend entirely on how much testing is being done and on the amount of soot produced by the test specimens. The gas sample ring cleaning should coincide with the ductwork cleaning.
2. **Sample Lines -** The gas sample lines should be replaced once a year, at a minimum. If clogging occurs, the lines should be blown out using compressed air, starting from the gas analyzer and working back towards the sampling ring. **Never blow compressed air into the gas analyzer.** If clogging continues to occur, replace the sample lines. After replacing any sample lines, complete the following leak check procedure:
   a. Check to make sure that both Sample Gas valves on the cone calorimeter are switched to the "Sample Gas" position.
   b. Ensure that the desiccant tubes are full.
   c. Turn on the gas sample pump and check for leaks or blockages.

      Ensure that the pressure to the gas analyzers is 5 psi on the gauge inside the rack.

      The flow to the gas analyzers should be 3 - 3.5 1pm on the rotameters.

      If leaks are present, locate the source of the leaks and correct the problem.
   d. Turn off sample pump.
3. **Soot Filtration -** The soot filtration system consists of four filters, three of which contain a paper filter element. The first, and largest filter, is used for course filtration and will require frequent replacement and cleaning. The second filter is used for finer filtration and will require replacement at a less frequent rate than the course filter. The course paper element needs to be checked and replaced (as necessary) at the beginning of each test day, prior to the C-factor test, and prior to each test. The second paper element should be checked periodically and replaced if it shows signs of use. The third filter is an enclosed high-efficiency particulate air (HEPA) filter sealed in a plastic casing. This filter is located at the inlet to the sample pump and

needs to be checked at minimum every six months for soot build up. If the filter is discolored, then it should be replaced. The final filter is a micro filter, which is found in-line with the pressure gauges in the sample gas line. This filter should be checked once per year for any soot buildup. If soot is present in the filter, then the unit should be replaced.

4. **Sample Pump -** If after all the above mentioned components of the gas sampling system have been cleaned and/or replaced and clogging still persists, the gas sample pump may need to be cleaned, serviced (e.g., replacing pump head), or replaced. It is a best practice to run the sample pump monthly for at least 10 minutes between test series to prevent the pump head from losing flexibility, which will result in lower sample line pressure.

B. Ductwork

At a minimum, the inside of the ductwork should be cleaned once a year of any dirt, soot, and ash. This material should be removed by brushing and vacuuming. The frequency of cleaning will depend entirely on how much testing is done and on the amount of soot produced by the test specimens. If there is a noticeable drift in the calibration constant (C-factor), particularly after a batch of sooty materials are tested, the ductwork should be cleaned at this time.

C. Laser Smoke Photometer

At a minimum, the laser smoke photometer should be cleaned once a year. The laser smoke photometer system cleaning should coincide with the ductwork cleaning. A noticeable decline in the laser intensity measurement may suggest soot build up on the optics and the laser smoke photometer should be inspected and cleaned. Within the smoke photometer itself, if only a modest soot accumulation has occurred, it is sometimes possible to blow it out without disassembly. If a significant amount of soot has occurred, then the photometer must be removed and cleaned. An optical re-alignment of the laser smoke photometer will then be required [4].

D. Specimen Area

Frequent cleaning is necessary for the area around the sample holder and the load cell platform. Material falling off the sample during testing tends to accumulate in this area and may interfere with the load cell reading. Vacuuming will normally eliminate any problem. At the same time, check that the aluminum foil protecting the Marinite board heat shield has not been moved so as to bind on the load cell.

VIII. CALIBRATION/SERVICE INTERVALS

The following cone calorimeter instruments need to be calibrated or serviced by the manufacturer or an approved calibration laboratory at the indicated time intervals.

A. Heat Flux Gauge
The heat flux gauge is sent out annually for calibration. If a problem is suspected with the heat flux gauge, it can be checked using a reference heat flux gauge. If a problem is determined prior to the 1 year service interval, then the heat flux gauge shall be sent out for service and calibration.

B. Mass Flow Meter
The mass flow meter is sent out annually for calibration. If a problem is suspected with the meter, a normal C-factor test can be performed using methane and then a second C-factor test can be conducted using ethanol [4]. If a discrepancy exists between the C-factors, the mass flow meter shall be sent out for service and calibrated prior to the 1 year interval.

C. Gas Analyzer
The gas analyzer is calibrated at the beginning of every test day using a zero gas and a span gas. In addition, the gas analyzer is functionally verified annually at the FRL according to manufacturer specifications. [6] If the analyzer does not pass the functional verification tests, it will be sent back to Fire Testing Technology for service. If the gas analyzer shows signs of a drift problem (e.g., has a problem maintaining a span value of 20.95% for oxygen) or any other problem prior to the annual interval, it shall be sent back to the manufacturer for service.

D. Data Acquisition (DAQ)
The data acquisition (DAQ) unit is sent out annually for calibration. If the unit stops working or yields questionable results prior to the 1 year service time period, then the unit shall be sent out for service and calibration.

E. Load Cell
The load cell is checked or set daily using calibrated weights. In addition, the load cell is functionally verified annually. If a problem is suspected with the load cell, replace with the spare calibrated load cell and send the unit out for service and calibration. Refer to the FTT Load Cell Setup Procedure for configuration of a new load cell [1].

F. Differential Pressure Transducer
The differential pressure transducer is calibrated annually. If a problem is suspected with the transducer, send the unit out for service and calibration.

G. Atmospheric Pressure Transducer
If used, the atmospheric pressure transducer is calibrated annually. If a problem is suspected with the transducer, send the unit out for service and calibration.

IX. REFERENCES

1. Fire Testing Technology Limited, Cone Calorimeter - Standard Operating Procedures (SOP), 2011
2. ASTM 1354-17*, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, ASTM International, West Conshohocken, PA, 2017
3. ISO 5660-1, *Reaction-to-fire tests -- Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method),* International Organization for Standardization, Geneva, Switzerland, 2015
4. Fire Testing Technology Limited, *User's Guide for the Cone Calorimeter*, Issue 1.7a, September 2001
5. Fire Testing Technology Limited, *User's Guide for FTT Load Cell Attachment,* Issue 2.0, September 2010
6. ATF FRL Standard Operating Procedure, Servomex Gas Analyzer Functional Verification, (ID 8000)

1) **Initial Setup**

   a) ***Supplies Required***

      i) ***Differential pressure probe(s)***

      ii) ***Tubing of appropriate size and material***

      iii) ***Thermocouple***

      iv) ***Differential pressure transducer with appropriate input range***

      v) ***115 VAC electrical power***

      vi) ***Data acquisition hardware***

      vii) ***Data acquisition connectivity***

      viii) ***FireTOSS client computer***

   b) ***Plumbing and Electrical/Data Connections***

      i) ***Connect differential pressure probe to transducer using plastic or metal tubing***

         (1) ***If using multiple probes, connect total and static pressure tubing using tee connections and make a single run for each to the transducer***

      ii) ***Connect pressure transducer to power supply***

      iii) ***Connect pressure transducer and thermocouple to data acquisition module***

      iv) ***Connect data acquisition module to FireTOSS network***

2) **Start-Up and Pre-Test**

a) ***The calibration marking on the pressure transducer shall be checked to confirm that the instrument is calibrated.***

b) ***Pressure transducers shall be connected to the data acquisition hardware using the smallest input range that will bound the output range of the transducer.***

c) ***Pressure lines connected to the probe shall be protected if it is anticipated that they will be exposed to excessive heat or pressure during the experiment.***

d) ***Perform functional verification of:***

i) ***Thermocouple with ambient***

ii) ***Pressure transducer with ambient***

3) **Experiment Procedures**

a) ***Prior to First Test of Series***

i) ***A zero pressure baseline shall be recorded with the pressure transducer prior to conducting experiments. During the baseline reading the high and low pressure ports of the pressure transducer shall be directly connected. The baseline value shall be the average pressure measured during a period with a minimum 2-minute duration.***

ii) ***Following the baseline test, the ports on the pressure transducer shall be opened to each of the two probe fittings.***

iii) ***Verify that the zero pressure baseline has been recorded on the FireTOSS data sheet.***

b) ***Prior to Each Test***

i) ***Perform functional verification of the pressure transducer and thermocouple with ambient.***

ii) ***Update FireTOSS data sheet.***

c) ***During Tes*t**

i) ***Monitor – The output of the pressure transducer and the thermocouple shall be recorded for the duration of the experiment.***

ii) ***Exception – When the velocity probe must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the probe was removed and the reason for instrument removal shall be recorded on the data sheet.***

4) **Shut-Down and Post-Test**

a) ***If an instrument was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.***

b) ***After the experiment, velocity probes located in areas where they may have been damaged shall be examined for visible damage or surface dirt.***

c) ***If surface dirt is observed, the accumulated soot shall be removed and lines shall be blown out with compressed air. If the probe is physically damaged, it shall be taken out of service until it has been repaired.***

d) ***If conditions occurred, either during the test or following the test, that could potentially affect the performance of the instrument, a functional verification shall be performed on the pressure transducer and thermocouple.***

5) **Maintenance**

   a) ***Check probes to ensure pressure ports are clear of obstructions***

6) **Calibration - All instrumentation associated with the differential pressure point velocity measurement instrumentation shall be calibrated annually. These Instruments Include:**

   a) ***Pressure transducer***

      i) ***Setra 267***

   b) ***Data acquisition***

      i) ***National Instruments Field Point Module***

      ii) ***Allen Bradley MicroLogix 1400***

1) Initial Setup

a) Supplies Required

i) Differential pressure probe

(1) Pitot-static probe

(2) Bi-directional probe

ii) Tubing of appropriate size and material

iii) Thermocouple

iv) Differential pressure transducer with appropriate input range

v) 115 VAC electrical power – extension cord(s)

vi) Data acquisition hardware

vii) Data acquisition connectivity – ethernet cable(s)

viii) FireTOSS client computer

b) Plumbing and Electrical/Data Connections

i) Connect differential pressure probe to transducer using plastic or metal tubing

ii) Connect pressure transducer to power outlet using extension cord

iii) Connect pressure transducer and thermocouple to data acquisition module

iv) Connect data acquisition module using ethernet cable

(1) In the FRL this connection is made to a FireTOSS port

(2) *For field experiments the data acquisition module may be connected to a FireTOSS client computer*

2) Start-Up and Pre-Test

a) *The calibration marking on the pressure transducer shall be checked to confirm that the instrument is calibrated.*

b) *Pressure transducers shall be connected to the data acquisition hardware using the smallest input range that will bound the output range of the transducer.*

c) *Pressure lines connected to the probe shall be protected if it is anticipated that they will be exposed to excessive heat or pressure during the experiment.*

d) *Perform functional verification of:*

i) *Thermocouple with ambient and heat source*

ii) *Pressure transducer with positive pressure source*

3) Experiment Procedures

a) *Prior to First Test of Series*

i) *A zero pressure baseline shall be recorded with the pressure transducer prior to conducting experiments. During the baseline reading the high and low pressure ports of the pressure transducer shall be directly connected. The baseline value shall be the average pressure measured during a period with a minimum 2-minute duration.*

ii) *Following the baseline test, the ports on the pressure transducer shall be opened to each of the two probe fittings.*

iii) *Verify that the zero pressure baseline has been recorded on the FireTOSS data sheet.*

b) ***Prior to Each Test***

i) *Perform functional verification of the pressure transducer and thermocouple with ambient.*

ii) *Update FireTOSS data sheet.*

c) ***During Test***

i) *Monitor The output of the pressure transducer and the thermocouple shall be recorded for the duration of the experiment.*

ii) *Exception – When the velocity probe must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the probe was removed and the reason for instrument removal shall be recorded on the data sheet.*

4) **Shut-Down and Post-Test**

a) *If an instrument was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.*

b) *After the experiment, velocity probes located in areas where they may have been damaged shall be examined for visible damage or surface dirt.*

c) *If surface dirt is observed, the accumulated soot shall be removed and lines shall be blown out with compressed air. If the probe is physically damaged, it shall be taken out of service until it has been repaired.*

d) *If conditions occurred, either during the test or following the test, that could potentially affect the performance of the instrument, a functional verification shall be performed on the pressure transducer and thermocouple.*

5) Maintenance

a) Check probes to ensure pressure ports are clear of obstructions

6) **Calibration**

All instrumentation associated with the differential pressure point velocity measurement instrumentation shall be calibrated annually. These Instruments Include:

a) Pressure transducer

i) MKS Baratron 220

ii) Setra 267

b) Data acquisition

i) National Instruments Field Point Module

ii) Yokogawa Darwin DA100

iii) Allen Bradley MicroLogix 1400

***iv)** Fluke 2680A/2686A/Netdaq*

I. Scope

This document covers the Standard Operating Procedures for digital camera use during experiments at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

II. Required Supplies

A. Digital Camera

B. USB cable to connect camera to laptop

C. Method to transfer photographs from camera to laptop (e.g., USB cable, multimedia card reader)

D. FireTOSS laptop

III. Start-Up and Pre-Test Procedures

A. Verify camera has sufficient battery life remaining

B. Before any tests are conducted at the start of the day, synchronize the camera to FireTOSS using *either* the Nikon software or manually

1. Synchronize using Nikon Software

a) Plug Camera into computer using USB cable and turn camera *ON*.

b) When the AutoPlay Window appears, click “Import File using Nikon Transfer 2” (Figure 1).

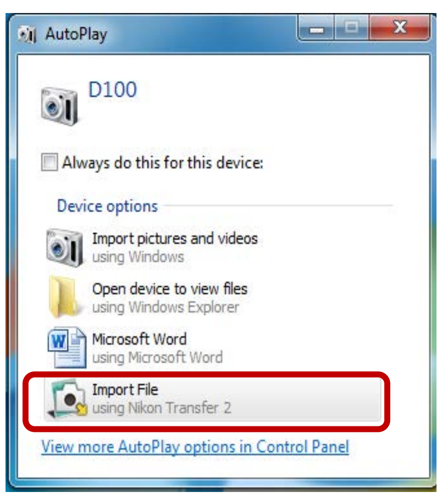


Figure 1: AutoPlay Window

c) Click Synchronize (Figure 2)

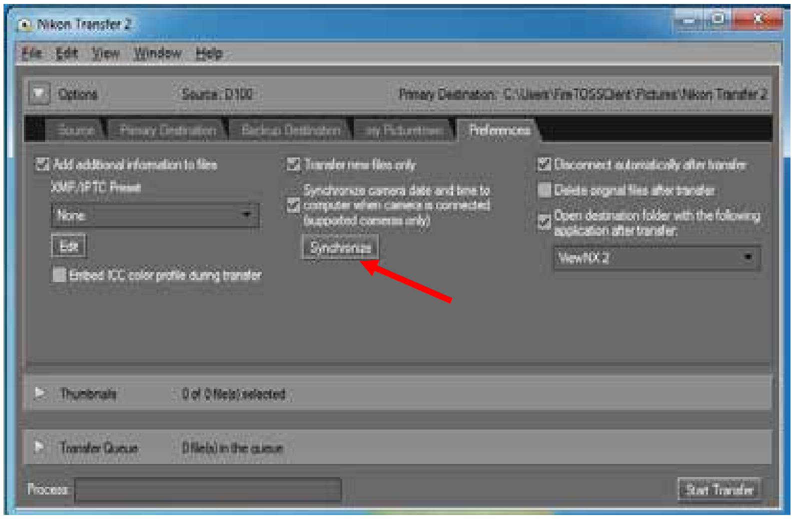


Figure 2: Nikon Transfer Interface

d) A message will appear stating the synchronized time (Figure 3). Although the Nikon Transfer Program only displays a synchronized time to the minute, the program actually synchronizes the camera to the second. Click OK.

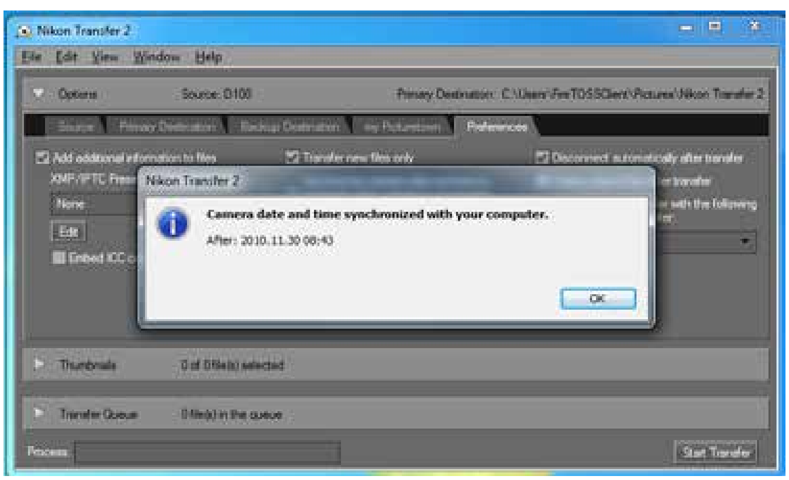


Figure 3: Nikon Transfer Synchronization Confirmation

e) Close Nikon Transfer and unplug camera from computer.

2. Synchronize Manually

a) Open computer date/time program (Figure 4)

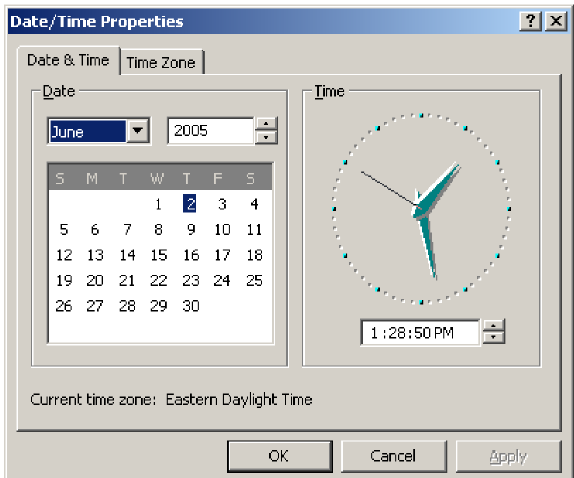


Figure 4: Date/Time Program

b) Open the cameras date/time tab in menu (see cameras user manual if needed)

c) Manually set camera clock to computer clock

IV. Experiment Procedures

Take photographs before, during, and after the test, as necessary

V. Shut-Down and Post-Test Procedures

A. Upload photographs to FireTOSS

1. Use desired method to transfer photos to FireTOSS (e.g., card reader on computer, multimedia card reader, connect camera to computer using USB cord).

   In FireTOSS, click "Import" from the menu bar and then "Upload Pictures" (Figure 5). Note that the user must be logged in to FireTOSS.

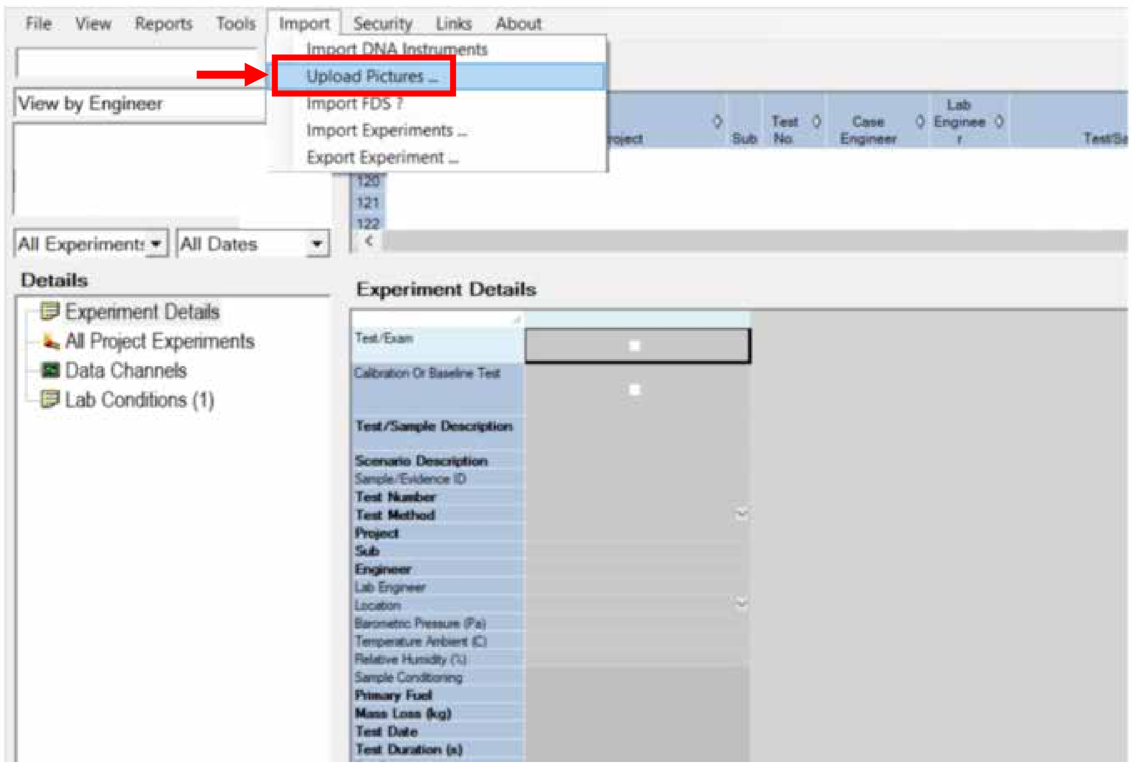


Figure 5: How to access picture upload program from FireTOSS

2. On the Upload Experiment Pictures box (Figure 6), enter the following information:
   a. Specify the directory where the photos are located
   b. Select FireTOSS synchronization status
   c. Select Photographer
   d. Verify correct Experiment ID is selected
   e. Select Picture Type
   f. Select photos to upload
   g. Determine if you want to delete original pictures after copy is verified
   h. Copy pictures (and close)

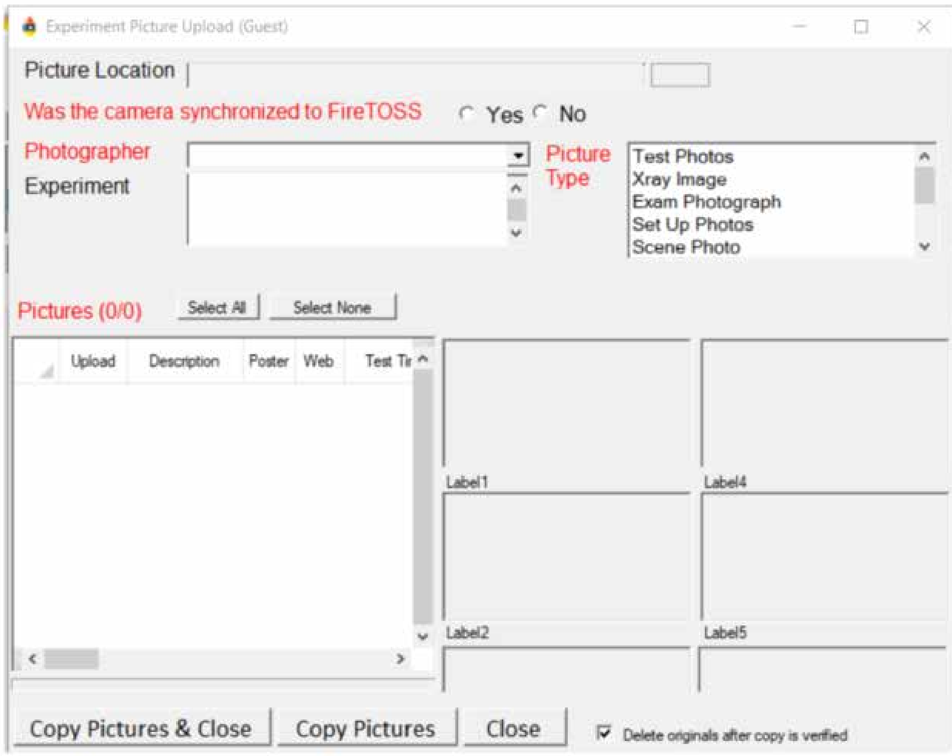


Figure 6: Picture Upload program

VI. Maintenance Procedures

Change Batteries When Low

Periodically Clean Lens of Camera

VII. Calibration Procedure/Accuracy

Digital cameras do not require calibration

Synchronize the camera clock with FireTOSS at the start of each day prior to any tests being conducted

Internal clock of a digital camera must be accurate to 1 second within a 24 hour period.

VIII. Technical References

For more information, refer to appropriate camera model User's Manual.

Bureau of Alcohol, Tobacco, Firearms and Explosives
Laboratory Services - Fire Research Laboratory
Policies and Procedures Guidelines
ATF-LS-FRL Engineering Activities

1. **Title:** Procedure for Engineering Activities

2. **Scope:**

   2.1. When the Fire Research Laboratory (FRL) performs work for a client a project is opened in the Laboratory Project Management System. There are four types of FRL Projects: Scene Examination, Evidence Examination, Laboratory, and Engineering Analysis. Each project consists of one or more "Engineering Activities" as defined in this document.

   2.2. This procedure defines the process used to accept, decline and perform Engineering Activities at the Fire Research Laboratory (FRL). Engineering Activities include <u>Documentation</u>, <u>Physical Examinations</u>, and <u>Analysis</u>.

   2.3. This procedure applies to engineering activities performed at the laboratory and off-site.

3. **Summary**

   The overall procedure for engineering activities is shown the flow chart in Figure 1. The left-hand boxes start the process with client requests for three types of activities. The dashed connectors indicate when multiple projects are conducted to support an analysis activity. A detailed description of the procedure for each type of activity is provided in section 4 through section 6.

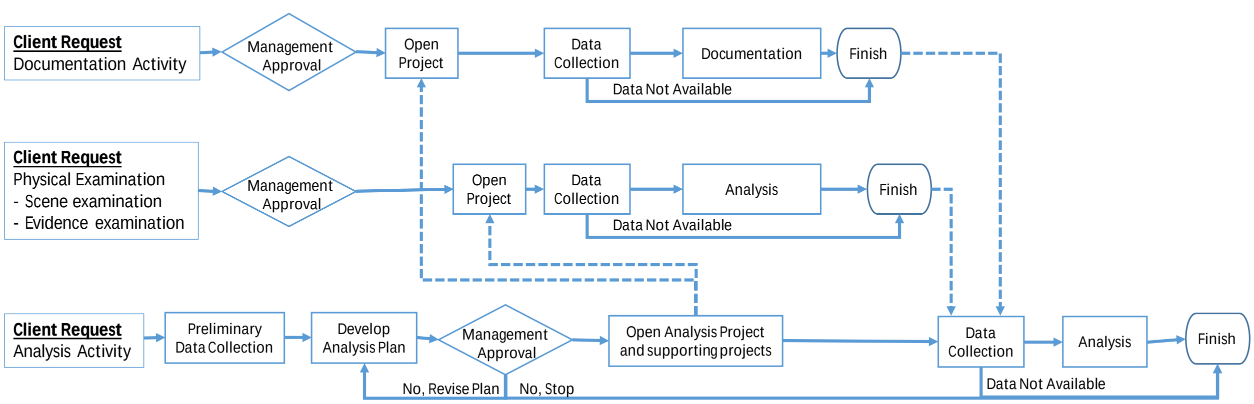


Figure 1. FRL Procedure for Engineering Activities

4. **Documentation Activities:**

   4.1. Documentation activities consist of gathering or generating information without performing an analysis to develop an opinion about how the information relates to an investigation. Documentation activities produce either stand-alone fact reports or are recorded as part of an existing project.

4.2. Examples of Documentation Activities

Conducting experiments to generate data. The result is a fact report that describes the experiments that were conducted and the measurements that were obtained.

Developing a description of electrical or gas utilities within a structure. This could involve contacting utility companies, local building departments, reading blueprints, and tracing wiring during a scene examination.

Developing a timeline related to events that occurred before, during and after a fire event.

4.3. Procedure for Documentation Activities.

Figure 1 shows a flow chart of the process followed for Documentation activities. Each step in the process is described in the text following the figure.

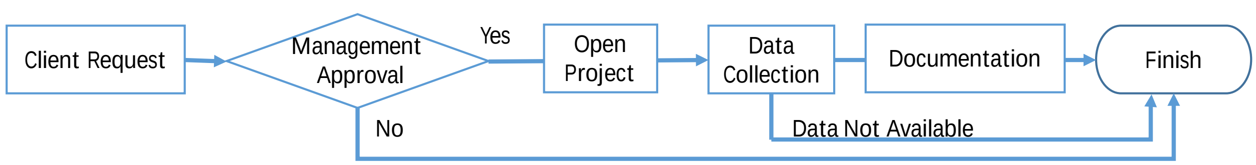


Figure 2. Flow Chart of the Process for Documentation Activities

4.4. **Client Request** – Client requests for Documentation activities are received in one of three ways.

4.4.1. External Request – The client requests a documentation activity.

4.4.2. Internal Request – When a lead engineer for an FRL project identifies the need for a Documentation activity, the engineer verbally relays the request to the Chief of the section that will perform the documentation activity.

4.4.3. Scene Examination – While an engineer is participating in a scene examination, the client can request the engineer to perform Documentation activities as part of the scene examination.

4.5. **Management Approval** – Management approval is required for Documentation activities that are not part of an existing project. After the initial approval, the manager has the option to cancel a Documentation activity if required data collection information is not available, see 7.3. The form of the management approval depends on the type of client request.

4.5.1. External Request – The manager indicates the approval of the request by opening a project in the Laboratory's project management system.

4.5.2. Internal Request – The manager indicates the approval of the request by opening a project in the Laboratory's project management system.

4.5.3. Scene Examination – There are two options for management approval for documentation activities requested during a scene examination.

4.5.3.1. If the documentation activity can be completed during the scene examination or in a reasonable amount of time after the scene examination, the activity is considered part of the scene examination project and no further management approval is required.

4.5.3.2. If the documentation activity requires an extended amount of time after the scene examination, the manager will decide whether the documentation activity is included in the scene examination project or if the client must submit an external request for the Documentation activity.

4.6. Data collection – Engineers conduct data collection activities to develop in the information that is needed to develop the documentation. Data collection is described in section 6.

4.7. Finish – The activities for the project will be recorded, reviewed and documented as defined in section 7.

5. Physical Examination Activities:

5.1. Physical examination activities consist of the evaluation of materials, products, systems, or other items leading to an opinion about how it related to the investigation. Physical examination projects produce laboratory reports with conclusions and opinions.

5.2. Examples of Physical Examination projects:

The inspection of fire damaged electrical devices using visual, microscopic, or X-Ray techniques. The result of the examination will be an opinion about whether the device could have been a potential ignition source for the fire.

The visual examination of a smoke alarm to evaluate the acoustic agglomeration of soot. The result of the examination will be an opinion about whether the alarm sounded during the fire event.

The visual examination of a water heater during a scene examination resulting in an opinion about whether the appliance could have caused a fire.

5.3. Procedure for Physical Examination Activities

Figure 2 shows a flow chart of the process followed for physical examination activities. Each step in the process is described in the text following the figure.

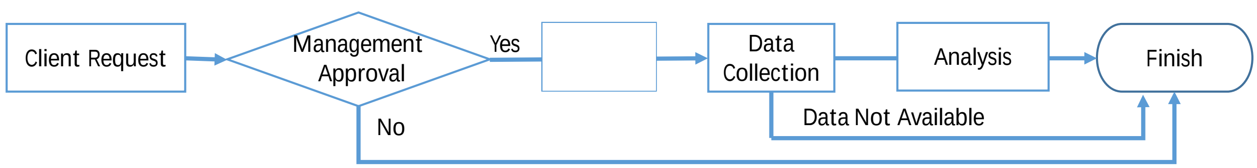


Figure 3. Flow Chart of Process for Physical Examination Activities

5.4. Client Request – Client requests for Physical Examination activities are received in one of three ways.

5.4.1. Evidence Transmittal – The first request type is the evidence transmittal form that the client sends with evidence that is sent to the laboratory.

5.4.2. External Request – The client requests a physical examination activity that will not be performed at the laboratory.

5.4.3. Scene Examination – During scene examinations, the engineer is expected to perform examinations on items as needed in the field. When an engineer determines that an examination cannot be completed during the scene examination, the engineer informs the client so that the client can decide whether to send the item to the laboratory as evidence.

5.5. Management Approval - Management approval is required for Physical Examination activities. After the initial approval, the manager has the option to cancel a Physical

Examination activity if required data collection information is not available, see 7.3. The form of the management approval depends on the type of client request.

5.5.1. Evidence Transmittal – When the client submits the evidence to the laboratory with an evidence transmittal form, the manager indicates the approval of the request by assigning the project to an engineer in the Laboratory's project management system.

5.5.2. External Request – When a request is received from a client for a physical examination activity that will not be conducted at the laboratory, the manager indicates the approval of the request by opening a project in the Laboratory's project management system.

5.5.3. Scene Examination – When the physical examination activity can be completed during the scene examination or in a reasonable amount of time after the scene examination, the physical examination activity is considered part of the scene examination project and no further approval is required.

5.6. Data collection – Engineers conduct data collection activities to develop in the information that is needed for the analysis. Data collection is described in section 6.

5.7. Analysis – The engineer uses their experience, training, and education to analyze the data that was collected and to develop an opinion.

5.8. Finish – The activities for the project will be recorded, reviewed and documented as defined in section 7.

6. Analysis Activities:

6.1. Analysis activities are conducted to answer a client's questions about aspects of the incident. Analysis projects produce laboratory reports with conclusions and opinions.

Figure **3** shows a flow chart of the process followed for Analysis activities. Each step in the process is described in the text following the figure.

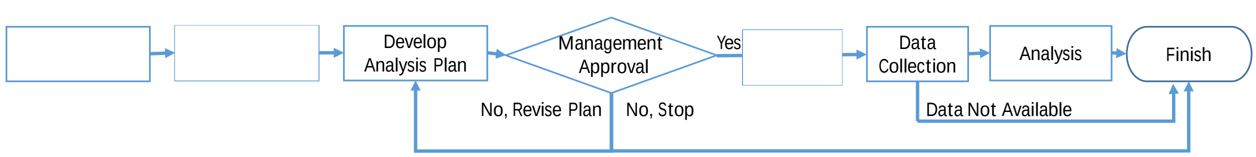


Figure 4. Flow Chart of Process for Analysis Activities

6.2. Client Request – The client sends a memo to the laboratory requesting assistance in answering questions about aspects of the incident.

6.3. Preliminary Data collection – Engineers conduct an initial data collection activity to develop in the information that is needed to develop an analysis plan. Data collection is described in section 6.

6.4. Develop Analysis Plan – The engineer develops a project plan that will assist the client to answer the questions that were posed in the request memo.

6.5. Management Approval – The manager reviews the analysis plan and makes a decision about whether to approve the project. As part of the review process, the manager can convene a panel of subject matter experts to review and provide feedback about the analysis plan. After the initial approval, the manager has the option to cancel the activity if required data collection information is not available, see 7.3. The manager has three options to approve a data analysis plan:

6.5.1. Yes – The manager approves the project plan. The manager indicates the approval of the request by opening a project in the Laboratory's project management system.

6.5.2. No, Revise Plan – The manager instructs the engineer to revise the plan and then resubmit the plan for approval.

6.5.3. No, Stop – The manager does not approve the analysis plan and decides that no further work should be done to develop a plan to answer the client's question.

6.6. Data collection – Engineers conduct data collection activities to develop in the information that is needed to for the analysis. Data collection is described in section 6.

6.7. Analysis – The engineer uses their experience, training, and education to analyze the data that was collected and to develop an opinion.

6.8. Finish – The activities for the project will be recorded, reviewed and documented as defined in section 7.

7. Data Collection

7.1. Collecting and generating information to support the FRL activities is an essential function at FRL. Obtaining information usually takes time and is usually an on-going activity throughout the process. Often the engineer will make a list of the types of information that is needed and start the process of obtaining the information. The engineer is allowed to move to subsequent steps in the process when they decide that enough of the required information will become available. .

7.2. Types of Data Collected

The types of data that is collected and generated for FRL Activities include, but are not limited to the following:

Engineering Calculations
Experimental Data
Investigative Reports
Literature Search
Manufacturer Documentation
Microscopic examinations
Photographs
Scene examination documentation
Visual examinations
Witness statements

7.3. When Required Data Is Unavailable

Sometimes data that is required for the activity will not be available. If the engineer determines information that is essential to the activity will not become available, the engineer informs their manager who will decide whether to cancel the activity or to develop a new plan.

8. Finish

8.1. Manager Does Not Approve Activity

The process for when a manager does not approve an activity depends on the form of the client request.

8.1.1. Evidence Transmittal – When a manager decides not to perform an activity requested on an evidence transmittal form, the manager shall follow the procedure defined in ATF-LS-4.4.

8.1.2. Written Request - When a manager decides not to perform an activity that a client requested in a written request, (e.g. memo, email, etc.), the manager will respond in writing (i.e. an email). The manager will store a copy of the client request and the response in an administrative project in FireTOSS.

8.1.3. Phone Request – When a manager decides not to perform an activity that a client requested via phone, the manager will inform the client and make a record of the communication in FireTOSS.

8.2. Activity Completed

When the activity has been completed records created by the activity shall be stored in accordance with ATF-LS-4.13. The technical and administrative reviews shall be conducted in accordance with ATF-LS-5.9.4. The results of the activity shall be reported in accordance to ATF-LS-5.10.

8.3. Activity Not Completed Because Required Data Is Not Available

When an activity cannot be completed because information required for the activity is not available, the lead engineer shall inform the manager. The manager will inform the client that the activity cannot be completed because the required information was not available. A record of the communication will be stored in FireTOSS. The project for the activity shall be closed

1. **Title:** Procedure for use of Engineering Calculations

2. **Scope:**
2.1 This procedure provides the approach accepted by the Fire Research Laboratory (FRL) for use of engineering calculations. . Engineering calculations typically include calculations done by hand and by spreadsheets or other computer-aided methods.

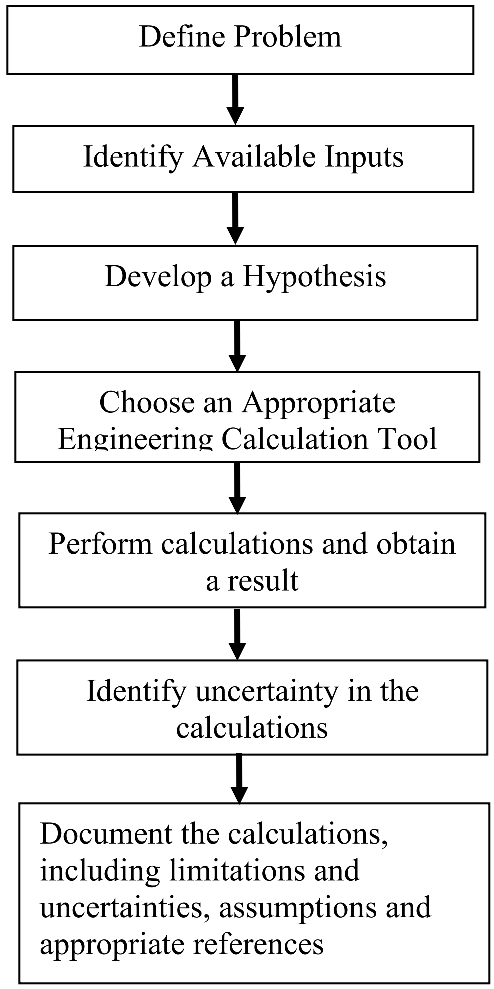
2.2 This procedure is not meant to restrict the methods of analysis available to the engineers, nor does it recommend particular calculations over others.

3. **Description:**
3.1 The choice of which method of calculation is used to solve a particular problem will impact the accuracy of the outcome and the level of uncertainty inherent in the results. Before using a given engineering calculation the engineer must be aware of its inherent limitations and assumptions. The project engineer and the reviewing engineer are responsible for verifying that the calculations being used are appropriate for the given scenario and that sufficient analysis is conducted to identify possible sources and ranges of error.
3.2 The primary source of engineering calculation information for FRL projects should be taken from engineering texts or peer reviewed journal articles. It is permitted that other references or derivation of calculations be used as long as proper documentation is provided (see Work Procedure for Technical Research) and approval is granted from the reviewing engineer.

4. **Uncertainty:**
There is a level of uncertainty involved in all engineering calculations that can be addressed in one of several ways, as appropriate for the particular problem. The project engineer should choose one of the following methods to address uncertainty, as appropriate for the particular case:
A) Uncertainty can be addressed by bounding the variables involved in the equations and providing a range of possible values for each calculation.
B) Uncertainty can be directly calculated using the methods described in NIST Technical Note 1297 "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results"
C) Uncertainty can be measured using a least-squares analysis, Monte Carlo analysis or other similar statistical technique.
D) In some instances qualitative statements are appropriate to describe the effects of any assumptions made during the calculation process.

5. **Procedure:**

5.1 The procedure for the use of engineering calculations is as indicated in the flow chart below.



5.2 The procedural steps for the use of engineering calculations (as illustrated in the flow chart above) are as follows:

Step 1 - Define the Problem: Identify the problem by establishing the goals of the engineering calculations and determining the desired output from the analysis.

Step 2 - Identify Available Inputs: Gather all of the relevant input variables that are available and determine whether there is enough information to proceed with an analysis. If there is not enough information available for an engineering calculation than an evaluation should be made as to whether computer modeling or laboratory testing will be required to solve the problem.

Step 3 - Develop a Hypothesis: Use engineering judgment and other available resources to develop a hypothesis.

Step 4 - Choose an Appropriate Engineering Tool: Choose a method of analysis to complete the required engineering calculations, starting with one of the approved references listed in section 3.2 of this procedure. If an appropriate tool is not available in any of these references outside sources may be used with proper documentation.

Step 5 - Perform Calculations: Calculations should be performed in a way that can be recorded (i.e. written notes or saved excel spreadsheets). These calculations should include sufficient documentation so that they can be easily reviewed and/or recreated by another engineer.

Calculations and data transfers which were not derived from a validated electronic process should be checked. The case record or analysis report should include an indication that such checks have been carried out and by whom. It is preferable for a second person to perform the check.

Step 6 - Identify Uncertainty: Identify/quantify the uncertainty involved in the calculations in accordance with Section 4 of this procedure.

Step 7 – Documentation: Documentation shall be in accordance with the FRL procedure for “Technical Research”.

6. Documentation:

Documentation of engineering calculation analyses will be in accordance with the FRL procedure for Technical Research and will provide sufficient information that another engineer with a similar level of training can review and/or recreate the engineering calculation work.

Scope

This document lists the requirements for documenting and reviewing calculations that are incorporated into the compiled FireTOSS code that is used by the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), Fire Research Laboratory (FRL). FireTOSS is the set of custom software applications that make up the FRL's Laboratory Information Management System (LIMS) [1]. The Calculations program is an application that uses instrument data and parameters to calculate engineering quantities and perform statistical analysis of experimental data. The program is run at the conclusion of every experiment that is run in the FRL. The Calculations program source code, and all required documentation, is maintained by a designee of the FRL Laboratory Section Chief (LSC). Changes to the Calculations program are tracked using Apache Subversion (SVN), which is a software versioning and revision control system.

Documentation of the Calculations program falls into three categories: documentation and review of analysis subroutines, instrument review, and unit conversion review. Analysis subroutines contain the underlying engineering and statistical algorithms in the Calculations program. They shall be documented according to the requirements listed in the Computer Algorithm Documentation section below. Each analysis subroutine shall be subject to technical review according to the requirements listed in the Computer Algorithm Review section.

FireTOSS instruments for which engineering or statistical calculations are performed shall be subject to technical review according to the requirements listed in the FireTOSS Instrument Calculation Review section.

All unit conversions shall be subject to technical review according to the requirements listed in the FireTOSS Unit Conversion Section.

A list of all analysis subroutines, instruments, and unit conversions in the Calculations program shall be maintained by the LSC or designee.

Computer Algorithm Documentation

The Computer Algorithm Documentation form provides the reader with a general understanding of the algorithm. The documentation, at a minimum, shall provide the following information:

A general description of the program/routine which includes the following information:

- Name of program / routine
- Type (Standalone program or subroutine)
- Unique Identification (UI) number
- A description of the purpose
- Limitations of the algorithm
- Language

A list of input parameters, including the data type and units.

A list of output parameters, including the data type and units.

A list of error codes.

A listing of the code.

A revision history.

The document file name shall be structured as follows:

FRL Computer Algorithm Documentation_*Algorithm Name* XXXX

where XXXX represents the Unique Identification (UI) number assigned to that algorithm and *Algorithm Name* shall be replaced with the actual Algorithm Name.

Computer Algorithm Review

Each analysis algorithm in the FireTOSS calculation program shall be subject to a technical review. The Computer Algorithm Review Form serves as a guide for this review. The review cannot be performed by the author of the algorithm. The review is divided into four components. The first component is a general review of functionality and a check on whether the code incorporated version control and was archived correctly. The second component is an administrative review of the Computer Algorithm Documentation Form to ensure that it is complete and accurate. The third component is a review of the code. The primary focus of this review component is to ensure that the code has been written in a way that makes sense -i.e., that meaningful variable name have been used and that it has been documented adequately. There is also a check to ensure that any underlying theory has been implemented correctly. The fourth review component consists of a comparison against independent code using a minimum of five data sets. The reviewer is encouraged to use data sets that test the limits of the algorithm.

The document file name shall be structured as follows:

FRL Computer Algorithm Review Form_*Algorithm Name* XXXX

where XXXX represents the Unique Identification (UI) number assigned to that algorithm and *Algorithm Name* shall be replaced with the actual Algorithm Name.

FireTOSS Instrument Calculation Review

While each analysis algorithm is reviewed independently, the calculations program calls multiple subroutines for instruments associated with an experiment at the conclusion of each experiment. A review shall be performed to ensure that calculations are performed correctly and that data and parameters are stored correctly for each instrument. The FireTOSS Instrument Calculation Review Form is intended to serve as a guide for the review of calculations associated with individual instruments.

The document file name shall be structured as follows:

FRL FireTOSS Instrument Calculation Review Form - *Instrument*

where *Instrument* shall be replaced with the actual Instrument name.

FireTOSS Unit Conversion Review

Engineering quantities can be expressed in a wide range of units. FireTOSS uses a base system of units, but has the capability to express quantities in alternate units. Quantities are expressed in alternate units through a linear conversion. Each conversion shall be reviewed and the review shall be documented using the FireTOSS Unit Conversion Review Form.

The document file name shall be structured as follows:

FRL FireTOSS Unit Conversion Review Form

References

1. FireTOSS Laboratory Information Management System (LIMS) - Technical Reference Guide, ATF Fire Research Laboratory

I. Required supplies

A. Water supply and transport tubing

II. Start Up Procedures

A. Set-Up

1. **The calibration marking on the transducer shall be checked to confirm that the instrument is calibrated.**

2. **Transducers shall be connected to the data acquisition hardware using the smallest voltage input range that will bound the output range of the transducer. This is usually the 20 mV range.**

3. **All heat flux transducers shall be connected to a constant temperature flowing water source.**

4. **Water lines and wires connected to the heat flux transducer shall be protected if it is anticipated that they will be exposed to excessive heat during the experiment.**

B. Pre-Test

1. **It shall be verified that water is flowing through each transducer.**

2. **A baseline reading shall be recorded with the transducer prior to conducting experiments or whenever the water supply temperature changes. The baseline value shall be the average heat flux measured during a period with a minimum 2-minute duration.**

3. **During the baseline reading, the water temperature will be stable and at the same temperature as will be used during the experiments.**

4. **The water temperature used to cool the transducer shall be a minimum of 5°C above ambient. This temperature shall be recorded on the data sheet.**

III. Experiment Procedures

A. Water shall be supplied continuously at a constant temperature.

B. The output of the heat flux transducer shall be recorded for the duration of the experiment.

C. Exception – When the heat flux transducer must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the transducer was removed and the reason for instrument removal shall be recorded on the data sheet.

IV. Shut Down Procedures

A. After the experiment, heat flux transducers in areas where they may have been damaged shall be examined for visible damage or surface dirt.

V. Maintenance Procedures

A. If damage or surface dirt is observed the instrument shall be cleaned and/or repaired according to manufacturer's documentation.

B. If the heat flux exceeded 150% of the maximum transducer range during any point of a test, the instrument shall be taken out of service until its correct operating condition is confirmed.

VI. Calibration

A. Heat Flux Transducer calibration is performed by the manufacturer.

I. Required Supplies

A. Hot Wire Anemometer

Four models of hot wire anemometers are available. Table 1 summaries the features of each instrument and Figures 1-4 show the hot wire anemometers.

Table 1. Description of Hot Wire Anemometers

Model	Velocity Range	Remote Velocity Probe	Digital Display	Signal Output	Power/Signal Connection
FMA-900-MA	0.05 -0.51 m/s (10-100 fpm)	No	No	4-20 mA	Terminal Block
FMA-901-I	0.05 -1.0 m/s (10-200 fpm)	No	No	4-20 mA	7 Pin Connector
FMA-904-I-R	0.05 -10 m/s (10-2000 fpm)	Yes	No	4-20 mA	7 Pin Connector
FMA-1001R-VI	0 - 5.1 m/s (0-1000 fpm)	Yes	Yes	0-5 VDC	8 or 10 Pin Connector

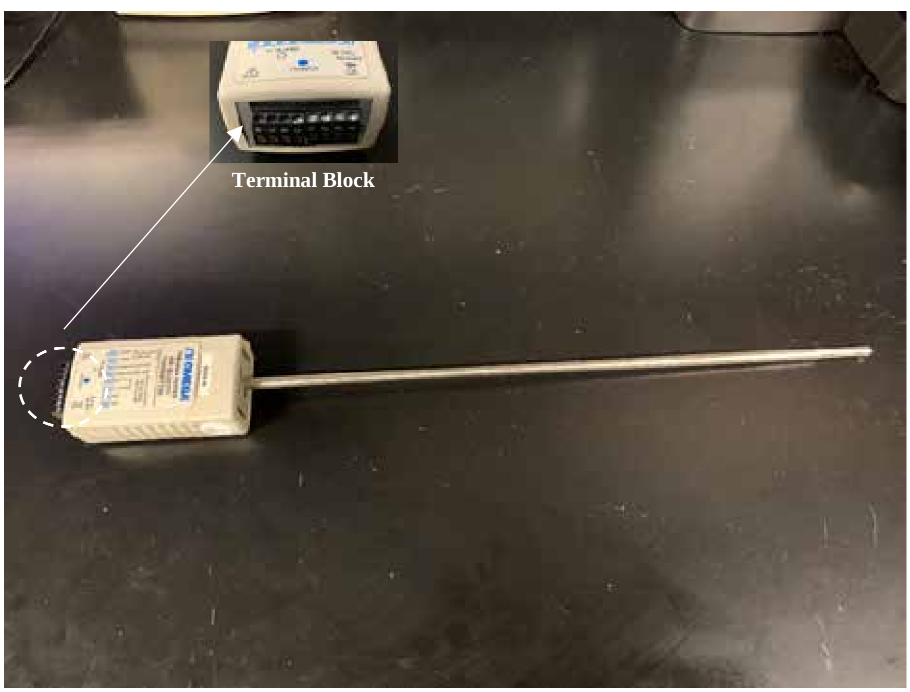


Figure 1. FMA-900-MA - Probe Attached to Electronics Box

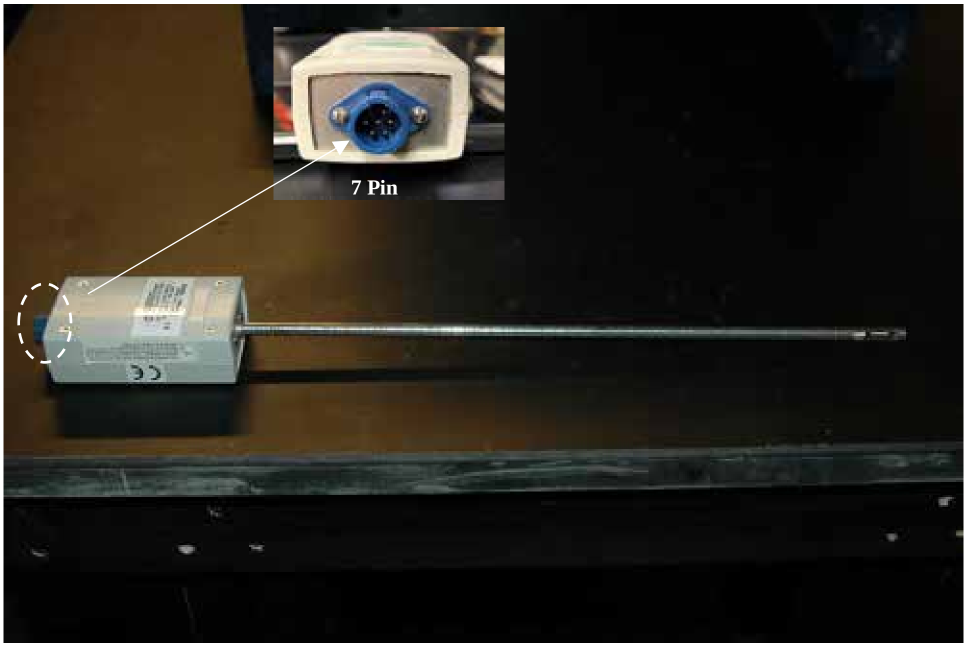


Figure 2. FMA-901-I - Probe Attached to Electronics Box

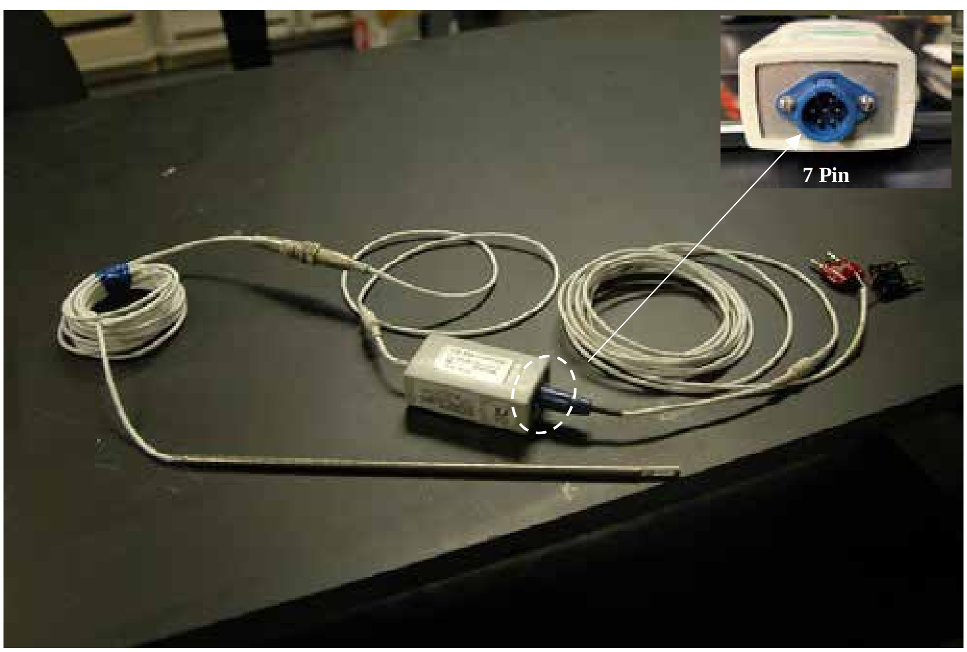


Figure 3. FMA-904-I-R – Remote Probe

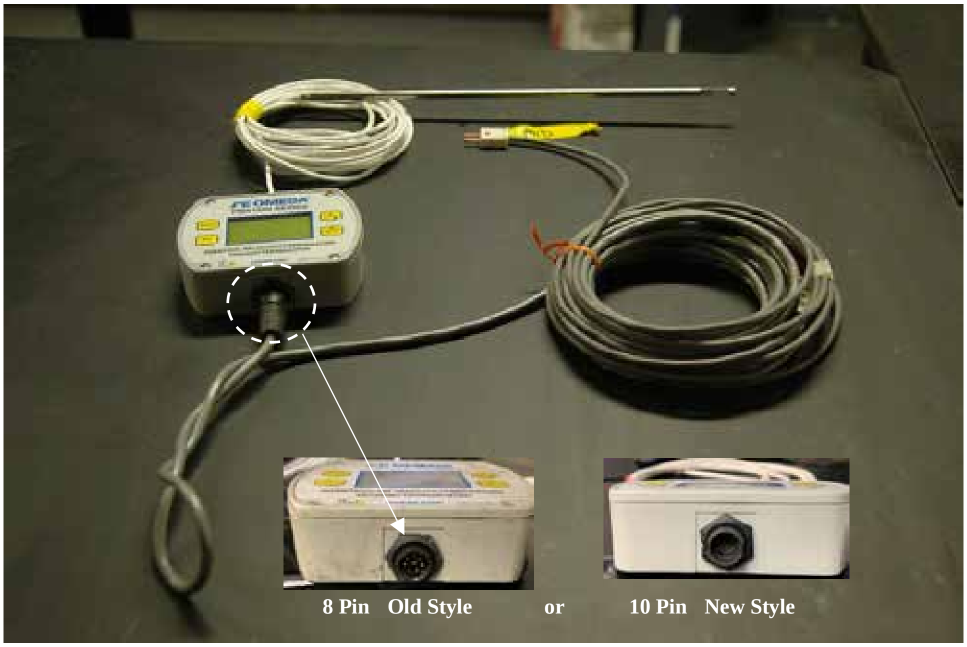


Figure 4. FMA-1001R-VI – Remote Probe and Digital Display

B. DAQ/Power Supply Patch Panel

Patch panel (Figure 5) connects the hot wire anemometers to the power supply.

Dedicated power supplies are installed in the patch panel (unregulated linear power supply Omega model U24Y101 with an output rating of 24 VDC @ 1000 mA).

Patch panel also converts the 4-20 mA output signal of the FMA 900 series hot wire anemometers to a 1-5 VDC output, using a 250 ohm resistor mounted to the back of the patch panel (Figure 6).

Figure 5. DAQ/power supply patch panel for hot wire anemometers

Figure 6. A 250 ohm resistors used in patch panels

C. Connecting Cable/Wires

FMA-900-MA

1. Signal/power cable
   - One end has exposed wires to connect to the terminal block on the hot wire anemometer and the other end has two banana plugs for power and the output signal.
2. Jumper cable
   - One end has a banana plug and the other end has a DAQ voltage connector (male).
3. DAQ Box voltage extension wire
   - One end has a DAQ voltage connector (male), and the other end has a DAQ voltage connector (female).

FMA 900 I and FMA 900 IR

1. Signal/power cable with connector
   - One end has a 7 pin (female) connector that attaches to the hot wire anemometer and other end has two banana plug connectors for power and the output signal.
2. Jumper cable
   - One end has a banana plug to connect to the patch panel and the other end has a DAQ voltage connector (male).
3. DAQ Box voltage extension wire
   - One end has a DAQ voltage connector (male), and the other end has a DAQ voltage connector (female).

FMA 1000 Series models

1. Signal/power connector cable
   - One end has either an 8 pin connector (female) or an 10 pin connector (female) that attaches to the hot wire anemometer, and the other end has one banana plug connector (power) and one DAQ voltage connector (signal).
     - The signal/power cable used with the 10-pin connector has six wires, of which only three wires are used (red, black, white).
     - The signal/power cable used with the 10-pin connector also has a USB cable attached, which is not used.

2. DAQ Box voltage extension wire
   - One end has a DAQ voltage connector (male), and the other end has a DAQ voltage connector (female).

D. Thermocouple

Type-K, 24 American Wire Gauge (AWG), Special Limits of Error (SLE)

One thermocouple required per hot wire anemometer

E. Data Acquisition System

Yokagowa DAQ box with power and communication cables

- Voltage module (0-6 volt range, 1 channel required per hot wire anemometer)
- Thermocouple module (1 channel required per hot wire anemometer)

II. Start-Up Procedures

1. Verify instrument is calibrated and will be throughout the test series.
2. Hot wire anemometers must be installed in the environment at least 5 minutes prior to testing to allow for ambient temperature compensation.
3. Determine location to mount hot wire anemometer.
   a. Hot wire anemometers are intended to be used in clean air or nitrogen environments. Care should be taken to mount the hot wire anemometers away from flammable or hazardous gases such as combustion byproducts.
   b. Hot wire anemometers can be mounted vertically or horizontally in open air or within pipes/ducts.
   c. If mounting the hot wire anemometer within a duct or pipe, run a length of straight pipe before and after the hot wire anemometer. Consult manufacturer documentation for specific length requirements, which depend on the configuration of the piping system.
   d. Align the sensor of the hot wire anemometers with the air flow. Make sure the air flow is perpendicular to the sensor window.
4. Place the patch panel near the location of the hot wire anemometers, so that the cables can reach the hot wire anemometers. Up to three hot wire anemometers can be attached to one patch panel.
5. Connect the appropriate signal/power cable to the hot wire anemometer.

   In general, the signal/power cable consists of at least wires that are red, black, white, and green.

The red and black wires are used to supply the power to the hot wire anemometer (red to positive, black to negative).

The white and green wires are used to carry the hot wire anemometer's data signal from the electrical box to the data acquisition equipment (white to positive, green to negative).

§ For the instruments that have an output signal of 0-5 VDC, the green wire is not used. Instead, a second wire is joined to the black power wire (negative).

6. Select the position on the patch panel (# 1, 2, or 3) to connect the hot wire anemometer (Figure 7).

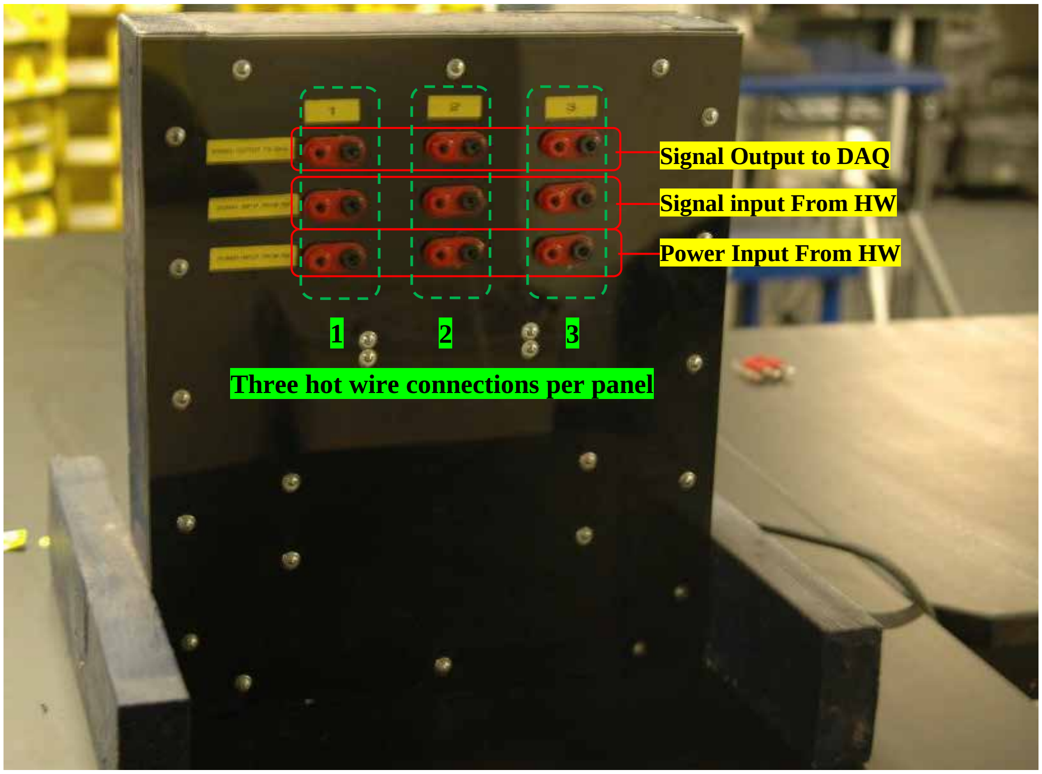


Figure 7. Patch panel connections

7. Use the following steps to connect the FMA 900 series instruments to the patch panel and DAQ box. Skip to Step 8 for the FMA 1000 series instruments.

   a. Figure 8 shows the basic wire connections between the hot wire anemometer and the patch panel and DAQ box.

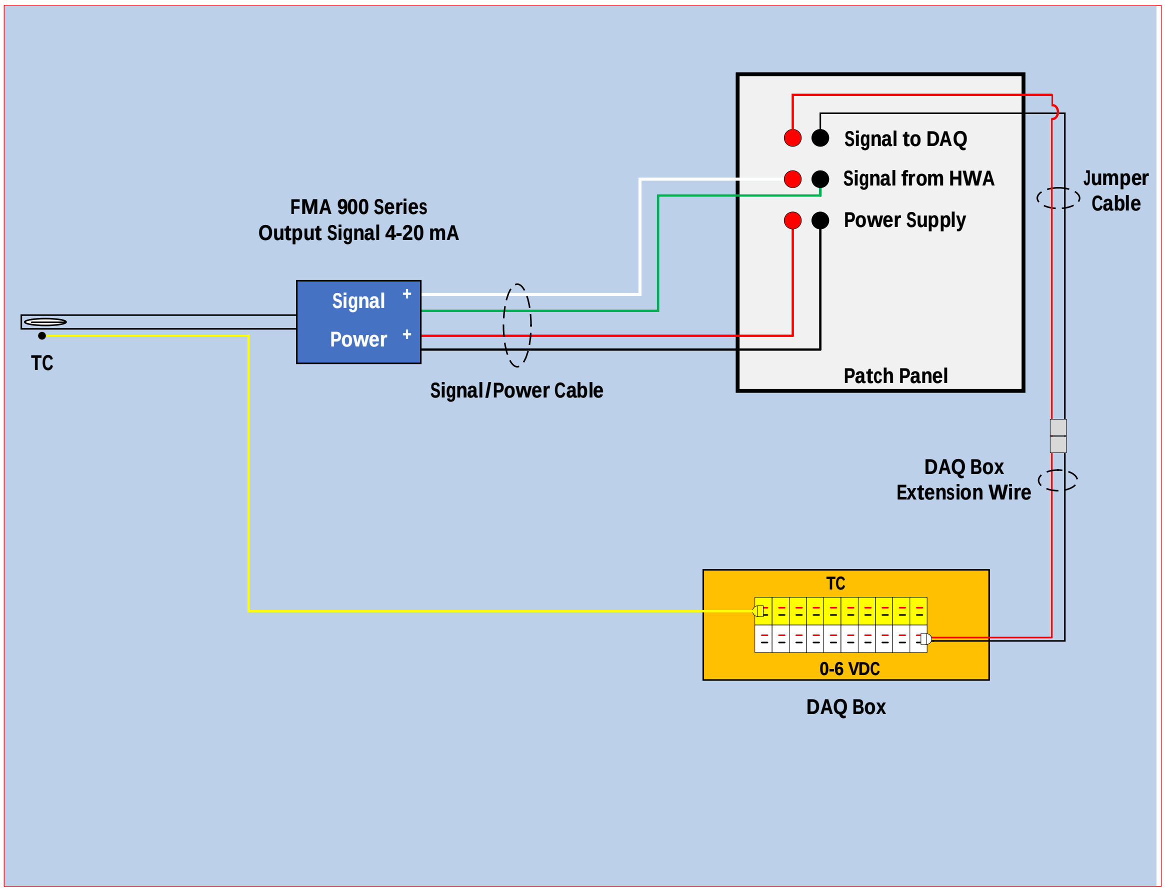


Figure 8. Wire connections for FMA 900 Series hot wire anemometers with the 4-20 mA output signal

   b. Connect the power/signal cable with the red/black wires to the bottom of the patch panel marked "*Power Input from HW*".

      § Insert the banana plug attached to the red wire into the red plug and the banana plug attached to the black wire into the black plug.

   c. Connect the signal/power cable with the green/white wires to the middle of the patch panel marked "*Signal Input From HW*".

- § Insert the banana plug attached to the *white* wire into the *red* plug and the banana plug attached to the *green* wire into the *black* plug.

d. Connect the banana plug attached to the end of a jumper cable to the plugs located at the top of the patch panel marked "*Signal Output to DAQ*".

- § Typically, the jumper cable will consist of a red or white wire (positive) and a black wire (negative).

e. Connect the jumper cable to the DAQ box using an extension wire. Plug the wire into an open voltage channel (0-6 VDC) on the DAQ box.

8. Use the following steps to connect the FMA 1000 series instruments to the patch panel and DAQ box.

a. Figure 9 shows the basic wire connections between the hot wire anemometer and the patch panel and DAQ box.

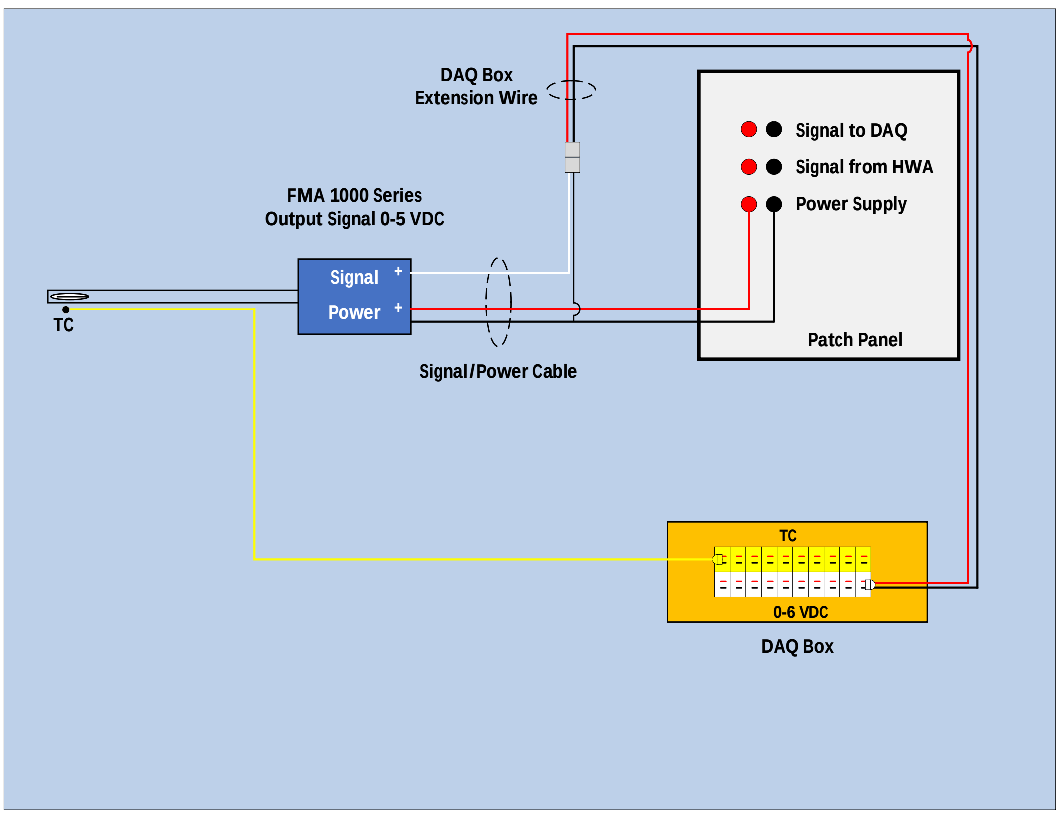


Figure 9. Wire connections for the FMA 900 Series hot wire anemometers with a 0-5 VDC output signal

b. Connect the power/signal cable with the red/black wires to the bottom of the patch panel marked "*Power Input from HW*".

§ Insert the banana plug attached to the red wire into the red plug and the banana plug attached to the black wire into the black plug.

c. Connect the output signal connector of the power/signal cable to an extension wire for the DAQ box. Plug the wire into an open voltage channel (0-6 VDC) on the DAQ box.

9. Install a single Type-K 24 AWG SLE thermocouple near the hot wire sensor to monitor the surrounding air temperature, if a thermocouple is not present.
10. Plug the thermocouple into an open temperature channel on the DAQ box.
11. Verify the output signal of the hot wire anemometer and thermocouple using the data acquisition system.

a. The hot wire anemometer can be checked by ***gently*** blowing air across the sensor.

b. The thermocouple can be checked using a flame from lighter. Make sure that the flame *does not* contact the sensor of the hot wire anemometer.

III. Experiment Procedures

1. Prior to the start of the test, verify the output signal of the hot wire anemometer and thermocouple.
2. During the test, record the output signal of the hot wire anemometer.
3. Monitor temperature of the surrounding air throughout the test.
4. If the surrounding air temperature exceeds 121 °C (250 °F) for remote sensing probes or 50 °C (122 °F) for attached probes, the hot wire anemometers must be taken out of service for the duration of the experiment. The elapsed time at which the hot wire instrument was taken out of service and the reason for its removal shall be recorded.
5. During the test, it may be necessary to totally remove the instrument from the setup, in order to prevent the instrument from being damaged by elevated temperatures. If the instrument is removed, then the time at which the hot wire anemometer was removed shall be reordered, along with the reason why.

IV. Shutdown/Post Test Procedures

1. After the experiment, check the sensor tip of the hot wire anemometer (Figure 10) for any visible damage or surface dirt.

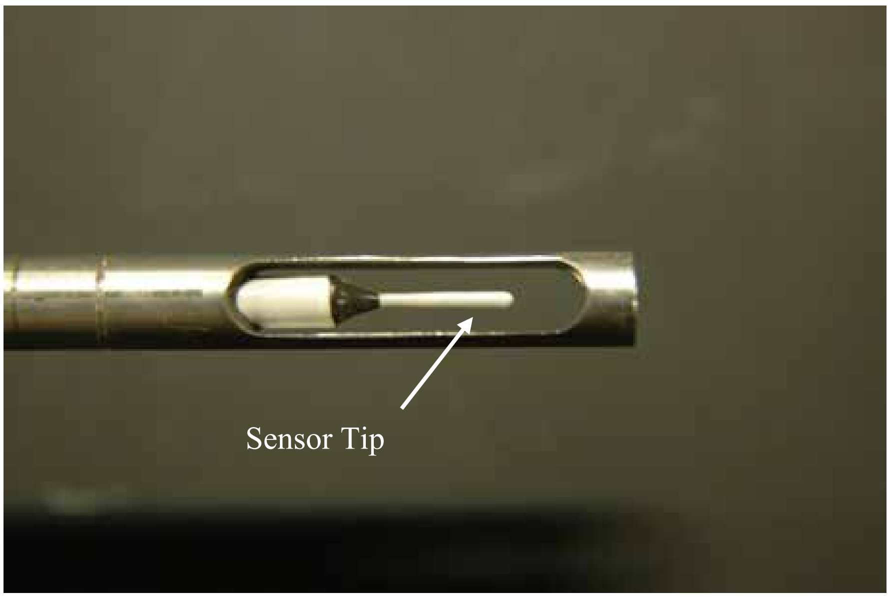


Figure 10. Hot wire anemometer sensor

2. If soot, debris, or damage is found, the test data will be reviewed for any irregularities with the data. If any irregularities are found, the data will not be used from the point at which the irregularities were first discovered.
3. If surface dirt is observed, the instrument shall be taken out of service until it has been cleaned according to manufacturer's instructions.
4. If visible damage is observed, the instrument is to be sent back to the manufacturer to be repaired. The unit must then be recalibrated, before it is put back into service.

V. Maintenance

Except for the intermittent cleaning of the sensor probe, no routine maintenance required.

If soot or debris are found, the component must be cleaned prior to testing.

If the probe becomes coated with dust, ***carefully*** blow the dust away with clean air.

If the probe is coated with sticky material, clean it with solvent which is compatible with epoxy, glass, and 304SS, and which will not leave a residue on the sensor.

You may clean the sensor with water or alcohol (Ethanol) and an artist's brush.

If the unit needs to be repaired, send it back to manufacturer.

VI. Calibration

Hot wire anemometers are calibrated annually.

I. Required Supplies

A. Vaisala PTU300 transmitter and PTU303 probe

B. Ethernet cable

II. Start-Up and Pre-Test Procedures

A. Verify the Laboratory Conditions station is calibrated.

B. Verify the Laboratory Conditions station is connected to the FireTOSS network using an Ethernet cable and that the unit is powered on.

C. Verify that probe is free of obstructions or anything else that could interfere with the measurements.

D. Verify the pressure port on the bottom of the unit is free from obstructions.

E. In the FireTOSS experiment design program , select the appropriate Laboratory Conditions station that is near the area in which the test is being conducted.

F. Verify the Laboratory Conditions station is working properly by looking at the data on the iFix Data Screen for Lab Conditions.

III. Experiment Procedures

A. Monitor the laboratory conditions data during the test.

IV. Post-Test and Shut-Down Procedure

A. Verify the data was collected properly and that there were no issues with the data.

B. Laboratory Conditions station shall remain powered on and connected to the FireTOSS network.

V. Maintenance Procedures

A. Periodically check the probe and pressure port for obstructions and dirt.

VI. Calibration Procedures

A. Calibrate the entire unit (transmitter and probe) annually.

The Fire Research Laboratory (FRL) coordinates with Special Agent/ Certified Fire Investigators (SA/ CFI) to apply engineering principles to crime scene and physical evidence evaluation for the purpose of assisting the client with understanding specific limited aspects of the fire event, such as ignition, material properties, visibility, etc. The FRL Project Scheme represents the standard approach and the FRL Analysis Scheme defines the services provided by the FRL. The SA/ CFI request for assistance memo verifies the scope of analysis provided by the FRL. The FRL provides support in the form of fire scene examinations/ documentation, reviews of investigative reports (timelines, witness statements, etc.), literature searches, calculations (non-fire dynamics), fire dynamics analyses and testing/ experimental simulations. The FRL simulation experiments can be categorized as either material/ product experiments or scenario experiments.

Material/ Product Experiments

Material/ product experiments are tests conducted to measure properties of single materials or groups of materials (products) or to measure the reactions of the items to specific test conditions. Physical evidence shall be submitted to the FRL by the SA/ CFI, when applicable.

Scenario Experiments

Scenario experiments are tests conducted to evaluate the reaction of items or the environment produced by group of items when subjected to a specific set of initiating conditions.

The test plan development for a simulation experiment is regarded as a rendition of the incident, or subset of the incident, as directed by the SA/ CFI request and takes into account the fire scene examination/documentation and investigative reports, as well as the FRL calculations and fire dynamics, when applicable. The test plan is constructed with FRL-approved methods and incorporates acquired information from prior FRL simulations to ensure the quality of the FRL services, the efficient and effective use of resources and the safety of the participants. Utilization of measuring devices in the simulation is intended to realize the data collection in correspondence with the manufacturer specifications and the expectations of the test plan. The execution of the simulation is continually monitored to assess conformance with the test plan.

The FRL-approved methods for the experiments are those methods published in international, regional or national standards and those methods that have been developed and evaluated in accordance with ATF-LS-5.4 Test Methods – Method Validation and the FRL commissioning procedures. Published standards are developed by consensus standards writing organizations that include, but are not limited to, the National Fire

Protection Association (NFPA), the American Society of Testing and Materials (ASTM), and the International Organization for Standardization (ISO).

Experiments can be conducted on-site at the FRL facility and off-site at other locations. Investigators and individuals authorized by FRL management may witness a simulation.

1) **Initial Setup**

a) ***Supplies Required***

i) ***Stainless steel braided hose for natural gas transport***

(1) **Diameter from main to gas cart: 3.8 cm (1½ inch)**

(2) **Diameter from gas cart to burner:**

(a) **2.5 cm (1 inch) for 1000 SLPM**

(b) **0.64 cm (¼ inch) for 100 SLPM**

(c) **5 cm (2 inch) for 3000 SLPM**

ii) ***Burner***

(1) **Sand Burner 1: 0.41 x 0.41 m**

(2) **Sand Burner 2: 0.41 x 0.41 m**

(3) **Sane Burner 3: 0.30 x 0.30 m**

(4) **Sand Burner 4: 0.20 x 0.20 m**

(5) **Sand Burner 5: 0.71 x 0.71 m**

iii) ***115 VAC electrical power – single extension cord***

iv) ***FireTOSS connectivity – single Ethernet cable***

v) ***FireTOSS client computer***

b) ***Plumbing and Electrical/Data Connections***

i) ***Connect appropriate stainless steel braided hose from fuel supply to cart and cart to burner***

ii) ***Perform a leak check on all connections***

iii) ***Connect cart to power outlet using extension cord*** *iv) Connect cart to FireTOSS port using ethernet cable*

Note: Make sure that mass flow controllers are NOT powered ON until ready for use. Make sure mass flow controller is UNPLUGGED. This is a precautionary measure to prevent burnout.

2) **Start-Up and Pre-Test**

a) ***Check calibration of mass flow controller(s), data acquisition hardware and pressure transducer – If out of calibration, see calibration technician***

b) ***Select appropriate burner setup for test***

i) ***For 0-50kW, use 100 SLPM gas train (Gas Train C)***

ii) ***For 0-500 kW, use single 1000 SLPM gas train (Gas Train A, B or D)***

iii) ***For 0-1300 kW, use 3000 SLPM gas train (Gas Train E)***

iv) ***For 0-1500 kW, use three 1000 SLPM gas trains (Gas Trains A, B and D)***

v) ***For 0-2800 kW, use three 1000 SLPM gas trains (Gas Trains A, B and D) and the 3000 SLPM gas train (Gas Train E)***

c) ***Position burner(s) where needed***

d) ***Set up and ignite propane pilot for Burners – Do NOT turn burner gas supply ON until pilot light has been ignited***

e) ***Plug power cord into mass flow controller***

f) ***Verify that mass flow controller set point is 0.0g*** *g) Turn natural gas ON*

i) In mezzanine, turn gas valve to ON position, turn the compressed air valve to ON position and turn control switch to manual position

ii) Pull out emergency shutoff "mushroom" button located on wall of burn room

iii) Turn wall main valve(s) to ON position

iv) Turn both valves on cart(s) to ON position

h) Check pressures to cart(s) to verify adequate gas supply

3) Experiment Procedures

a) During Test

i) Monitor pressure at cart to ensure adequate fuel supply

ii) Monitor mass flow controller set point to verify desired flow

b) Burner Control Through iFix

i) Launch iFix

ii) Select "Burner Control" button at bottom of screen

iii) Select the gas cart(s) to be used

iv) Select the gas to be used (generally natural gas)

v) Verify combustion calorimeter warning light is green.

vi) Select the program to run

(1) **Manual – User control of flow rate controlled with input box**

(2) **5 Point Cal – Burner follows a preset series of five flowrates**

(3) **8 Point Cal - Burner follows a preset series of eight flowrates**

(4) **Custom – Runs a Prescribed HRR Curve From a text file**

(a) **Text file must be located in the C:\ directory and have the name "BurnerControlX" where X is the gas train name (A,B,C,D,E)**

(b) **In text file, input the following: HRR,Duration**

(i) "HRR" is the desired Heat Release Rate of the specific step

(ii) "Duration" is the time duration of the specific step

(iii) Each line of the text file is interpreted as a "step" by the burner program. A correct text file should be formatted as such:

1. **HRR,Duration**
2. **HRR,Duration**
3. **HRR,Duration**
4. **…**

(iv) Upon the completion of the final step (line of the text file), the Burner Control Program will set all active Mass Flow Controller set points to zero (0).

vii) Start Program Selected

(1) **If using 5 Point Cal, 8 Point Cal, or Custom, press "Gas ON" button**

(2) **If using Manual program, enter starting value in input box and press "Enter" key. Subsequent values are also entered using this method.**

viii) Press "Gas OFF" button when finished test

4) **Shut-Down and Post-Test**

   a) ***Turn OFF natural gas.***

      i) ***Turn both valves on cart to OFF position***

      ii) ***Turn wall main valve to OFF position***

      iii) ***Push In emergency shutoff "mushroom" button located on wall of burn room***

      iv) ***In mezzanine, turn gas valve to OFF position, turn the compressed air valve to OFF position and turn control switch to OFF position***

   b) ***Power OFF mass flow controllers if no more tests are being performed by unplugging power cord from mass flow controller***

5) **Maintenance**

   a) ***Periodically check for leaks at connections***

   b) ***Power OFF mass flow controllers when not in use***

6) **Calibration - All instrumentation associated with the sand burner and natural gas cart shall be calibrated annually. These Instruments Include:**

   a) ***Mass flow controller***

   b) ***Pressure transducer***

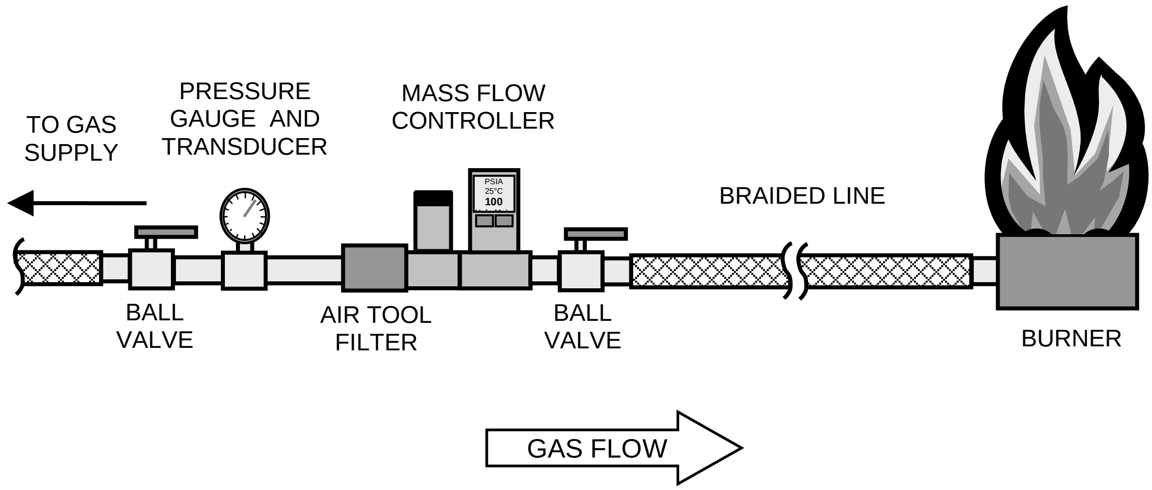


Figure 1 - Gas train diagram

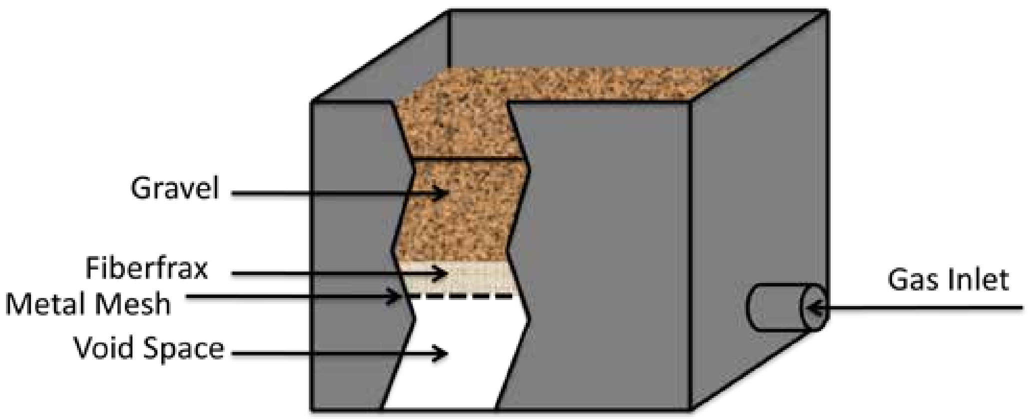


Figure 2 - Diagram of a typical sand burner

I. Required Supplies

a. Indicator Unit

i. Sartorius Combics 2 Model CAISL2-U, Asset # 99000791

ii. Power: 120 VAC power cord connected to indicator.

iii. Communication to Platform: Sartorius cable

iv. DAQ Communication: network cable connected to indicator.

b. Weighing Platform 1 (WP1)

i. Sartorius Model CAPP1U-50DD-LU

ii. Equipped with one 03167124 (30 kg/60 lb) capacity load cell

1. The cable from the load cell run to a junction box and is then sent to the indicator.

c. If recording scale data electronically,

i. Data acquisition (DAQ) setup: connected network cable from indicator to FireTOSS network jack.

d. If not recording scale data electronically,

i. Synchronized camera and/or an appropriate datasheet

II. Setup Procedures

a. Ensure weighing device is calibrated

b. Position the weighing platform

i. Move the weighing device to the location where measurements are to be taken.

ii. Level the device on the surface of the location. Perform this action until both the horizontal and vertical axes are level.

iii. Maintain an environmental temperature between (-10ºC and +40ºC). Excessive temperatures will invalidate results and may cause permanent damage to the loads cells. Perform a functional verification according to the instructions in the Function Verification Procedures section if the weighing device is subjected to intolerable temperatures at any time.

c. Connecting to the DAQ. Skip this step if not using the DAQ.

i. Connect the network cable from the indicator to a FireTOSS jack.

ii. Data Channel Tag: WD_0030KG_99000791_WEIGHT

d. Connecting the Instrument

i. Connect the power cable from the indicator to a 120 VAC outlet.

e. Using the Indicator Unit

i. Press the power button on the indicator.

ii. Check that the indicator is displaying the weight in kilograms.

iii. To ensure accurate results, the indicator must warm up for 30 minutes before operation. Only after this time will the indicator have reached the required operating temperature.

iv. Press the “Zero” button to zero the indicator without any load on the weighing platform.

v. If adding an additional frame and or heat protection on top of the platform, add that and then press the “Tare” button to tare the scale.

* INF 09 Message - This means tarring is not possible when the gross weight is less than zero. Action: Remove anything that is on the platform. Press the “Zero” button to zero the indicator. If using a frame and or heat protection then add that back to the platform. Then press the “Tare” button to tare the indicator. The indicator should now display, “0.00 kg”.

III. Experiment Procedures

a. Perform a functional verification according to the instructions provided in the Functional Verification Procedures section.

b. Activating DAQ Recording. Skip this step if not connected to the DAQ.

i. The output of the indicator is automatically saved in the DAQ, once the indicator has power and is connected to the FireTOSS network. Check in iFix.

ii. Check that computer icon is flashing on the indicator screen. This shows that there is communication.

c. Check that the indicator is displaying the weight in kilograms.

d. Check that the indicator is displaying, “0.00 kg”, with the platform by itself or any additional frame or heat protection that is not to be measured in the experiment.

e. Weigh the object

i. Place object to be weighed on the weighing platform in a manner such that the center of mass of the object is as close the center of the weighing platform as possible.

ii. Allow measurements to stabilize. The stabilization time for the indicator unit requires a minimum of 3 seconds.

iii. If the scale is not connected to the DAQ, record manually using a camera and/or the appropriate datasheet.

iv. The maximum measurement capacity for the weighing platform is 30 kg (60 lb). Results of 30 kg (60 lb) or more are invalid and a larger capacity weighing device is needed.

v. The maximum overload capacity for the load cells is as follows:

Corner: 45 kg (100 lb)

Side: 85 kg (190 lb)

Center 130 kg (290 lb)

If subject to a load greater than this, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.

f. If performing additional measurements, tare the indicator unit prior to each test.

g. During testing, if the weighing platform is repositioned, the weighing platform must be leveled and functionally verified prior to continuing tests.

IV. Shut Down and Maintenance Procedures

a. If a test series is complete, perform a functional verification according to the instructions in the Functional Verification Procedures section.

b. If necessary, wipe off any stains or spills on the weighing device.

c. Inspect the weighing device for any significant damage. If necessary, notify the calibration technician of the damage to arrange for calibration to confirm the functionality of the weighing device and the reliability of future test results.

d. Power down the indicator unit and unplug it and the Ethernet cable. Then store the weighing device in an area where it will not be subjected to heavy loads or to extreme temperatures. **The load cells can be permanently fatigued regardless of the device being on or off.**

V. Functional Verification Procedure

a. Setup up the device according to the instructions in the Setup Procedures section.

b. Zero the weighing device

c. Functionally verify the indicator display:

- **i.** Apply a load of a known magnitude to the center of the weighing platform and observe the measurements in the DAQ system and on the indicator unit for 5 minutes.
  - **1.** If there is no significant measurement inaccuracy or measurement creep, the weighing device is functionally verified.
  - **2.** If the indicator displays correct readings and the DAQ system displays intolerable readings, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.
  - **3.** If the measurement readings are intolerable on the indicator and in the DAQ system, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.
- **ii.** If functionally verified, remove the applied load and zero the indicator unit prior to taking the next measurement.

I. Required Supplies

a. Indicator Unit

i. Sartorius Combics 2 Model CAIS2-U, Asset # 99000789

ii. Power: 120 VAC power cord connected to indicator.

iii. Communication to Platform: Sartorius cable

iv. DAQ Communication: network cable connected to indicator.

b. Weighing Platform 1 (WP1)

i. Sartorius Model CAPP1U-250GG-LU

ii. Equipped with 1 Model 011253A (150 kg/300 lb) capacity load cell

1. The cable from the load cell runs into a junction box and is then sent to the indicator.

c. If recording scale data electronically,

i. Data acquisition (DAQ) setup: connected network cable from indicator to FireTOSS network jack.

d. If not recording scale data electronically,

i. Synchronized camera and/or an appropriate datasheet

II. Setup Procedures

a. Ensure weighing device is calibrated

b. Position the weighing platform

i. Move the weighing device to the location where measurements are to be taken.

ii. Level the device on the surface of the location. Perform this action until both the horizontal and vertical axes are level.

iii. Maintain an environmental temperature between (-10ºC and +40ºC). Excessive temperatures will invalidate results and may cause permanent damage to the loads cells. Perform a functional verification according to the instructions in the Function Verification Procedures section if the weighing device is subjected to intolerable temperatures at any time.

c. Connecting to the DAQ. Skip this step if not using the DAQ.
   i. Connect the network cable from the indicator to a FireTOSS jack.
   ii. Data Channel Tag: WD_0150KG_99000789_WEIGHT
d. Connecting the Instrument
   i. Connect the power cable from the indicator to a 120 VAC outlet.
e. Using the Indicator Unit
   i. Press the power button on the indicator.
   ii. Check that the indicator is displaying the weight in kilograms.
   iii. To ensure accurate results, the indicator must warm up for 30 minutes before operation. Only after this time will the indicator have reached the required operating temperature.
   iv. Press the “Zero” button to zero the indicator without any load on the weighing platform.
   v. If adding an additional frame and or heat protection on top of the platform, add that and then press the “Tare” button to tare the scale.

   * INF 09 Message - This means tarring is not possible when the gross weight is less than zero. Action: Remove anything that is on the platform. Press the “Zero” button to zero the indicator. If using a frame and or heat protection then add that back to the platform. Then press the “Tare” button to tare the indicator. The indicator should now display, “0.00 kg”.

III. Experiment Procedures

a. Perform a functional verification according to the instructions provided in the Functional Verification Procedures section.
b. Activating DAQ Recording. Skip this step if not connected to the DAQ.
   i. The output of the indicator is automatically saved in the DAQ, once the indicator has power and is connected to the FireTOSS network. Check in iFix.
   ii. Check that computer icon is flashing on the indicator screen. This shows that there is communication.
c. Check that the indicator is displaying the weight in kilograms.
d. Check that the indicator is displaying, “0.00 kg”, with the platform by itself or any additional frame or heat protection that is not to be measured in the experiment.

e. Weigh the object

i. Place object to be weighed on the weighing platform in a manner such that the center of mass of the object is as close the center of the weighing platform as possible.

ii. Allow measurements to stabilize. The stabilization time for the indicator unit requires a minimum of 3 seconds.

iii. If the scale is not connected to the DAQ, record manually using a camera and/or the appropriate datasheet.

iv. The maximum measurement capacity for the weighing platform is 150 kg (300 lb). Results of 150 kg (300 lb) or more are invalid and a larger capacity weighing device is needed.

v. The maximum overload capacity for the load cells is as follows:

Corner: 150 kg (300 lb)

Side: 200 kg (440 lb)

Center 300 kg (660 lb)

If subject to a load greater than this, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.

f. If performing additional measurements, tare the indicator unit prior to each test.

g. During testing, if the weighing platform is repositioned, the weighing platform must be leveled and functionally verified prior to continuing tests.

IV. Shut-Down and Maintenance Procedures

a. If a test series is complete, perform a functional verification according to the instructions in the Functional Verification Procedures section.

b. If necessary, wipe off any stains or spills on the weighing device.

c. Inspect the weighing device for any significant damage. If necessary, notify the calibration technician of the damage to arrange for calibration to confirm the functionality of the weighing device and the reliability of future test results.

d. Power down the indicator unit and unplug it and the Ethernet cables. Then store the weighing device in an area where it will not be subjected to heavy loads or to extreme temperatures. **The load cells can be permanently fatigued regardless of the device being on or off.**

V. Functional Verification Procedure

a. Setup up the device according to the instructions in the Setup Procedures section.

b. Zero the weighing device

c. Functionally verify the indicator display:

i. Apply a load of a known magnitude to the center of the weighing platform and observe the measurements in the DAQ system and on the indicator unit for 5 minutes.

1. If there is no significant measurement inaccuracy or measurement creep, the weighing device is functionally verified.

2. If the indicator displays correct readings and the DAQ system displays intolerable readings, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.

3. If the measurement readings are intolerable on the indicator and in the DAQ system, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.

ii. If functionally verified, remove the applied load and zero the indicator unit prior to taking the next measurement.

I. Required Supplies

a. Indicator Unit

i. Sartorius Combics 3 Model CIS3-U, Asset # 99000695

ii. Power: 120 VAC power cord connected to indicator.

iii. Communication: Sartorius cable connected to indicator.

iv. DAQ Communication: network cable connected to indicator.

b. Weighing Platform 1 (WP1)

i. Sartorius Model CAPP4U-1000KK-LU

ii. Equipped with four GWT-011462 500 lb capacity load cells

1. The cables from the load cells run to a junction box and output as serial data to the indicator with a Sartorius PR6130 Cable.

c. If recording scale data electronically,

i. Data acquisition (DAQ) setup: connected network cable from indicator to FireTOSS network jack.

d. If not recording scale data electronically,

i. Synchronized camera and/or an appropriate datasheet

II. Setup Procedures

a. Ensure weighing device is calibrated

b. Position the weighing platform

i. Move the weighing device to the location where measurements are to be taken.

ii. Level the device on the surface of the location. Perform this action until both the horizontal and vertical axes are level. The level on the platform is broken. Use a 3 foot or longer level to check the platform.

iii. Maintain an environmental temperature between (-10ºC and +40ºC). Excessive temperatures will invalidate results and may cause permanent damage to the loads cells. Perform a functional verification according to the instructions in the Function Verification Procedures section if the weighing device is subjected to intolerable temperatures at any time.

c. Connecting the Instrument

  i. Connect the network cable from the indicator to a FireTOSS jack.

  ii. Data Channel Tag: WD_0450KG_99000695_WEIGHT

d. Connecting to the Instrument.

  i. Connect the power cable from the indicator to a 120 VAC outlet

e. Using the Indicator Unit

  i. Press the power button on the indicator.

  ii. Check that the indicator is displaying the weight in kilograms.

  iii. To ensure accurate results, the indicator must warm up for 30 minutes before operation. Only after this time will the indicator have reached the required operating temperature.

  iv. Press the “Zero” button to zero the indicator without any load on the weighing platform.

  v. If adding an additional frame and or heat protection on top of the platform, add that and then press the “Tare” button to tare the scale.

  * INF 09 Message - This means tarring is not possible when the gross weight is less than zero. Action: Remove anything that is on the platform. Press the “Zero” button to zero the indicator. If using a frame and or heat protection then add that back to the platform. Then press the “Tare” button to tare the indicator. The indicator should now display, “0.00 kg”.

III. Experiment Procedures

a. Perform a functional verification according to the instructions provided in the Functional Verification Procedures section.

b. If necessary, return to main weighing screen by pressing the button below the “←←” on the screen.

c. Activating DAQ Recording. Skip this step if not connected to the DAQ.

  i. The output of the indicator is automatically saved in the DAQ, once connected to the FireTOSS network and the indicator has power.

  ii. Check that computer icon is flashing on the indicator screen. This shows that there is communication.

d. Check that the indicator is displaying the weight in kilograms.

e. Check that the indicator is displaying, "0.00 kg", with the platform by itself or any additional frame or heat protection that is not to be measured in the experiment.

f. Weigh the object

i. Place object to be weighed on the weighing platform in a manner such that the center of mass of the object is as close the center of the weighing platform as possible.

ii. Allow measurements to stabilize. The stabilization time for the indicator unit requires a minimum of 3 seconds.

iii. If the scale is not connected to the DAQ, record manually using a camera and/or the appropriate datasheet.

iv. The maximum measurement capacity for the weighing platform is 1500 lb / 600 kg. Results of 1500 lb / 600 kg or more are invalid and a larger capacity weighing device is needed.

v. The maximum overload capacity for the load cells is as follows:

Corner: 3300 lb / 1500 kg

Side: 6600 lb / 3000 kg

Center 9900 lb / 4500 kg

If subject to a load greater than this, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.

g. If performing additional measurements, tare the indicator unit prior to each test.

h. During testing, if the weighing platform is repositioned, the weighing platform must be leveled and functionally verified prior to continuing tests.

IV. Shut-Down and Maintenance Procedures

a. If a test series is complete, perform a functional verification according to the instructions in the Functional Verification Procedures section.

b. If necessary, wipe off any stains or spills on the weighing device.

c. Inspect the weighing device for any significant damage. If necessary, notify the calibration technician of the damage to arrange for calibration to confirm the functionality of the weighing device and the reliability of future test results.

d. Power down the indicator unit and unplug WP1 and Ethernet cables. Then store the weighing device in an area where it will not be subjected to heavy loads or to extreme temperatures. **The load cells can be permanently fatigued regardless of the device being on or off.**

V. Functional Verification Procedure

a. Setup up the device according to the instructions in the Setup Procedures section.

b. Zero the weighing device

c. Functionally verify the indicator display:

- **i.** Apply a load of a known magnitude to the center of the weighing platform and observe the measurements in the DAQ system and on the indicator unit for 5 minutes.
    1. If there is no significant measurement inaccuracy or measurement creep, the weighing device is functionally verified.
    2. If the indicator displays correct readings and the DAQ system displays intolerable readings, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.
    3. If the measurement readings are intolerable on the indicator and in the DAQ system, remove the weighing device from service and notify the calibration technician to arrange for a calibration of the weighing device. Repair or replace components as necessary.
- **ii.** If functionally verified, remove the applied load and zero the indicator unit prior to taking the next measurement.

1. Scope

This document contains the Standard Operating Procedure (SOP) for the Servomex 4100 gas analysis rack. The gas analysis rack consists of a Servomex 4100 gas analyzer and various other components (sample pump, gas filters, etc.) that are used to measure the concentrations of Oxygen (O_2), Carbon Monoxide (CO), and Carbon Dioxide (CO_2). The Servomex gas analysis rack is primarily used with the Fire Product Collectors, but can also be used as a standalone point source gas measuring system. Figure 1 shows the overall gas analysis rack setup.

Figure 1. Servomex 4100 Gas Analysis Rack

2. Required Supplies

A. Calibration Gases

1. CO/CO_2/Nitrogen (N_2) span gas (0.8% CO / 8.0% CO_2 / N_2 Balance)
2. N_2 Zero Gas (100%)

B. Desiccant

C. Gas bladder (only required if measuring delay times of gases)

3. Initial Setup

A. Verify that all instrumentation is connected to the data acquisition (DAQ) system.

B. Verify that all instrumentation and DAQ systems are powered.

C. Clean out gas sample lines using compressed air. Always blow compressed air away from analyzer inlet. After cleaning, verify that all tubing has been reconnected.

D. Check calibration status of all instrumentation.

1. Gas analyzers (yearly in-house verification required)
2. Span gases (replaced yearly)

E. Verify there is sufficient calibration gases to run the calibration.

4. Start-Up and Pre-Test

A. Verify that power is being supplied to rack and that the analyzer power button is in the ON setting (see Figure 2). The red light within the button should be illuminated and the analyzer display screen should be on.

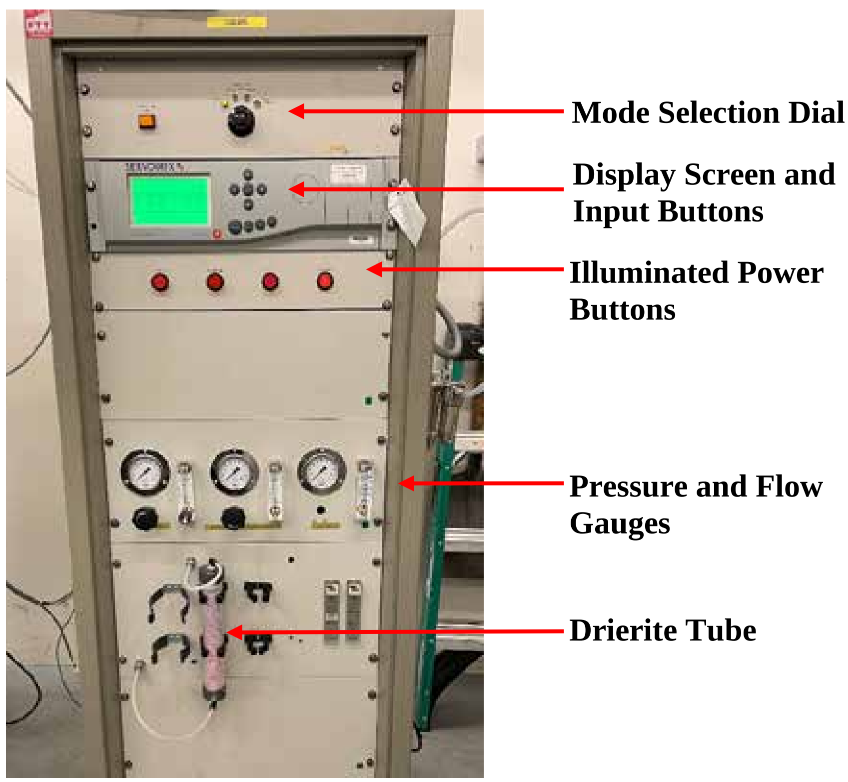


Figure 2. Analyzer Rack

B. Drain cold trap. The cold trap drain is located inside the back of the rack at the very bottom (see Figure 3). Make sure that valve is closed after draining the water. The black handle on the valve will be perpendicular to the valve when the drain is in the closed position.

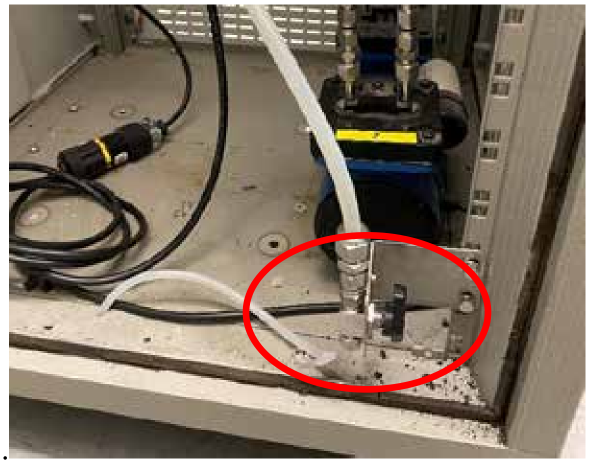


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Figure 3: Cold Trap Drain Valve

C. Turn cold trap ON. Make sure button is illuminated.

D. Check all filters and replace if necessary.

E. Check desiccant and replace if necessary. If using Drierite, it should be blue when ready to use and pink when it needs to be replaced.

F. Make sure Mode selection dial is turned to "AUTO".

G. Turn sample pump on. Make sure button is illuminated.

H. Gas sample pressures should be 5 psi for O_2 and CO/CO_2, and 7 psi for the Bypass. The O_2 flow rate shall be set to 3 LPM and the CO/CO_2 flow 3.5-4 LPM.

I. Allow pump to run for approximately 15 minutes.

J. Verify that N_2 and CO/CO_2 calibration gas cylinders are turned on and at a pressure of at least 15 psi.

K. Verify the gas cylinders are supplying gas to the gas analysis rack.

   1. Turn the Mode selection dial to the Zero position and verify that the pressure in the O_2 line and CO/CO_2 line are reading 5 psi.

   2. Turn the Mode selection dial to the calibration gas and verify that the CO/CO_2 pressure is reading 5 psi.

3. If an autocal is performed and either the pump, nitrogen gas, or the CO/CO_2 span gas are not supplying gas to the gas analyzer, then a warning will appear on the gas analyzer's screen displaying a Lo Cal or Hi Cal error.

L. Verify that the analyzer does not have any error messages on the display screen.

M. Perform a calibration.

1. Press menu button.
2. Select "Calibrate" from on-screen menu and press enter button.
3. Enter password by using the up/down arrow keys (¡ ¡) to adjust the numbers and the right and left arrow keys (¡ ¡) to change which number is being adjusted. The password on all of the Servomex Analyzers is 4000.
4. Select "AutoCal" and press enter.
5. Select "One Cycle" and press enter.
6. Select "Cal Group 1" and press enter.
7. The AutoCal icon should appear on the screen.
8. The Autocal process should complete after approximately 15 minutes.
9. The analyzer should display these approximate values following a successful calibration:

   O_2: 20.95%

   CO: 0.00%

   CO_2: 0.04%

10. If values displayed by analyzer do not match the expected values, check all settings and calibration gases, and perform a second calibration. If, after a second calibration, the values are still different from the expected values, troubleshoot and if no issues are found take analyzer out of service.

N. After a successful calibration, turn off calibration gas cylinders.

O. The analyzer is now ready to be used.

5. Measure Delay Times

A. Fire Product Collector Use

The delay times of the gases were determined during the commissioning of each FPC and are stored in the FireTOSS database for each FPC.

The delay times may need to be verified if inconsistencies in the data are observed during a routine FPC C-factor test.

B. Stand-Alone Use

Delay times must be calculated using the following procedure.

a. Fill gas bladder with the CO/CO_2 span gas.

b. With DAQ running, attach bladder valve to end of sample line.

c. The time from when the bladder valve is turned on to the initial response by the analyzer is the delay time. Repeat 2-3 times and then use the average of the delay times.

6. Experiment Procedures

A. Monitor data to ensure that no anomalies occur.

B. If all gas measurements drop drastically during a test, then the most likely issue is that the sample line or filter is clogged, and insufficient gas is reaching the analyzer.

1. The pump to the gas analyzer should be turned off and an event shall be added to the experiment noting that the pump to the gas analyzer was turned off.
2. If the issue is resolved (e.g., filter replaced), then an event shall be added to the experiment noting when the pump to the gas analyzer was turned on.

7. Shut Down and Post-Test

A. After the test has been completed power off cold trap and sample pump on analyzer rack.

B. If any problems arose during testing (i.e., clogged sample line or filters) perform necessary maintenance.

8. Maintenance Procedures

A. Blow out sample lines using compressed air prior to each test series or as needed.

B. Change paper filters located in metal filter housing on side of rack as needed. Clean or change sintered metal filter as needed. These filters keep soot and debris out of the pump and analyzers.

C. Change the desiccant when needed. If using Drierite, it should be blue in color when ready to use and pink when it needs to be replaced. If the desiccant is not changed frequently, excess water could enter the pump or gas analyzer.

9. Calibration

A. Perform auto-calibration prior to first test of each day or as needed/desired.

B. Analyzers shall be functionally verified in-house annually. The ATF procedure for functional verification meets or exceeds the testing protocol for verification from Fire Testing Technology (FTT). Analyzers that do not pass in-house verification will be sent to FTT for additional verification and maintenance. Records of verifications are kept by the calibration technician.

This document contains the Standard Operating Procedure (SOP) for the Functional Verification of Servomex Analyzers at the ATF Fire Research Laboratory (FRL). Functional verification consists of two separate processes: the adjustment of the CO and CO_2 transducer differential signal and the analyzer drift tests.

I. Required Supplies

A. Servomex Gas Analyzer – Model 4100C

B. Gas Analyzer Exercise Rack

C. Computer connected to FireTOSS/iFix Network

D. Calibration Gases

Nitrogen (Zero Grade)

CO/CO_2 Span gas ~ 0.8% CO, 8% CO_2, Balance N_2 (Primary Standard)

O_2 Span gas ~ 21% O_2, Balance N_2 (Primary Standard)

E. Digital Multimeter with a display that has a minimum of 3 decimal places

F. Screw Drivers

Flat Head

Philips Head

G. 9/32 inch Nut driver

H. Needle nose pliers

II. Start Up Procedures

1. Place the gas analyzer in a location where there is sufficient space to remove the top cover and reach the transducers inside the chassis.

2. Plug the gas analyzer into an electrical outlet and turn on the instrument.

3. The gas analyzers will take approximately 15 minutes to warm up. The analyzer will display a warm up signal on the main display screen during this time. Upon completion of warm up period, the signal will no longer be displayed on the screen.

   Do not proceed to the Experimental Procedures until the instrument has completely warmed up.

III. Experiment Procedures

A. Cell Voltage/Differential Signal Adjustment Procedure

The following describes how to readjust the offset found on the zero signal of the CO_2 transducer and CO transducer. For additional references, including detailed images of the inner components of the Servomex analyzer, refer to Fire Testing and Technology (FTT) documentation on the adjustment of cell voltages [1, 2]. Appendix A also provides photographs showing the internal components of the gas analyzer.

1. Connect the nitrogen gas line to the *Sample Inlet 2* port on the back of the gas analyzer.

2. Connect an exhaust line to the *Sample Outlet 2* port on the back of the analyzer. The exhaust line can be from either a gas analyzer rack or the gas exercise rack.

3. Flow nitrogen gas through the CO/CO_2 cells at 5 psi for at least 15 minutes.

4. With the nitrogen gas flowing, turn off the gas analyzer and unplug the power cord. Power is removed from the instrument to prevent any static discharge to the gas analyzer's internal electronics during the verification process, which could damage the electrical components.

   Prior to contacting any electronics within the analyzer, discharge any static from your hand to the metal analyzer chassis.

5. Remove the top cover of the gas analyzer.

6. Locate the metal U-shaped mounting bracket that contains both the CO_2/CO transducer boards. The mounting bracket is located behind the front panel on the right side of the chassis (Figure A1).

7. Remove the mounting bracket with the transducer boards still attached.

   a) Partly unscrew the four (4) nuts holding the mounting bracket to the bottom of the chassis.

   b) Slide the mounting bracket to the left to remove the bracket. You may need to move tubing and ribbon cables out of the way to lift the mounting bracket high enough to access the transducer boards. If the ribbon cable is disconnected while moving the mounting bracket, be sure to reconnect the cable prior to turning on the analyzer.

8. Locate the CO_2 transducer board on the mounting bracket. The CO_2 transducer board is located closest to the front panel (Figure A1).

9. Connect the leads of the multimeter to TP7 (ground) and TP 2 (load) on the CO_2 transducer board. The TP 7 is typically positioned on the top left hand side of the printed circuit board and TP 2 is on the same side towards the bottom of the board (Figure A2). Verify the connection points prior to connecting the multimeter (they are labeled on the board), as the transducer board is not always oriented the same way for all analyzers.

10. Turn on the multimeter and set it to DC voltage.

11. Plug in the power cord back into the gas analyzer and turn on the power. *Wait for the gas analyzer to finish warming up before taking any voltage readings.*

12. While the gas analyzer is warming up, open the "*Functional Verification Report Template - Cell Voltage and Diff Sig.pdf*", which is located in the CAIG folder on the Occoquan share drive (Occoquan\Calibration Lab\Gas Analyzer\Functional Verification\CO-CO2 Cell Voltage and Diff Sig\).

13. After the gas analyzer has finished warming up, check the Differential Signal for the CO_2 cell (*CO2 DIF SIG)* on the gas analyzer screen.

    a) Push the *Menu* button on the gas analyzer and select *Diagnostics* from the *Setup* menu.

    SETUP à DISPLAY à DIAGNOSTICS

    b) Press the up arrow on the gas analyzer until *I2 CO2 DIF SIG* is displayed on the screen.

14. Record the CO2 DIF SIG value displayed on the gas analyzer in the "As Found DIF SIG" box on the *Functional Verification Report* sheet.

15. Record the CO_2 Cell Voltage value displayed on the digital multimeter in the "As Found Cell Voltage" box on the *Functional Verification Report* sheet.

16. The CO_2 cell voltage must be **2.50 volts +/- 0.07 volts**. If not, the coarse zero potentiometer on the CO_2 cell must be adjusted. Skip to Step 17 if the cell voltage is within the specifications.

    a) Nitrogen must be flowing while this adjustment is made.

    b) The coarse zero potentiometer is located on the side of the CO_2 cell near the bottom (Figure A3).

    c) The voltage is adjusted by rotating the screw on the potentiometer clockwise to increase the voltage or counter-clockwise to decrease the voltage.

    Note that the potentiometer is very sensitive, so only a minor adjustment is required. In addition, there is a delayed response when an adjustment is made. Therefore, only make minor adjustments and wait for the reading to stabilize before making any additional adjustments.

17. Check the *CO2 DIF SIG* value on the gas analyzer screen. The value displayed should be **0.00 ± 0.05**. If not, the zero potentiometer for the *CO2 DIF SIG* must be adjusted. Skip to Step 18 if the cell voltage is within the specifications.

    a) The CO2 DIF SIG zero potentiometer is located behind TP 2 on the circuit board (Figure A2). The potentiometer is blue in color.

    b) The voltage is adjusted by rotating the screw on the potentiometer clockwise to increase the voltage or counter-clockwise to decrease the voltage.

18. Record both the adjusted Cell Voltage and Differential Signal in the "As Left" boxes on the *Functional Verification Report* sheet.

    If the adjustment could not be made to within the limits, make a note in the report indicating this issue. The unit must then be taken out of service and sent to the manufacturer for service/repair.

19. Perform a "zero calibration" of the analyzer and check the reading on the display to ensure the CO_2 is at 0.0%.

    Menu à Calibrate à Password à Enter "4000" à CO2 à Low CAL à Enter "0.000%" à Enter

Press MEASURE to exit back to the main measurement screen.

20. Remove the CO cell.

    a) The CO cell is a long black tube located on the right hand side of the chassis (Figure A1). It is also located above the transformer.

    b) Unscrew the CO cell from the right side of the chassis.

    c) Lift the cell out to get easy access to the coarse zero adjustment potentiometer.

21. Locate the CO transducer board on the U-shaped mounting bracket. The CO transducer board is located farthest from the front panel and opposite of the CO_2 transducer board (Figure A1).

22. Connect the leads of the multimeter to TP7 and TP 2 on the CO transducer board. The TP 7 is typically positioned on the top left hand side of the printed circuit board and TP 2 is on the same side towards the bottom of the board (Figure A4, note TP 2 is not visible in Figure A4). Verify the connection points prior to connecting the multimeter (they are labeled on the board), as the transducer board is not always oriented the same way for all analyzers.

23. Check the Differential Signal for the CO cell (*CO DIF SIG)* on the gas analyzer screen.

    a) Push the *Menu* button on the gas analyzer and select *Diagnostics* from the *Setup* menu.

       SETUP à DISPLAY à DIAGNOSTICS

    b) Press the up arrow on the gas analyzer until *I2 CO DIF SIG* is displayed on the screen.

24. Record the CO DIF SIG value displayed on the gas analyzer in the "As Found DIF SIG" box on the *Functional Verification Report* sheet.

25. Record the CO Cell Voltage value displayed on the digital multimeter in the "As Found Cell Voltage" box on the *Functional Verification Report* sheet.

26. The CO cell voltage must be **2.50 volts +/- 0.07 volts**. If not, the coarse zero potentiometer on the CO cell must be adjusted. Skip to Step 27 if the cell voltage is within the specifications.

    a) Nitrogen must be flowing while this adjustment is made.

b) The coarse zero potentiometer is located on one of the mounts of the CO cell near the bottom (Figure A5).

c) The voltage is adjusted by rotating the screw on the potentiometer clockwise to increase the voltage or counter-clockwise to decrease the voltage.

Note that the potentiometer is very sensitive, so only a minor adjustment is required. In addition, there is a delayed response when an adjustment is made. Therefore, only make minor adjustments and wait for the reading to stabilize before making any additional adjustments.

27. Check the *CO DIF SIG* value on the gas analyzer screen. The value displayed should be **0.00 ± 0.05**. If not, the zero potentiometer for the *CO DIF SIG* must be adjusted. Skip to Step 28 if the cell voltage is within the specifications.

   c) The CO DIF SIG zero potentiometer is located behind TP 2 on the circuit board. The potentiometer is blue in color.

   d) The voltage is adjusted by rotating the screw on the potentiometer clockwise to increase the voltage or counter-clockwise to decrease the voltage.

28. Record both the adjusted Cell Voltage and Differential Signal in the “As Left” boxes on the *Functional Verification Report* sheet.

   If the adjustment could not be made to within the limits, make a note in the report indicating this issue. The unit must then be taken out of service and sent to the manufacturer for service/repair.

29. Perform a “zero calibration” of the analyzer and check the reading on the display to ensure the CO is at 0.0%.

   Menu à Calibrate à Password à Enter “4000” à CO à Low CAL à Enter “0.000%” à Enter

   Press MEASURE to exit back to the main measurement screen.

30. Reattach the CO cell to the side of the chassis and reinstall the CO/CO_2 transducer board mounting bracket.

31. Reattach the top cover of the analyzer chassis

32. Stop the flow of nitrogen to the gas analyzer.

33. Turn off the gas analyzer.

34. If the analyzer has passed the cell voltage/differential signal adjustment procedure, ensure that it is placed into one of the six (6) analyzer exercise rack slots for the drift test.

35. Save the *Functional Verification Report* file on the Occoquan share drive (Occoquan\Calibration Lab\Gas Analyzer\Functional Verification\CO-CO2 Cell Voltage and Diff Sig\) in the folder matching the FRL asset number of the gas analyzer. Use the following format for the file name: *Analyzer Asset Number* - Cell Voltage and Differential Sig *Date*.

B. Oxygen Span Drift Test

The following steps describe the procedure to run a span drift test with the O_2 transducer. The following limits for O_2 drift have been adopted from FTT [3]:

50 ppm drift/50 ppm noise.

1. Setup the O_2 Span drift test in FireTOSS.
   a) Add the *Functional Verification Drift Object* into the test.
   b) Select the desired rack for the analyzer to be tested (this pulls in the correct FireTOSS tags).
   c) Make sure to fill in all required fields.
2. Ensure that the nitrogen gas bottle for the exercise rack is open and set to 15 psig.
3. Select the rack slot for the desired analyzer on the touch screen located in the rack to the left of the analyzers. Press the Oxygen Zero button for nitrogen flow. Ensure that the O_2 transducer is receiving 5 psi of gas flow.
4. Allow nitrogen to flow for 10 minutes and then perform a manual low (zero) calibration on the analyzer.
5. After the zero calibration, turn off the flow of nitrogen to the analyzer and close the valve to the nitrogen bottle.
6. Ensure that the Oxygen Span gas bottle for the exercise rack is open and set to 15 psi.

7. Select the rack slot for the desired analyzer on the touch screen located in the rack to the left of the analyzers. Press the Oxygen Span button for Span gas flow. Ensure that the O_2 transducer is receiving 5 psi of gas flow.

8. Start the test in iFix. The first 15 minutes of the test will allow the analyzer to purge and stabilize, and the remaining 30 minutes will be used for calculations. MAKE SURE TO RUN A HIGH CALIBRATION OF THE OXYGEN CELL TO THE VALUE LISTED ON THE GAS BOTTLE AFTER 10 MINUTES.

9. Upon completion of the O_2 Drift test, end the FireTOSS experiment, turn off the flow of gas by pressing the Oxygen Span Button on the touch screen and close the valve on the oxygen span bottle.

C. CO/CO_2 Span Drift Test

The following steps describe the procedure to run a span drift test with the CO/CO_2 transducers. The limit for CO_2 drift has been established after consideration of FTT documentation [3] and experimental data collected at the FRL. The limits for CO drift have been adopted from FTT [3]:

CO_2: 50 ppm drift / 50 ppm noise
CO: 100 ppm drift / 100 ppm noise

1. Setup the CO/CO2 Span drift test in FireTOSS
    a) Add the Functional Verification Drift Object into the test.
    b) Select the desired rack for the analyzer to be tested (this pulls in the correct FireTOSS tags).
    c) Make sure to fill in all required fields.
2. Ensure that the nitrogen gas bottle for the exercise rack is open and set to 15 psig.
3. Select the rack slot for the desired analyzer on the touch screen located in the rack to the left of the analyzers. Press the CO/CO_2 *Zero* button to start the flow of nitrogen. Ensure that the CO/CO_2 transducers are receiving 5 psi of gas flow.
4. Allow nitrogen to flow for 10 minutes and then perform a manual low (zero) calibration on the analyzer.

5. After the zero calibration, turn off the flow of nitrogen to the analyzer and close the valve to the nitrogen bottle.

6. Ensure that the CO/CO_2 Span gas bottle for the exercise rack is open and set to 15 psi.

7. Select the rack slot for the desired analyzer on the touch screen located in the rack to the left of the analyzers. Press the CO/CO_2 *Span* button for to start the flow of the span gas. Ensure that the CO/CO_2 transducers are receiving 5 psi of gas flow.

8. Start the test in iFix. The first 15 minutes of the test will allow the analyzer to purge and stabilize, and the remaining 30 minutes will be used for calculations. MAKE SURE TO RUN A HIGH CALIBRATION OF THE CO/CO_2 CELLS AFTER 10 MINUTES.

9. Upon completion of the CO/CO_2 Drift test, end the FireTOSS experiment, turn off the flow of gas by pressing the CO/CO_2 Span Button on the touch screen, and close the valve on the CO/CO_2 span bottle.

IV. Shutdown Procedure

A. Verify that all of the gas bottles are closed.

B. If the gas analyzer is to be place in a different rack, then remove it from the exercise rack and place in the appropriate gas analyzer rack. Otherwise, leave the unit in the exercise rack.

C. If the analyzer meets all specifications from each test, have the Calibration Tech printout a new calibration sticker and place it on the gas analyzer. In addition, have the Calibration Tech verify that the gas analyzer is assigned to the correct location (e.g., 1 MW Square FPC) in the calibration database.

V. Maintenance Procedure

A. If the gas analyzer cannot be brought into specifications, then the unit must to be sent to the manufacturer for further analysis.

VI. Functional Verification Procedure

A. This procedure shall be performed annually. It may be performed more frequently, if there appears to be issues with the gas analyzer.

References

1. *How to adjust the CO2 cell voltage (FTT version) v.2.docx,* Fire Testing Technology Limited, West Sussex, United Kingdom, 2014
2. *How to adjust the CO cell voltage.pdf,* Fire Testing Technology Limited, West Sussex, United Kingdom ,2008
3. *Servomex Analyzer Service Report*, Fire Testing Technology Limited, West Sussex, United Kingdom, November 15, 2016

Appendix A – Photographs

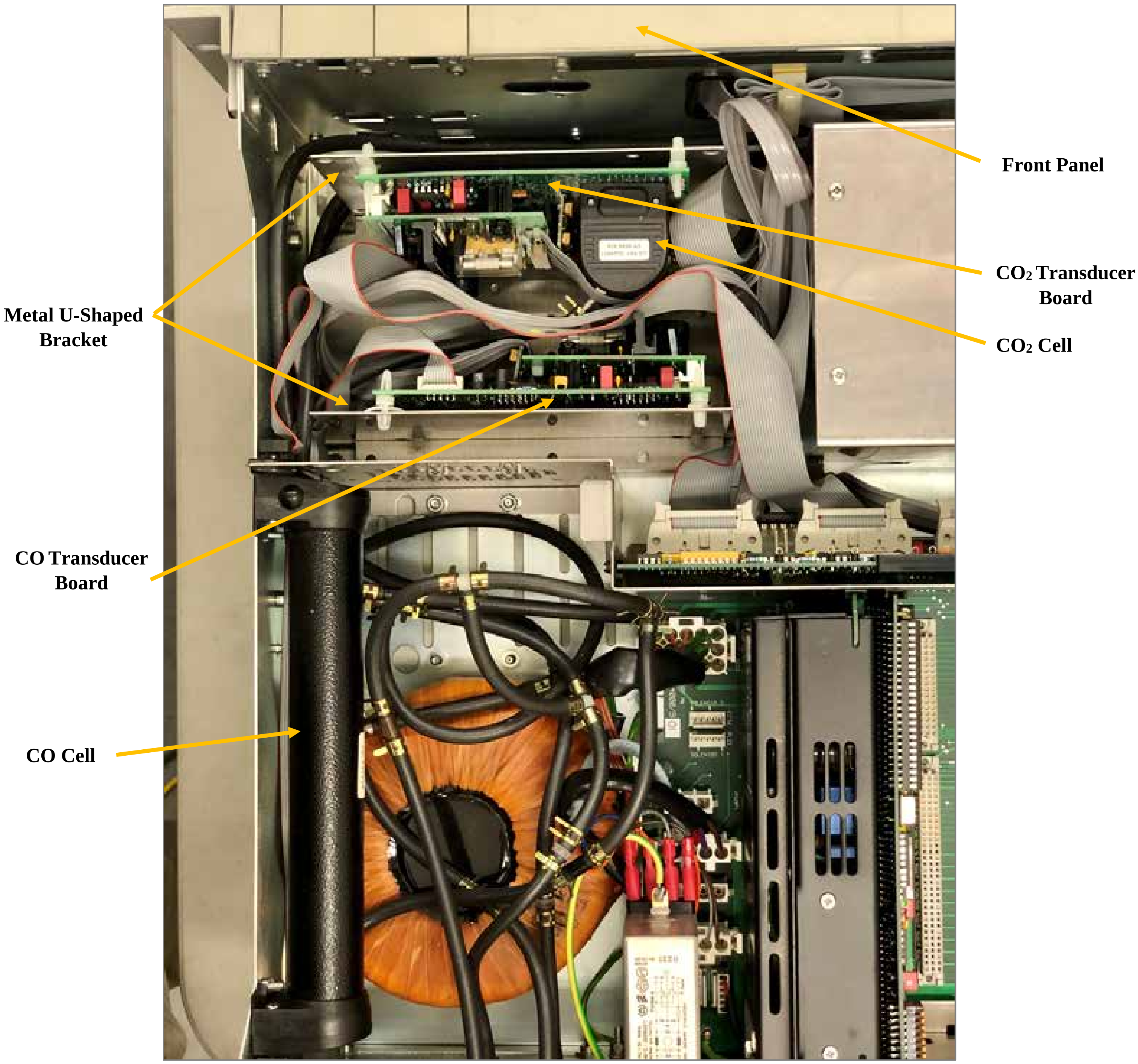


Figure A1. Internal components of the Servomex Gas Analyzer

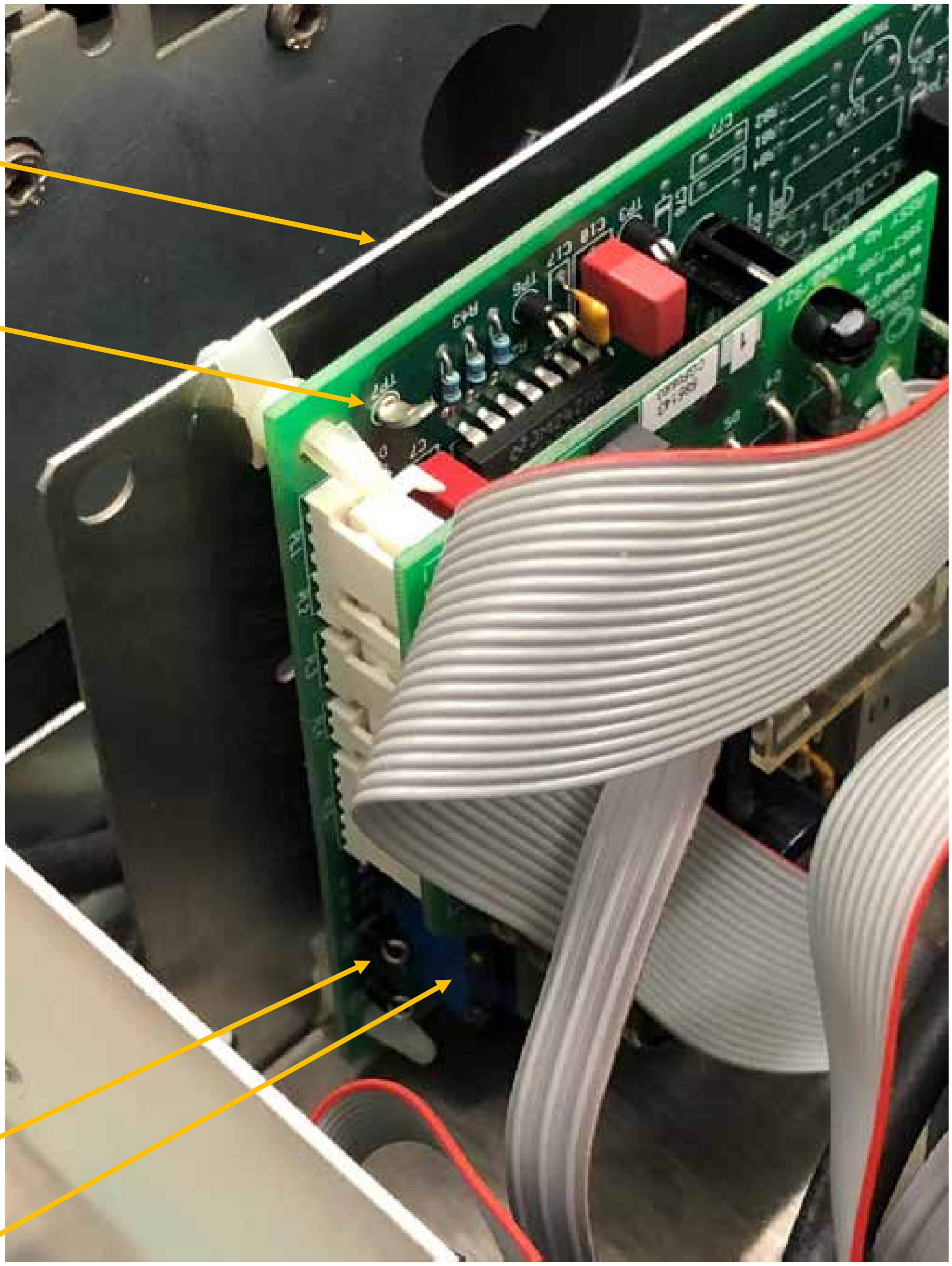


Figure A2. CO_2 Transducer Board

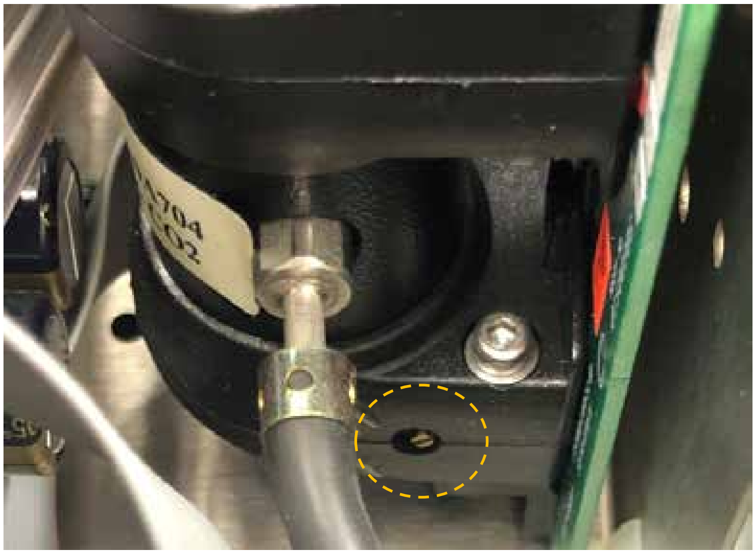


Figure A3. CO_2 Cell Coarse Zero Potentiometer

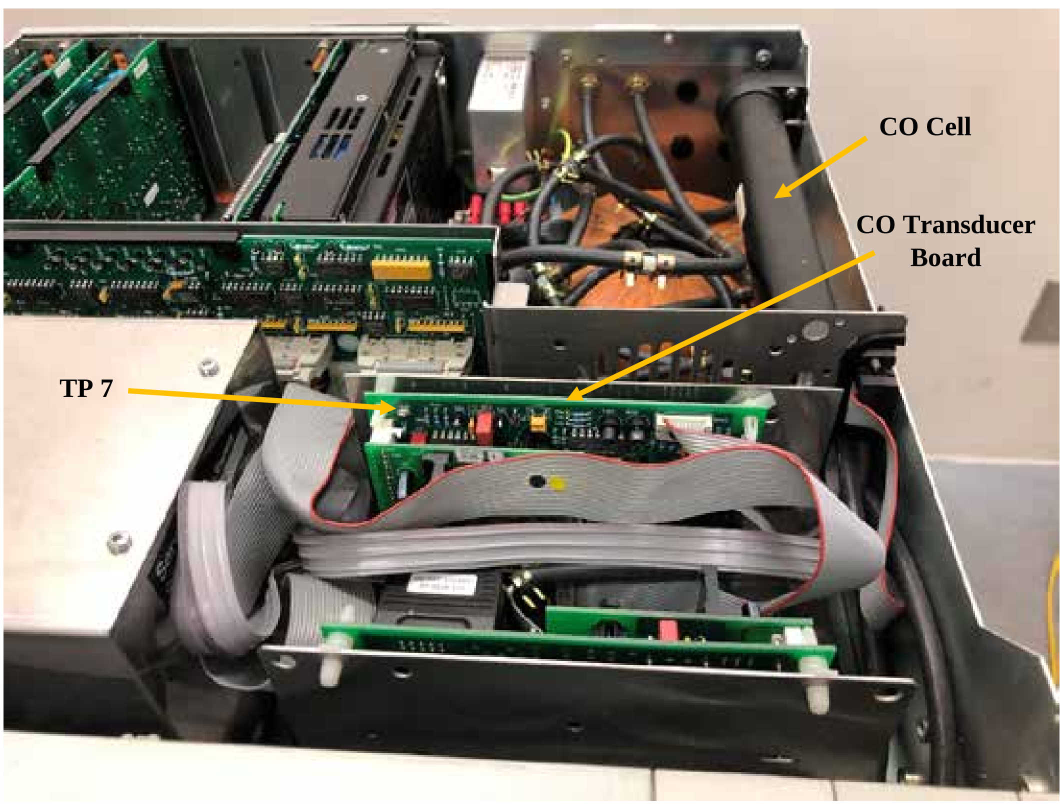


Figure A4. CO Transducer Board

Figure A5. CO Cell Coarse Zero Potentiometer

1. Scope

This Standard Operating Procedure (SOP) is to be used with the Siemens Gas Analysis Cart. The gas cart contains two sets of Siemens Oxymat 61 Oxygen (O_2) analyzer and the Siemens Ultramat 23 Carbon Monoxide (CO)/Carbon Dioxide (CO_2) gas analyzers, in addition to the other components required to obtain gas samples (sample pump, filters, etc.). The movable Siemens gas analysis cart is shown in Figure 1.

Figure 1. Siemens Gas Analysis Cart

2. Supplies Required

A. Tubing, 3/8 inch diameter

1. Use stainless steel tubing if near fire/heat source, otherwise use plastic tubing.
2. Transition to plastic tubing away from the fire/heat source, if stainless steel tubing is initially used.

B. Calibration Gases

1. Nitrogen (N_2) Zero Gas (100%)
   a. One (1) Cylinder with dual output adapter
      i. One 0-25 psig CGA 580 regulator; to use as calibration zero gas
      ii. One 0-200 psig CGA 580 regulator, as reference gas for the oxygen analyze

b. 1/4 in. tubing and Swagelok fittings

2. CO/CO2/N2 span gas (4.5% CO / 22.5% CO2 / N_2 Balance)

a) 1 Cylinder with 0-25 psig CGA 350 regulator,

b) 1/4 in. tubing and Swagelok fittings

C. ELECTRICAL POWER

120 VAC power to power analyzers and sampling pump

Single extension cord required

D. DESICCANT

Used for removal of liquid from gas sample

E. ICE SUPPLY

For use with the cold trap

3. Initial Setup

The overall layout of the flow paths for the sample gas and calibration gases are shown in Figure 2.

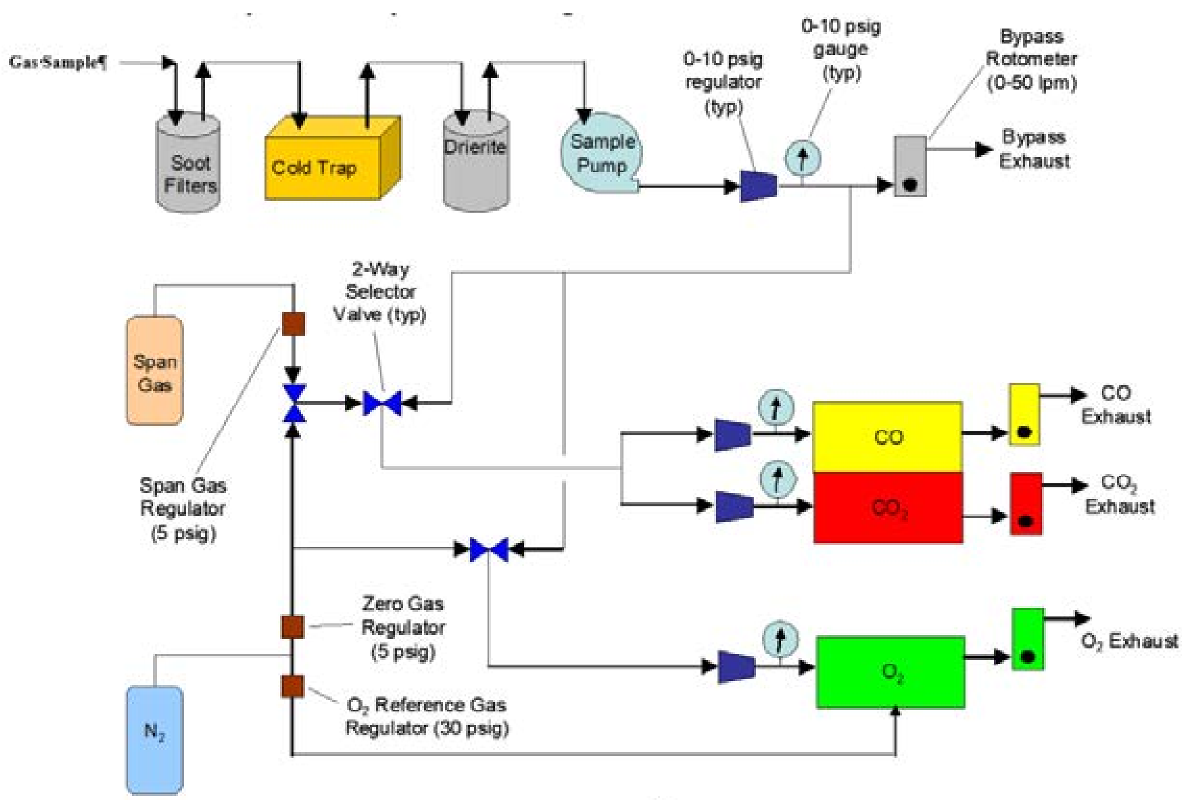


Figure 2 - Gas Analysis Cart Flow Diagram

A. Connect CO/CO_2 span gas to Swagelok inlet port on front of cart.
B. Connect N_2 zero gas to the Swagelok inlet port on the front of the cart.
C. Connect N_2 reference gas to the Swagelok inlet port on the front of the cart
D. Connect sample line tubing to sintered metal filter inlet on side of cart.
E. Connect tubing between sintered metal filter outlet and cold trap.
F. Connect tubing between cold trap and desiccant filter column.
G. Connect tubing between desiccant filter column and sample inlet port on side of cart.
H. Connect analyzer and bypass exhaust tubing to exhaust connections on side of cart, if used.
I. Connect data output wires to data acquisition (DAQ) box.
   1. Three (3) connections required; one for each gas (CO, CO_2, O_2)
   2. Each gas measured by the gas analyzer has a current output signal of 4-20 mA. This current output signal is converted to a 1-5 VDC output signal by connecting a 250 ohm resistor across the connections for the output signals.

Note: Tubing for most connections is stored in storage cabinet on cart and is color coded for ease of connecting.

Note: Do Not Turn Analyzers On At This Time!

4. Start-Up and Pre-Test

A. Check/clean filters and sampling line.
   1. Replace desiccant in tube on side of cart if necessary. If using Drierite, it is blue when ready to use and pink when it needs to be replaced.
   2. Check/clean cold traps and fill cooler containing cold traps on top of cart with ice.
   3. Check/clean sintered metal filters on side of cart.
   4. Blow out sample line utilizing compressed air. **Always Blow Compressed Air Away from Analyzer Inlet.**
B. Start flow of reference gas to oxygen analyzer. Set regulator to 30 psig.
C. Start flow of zero gas, N2 to CO/CO2 analyzer.
   1. Cylinder valve open and regulator set to ~5 psig.

2. Middle ball valve on front of cart set to calibrate.
3. Bottom ball valve on front of cart set to nitrogen.
4. Adjust rotometer valves for CO and CO_2 to get flow indicators on front of analyzer to middle of tube (1 LPM each). Adjust rotometer valves for O_2 to 0.5 LPM.

D. Connect electrical power to cart and allow analyzers to warm-up for 30 min.

1. CO/CO2 analyzer will go through AutoCal cycle twice – 5 min into warm-up and 30 min into warm-up.
2. Press Esc when prompted to complete AutoCal.

E. Calibrate analyzers.

1. Zero Calibration

a) Start flow of zero gas, N_2, to both O_2 and CO/CO_2 analyzers

1) N_2 cylinder valve open and regulator set to 5 psig
2) Top ball valve (O2) on front of cart set to “Zero Gas”
3) Adjust rotometer valve for O2 to get 0.5 LPM
4) Bottom ball valve on front of cart set to “N2”
5) Middle ball valve on front of cart set to “Calibrate”
6) Adjust rotometer valves for CO and CO2 to get flow indicators on front of analyzer to middle of tube (1 LPM each)
7) Adjust all three sample pressure using the regulators plumbed to the discharge side of the analyzers. CO/CO2 = 2 psig, O2 = 3 psig.

b) Calibration of Siemens Ultramat 23 CO/CO2 analyzer

1) Press Cal button on front of analyzer
2) Press Esc when prompted

c) Calibration of Siemens Oxymat 61 O2 analyzer

1) Press **Enter** on the blue pad on front of Analyzer near O2 on screen
2) Use blue pad to select “Calibration”
3) Enter “222” followed by the Enter key if prompted for code
4) Select “Zero Calibration”
5) Select “Start Calibration”
6) Use **ESC** key to return to calibration menu

2. Span Calibration

a) Start flow of span gas to CO/CO2 analyzers

1) Span gas cylinder valve open and regulator set to 5 psig

2) Switch bottom ball valve on front of cart set to "Cal Gas"

3) Middle ball valve on front of cart set to "Calibrate"

4) Adjust rotometer and regulator valves for CO and CO2 to get flow indicators on front of analyzer to middle of tube (1.0 LPM each) and 2 psig, respectively.

b) Calibration of Siemens Ultramat 23 CO/CO2 Analyzer

1) Press **Enter** button on front of analyzer to go to Main Menu

2) Use arrow keys to select "Calibration" and press Enter button

3) Use arrow keys to enter "222" as Code

4) Select "Calibr. IR Channels"

5) Select "CO" using arrow keys

6) If this is the first test of the series, select "Set Span Gas Values" and verify M1 and M2 are same as cylinder span gas values, adjust if necessary. Press Enter to return to CO calibration menu.

7) Select "Start with MR1"

8) Displayed set span should match span gas CO concentration (on cylinder label – 4.5%)

9) Press **Enter** when prompted

10) Press **Esc** to return to component selection menu

11) Select CO2 using arrow keys

12) If this is the first test of the series, select "Set Span Gas Values" and verify M1 and M2 are same as cylinder span gas values, adjust if necessary. Press Enter to return to CO2 calibration menu.

13) Select "Start with MR1"

14) Displayed set span should match span gas CO2 concentration (on cylinder label – 22.5%)

15) Press **Enter** when prompted

16) Press **Esc** several times to exit menus

17) Switch middle ball valve on front of cart to sample

c) Calibration of Siemens Oxymat 61O2 analyzer

1) Switch top ball valve on front of cart to sample
2) Start pump using toggle switch at top of cart
3) Adjust bypass rotometer flow so that the bypass pressure gauge on side of cart reads 4 psig.
4) Adjust oxygen rotometer valve and regulator to get 0.5 LPM and 3 psig.
5) Adjust CO and CO2 Rotometer Valves and Regulators to get 1.0 LPM and 2 psig.
6) Readjust all three sets of rotometers and regulators to achieve desired flow rates and pressure if necessary.
7) Select “Span Calibration”
8) Select “Start Calibration”
9) Use **ESC** key to exit menus

F. Check flow rates and pressures through cart.

1. Adjust bypass rotometer valve to so that bypass pressure gauge reads 4 psig.
2. Adjust O2 rotometer and regulator valves to get flow rate of 0.5 LPM and pressure of 3 psig.
3. Adjust CO and CO2 rotometers and regulator valves to get flow indicators on front of analyzer to middle of tube (1.0 LPM each) and 2 psig, respectively.

5. Determine Analyzer Response Delay Time

A. Fill gas bladder with CO/CO_2 span gas.

B. With data acquisition running, attach bladder valve to end of sample line.

C. The time from when the bladder valve is turned on to the initial response by the analyzer is the delay time. Repeat 2-3 times and then use the average of the delay times.

6. Experiment Procedures

A. Monitor data to ensure that no anomalies occur.

B. If all gas measurements drop drastically, then the most likely issue is that the sample line or filter is clogged, and insufficient gas is reaching the analyzer.

1. Check flow rate through analyzers.

2. Stopping of flow during test would be due to clog in sample line and data after clog would not be reflective of conditions at measuring point.
   a) O_2 analyzer will give a zero value when flow of sample has stopped.
   b) CO and CO_2 analyzers will hold the last value when the sample flow has stopped.
3. The pump to the gas analyzer should be turned off and an event shall be added to the experiment noting that the pump to the gas analyzer was turned off.
4. If the issue is resolved (e.g., filter replaced), then an event shall be added to the experiment noting when the pump to the gas analyzer was turned on.

7. Shut-Down and Post-Test

A. Shut down pump with toggle switch on front of cart.

B. Shut down power to analyzers if testing series has concluded.

8. Maintenance Procedures

A. Blow out sample lines using compressed air prior to each test series or as needed.

B. Change paper filters located in metal filter housing on side of rack as needed. Clean or change sintered metal filter as needed. These filters keep soot and debris out of the pump and analyzers.

C. Change the desiccant when needed. If using Drierite, it should be blue in color when ready to use and pink when it needs to be replaced. If the desiccant is not changed frequently, excess water could enter the pump or gas analyzer.

9. Calibration

A. Perform a calibration prior to first test of each day or as needed/desired.

B. The Siemens analyzers require service/maintenance by Siemens every two years. Calibration records will be maintained by the FRL calibration technician.

I. Required Supplies

a. Functional stopwatch.

b. Trained stopwatch operator.

c. Access to the GPS clock in the Plenum Shed 1 (P-S1), which is located in the mezzanine above the Medium Burn Room.

II. Setup Procedures

a. Ensure that the stopwatch has been functionality verified in accordance with the procedure provided in the Calibration Procedures section of this document.

b. Position stopwatch and operator appropriately to monitor event requiring stopwatch measurements.

c. Familiarize operator with experiment to allow accurate stopwatch operations during experiment.

d. If necessary, prepare materials for manually recording information from stopwatch.

III. Experiment Procedures

a. Operate the stopwatch according to test examiner's specifications.

b. Monitor the functionality of the stopwatch throughout the test series.

IV. Shut-Down and Maintenance Procedures

a. Reset the stopwatch counter to zero.

b. Inspect the stopwatch for excessive physical damage. If necessary, replace the stopwatch with a similar functioning unit that has been functionally verified.

V. Calibration Procedures

a. Stopwatches used at the FRL are not calibrated but are functionally verified on an annually basis using the procedures listed below. Functionally verified stopwatches are labeled with the date of the most recent functional verification as well as the due date for the next functional verification.

b. Inspecting the functionality of a stopwatch

- **i.** Have a trained stopwatch operator perform the functional verification using the Master GPS clock in the P-S1 of the FRL.
- **ii.** Start the stopwatch and observe the starting time according to the GPS clock and allow the stopwatch to run for a predetermined amount of time.
- **iii.** Stop the stopwatch at the end of the predetermined time period according to the GPS clock. Compare the duration measured by the stopwatch to the predetermined duration measured by the GPS clock and calculate the error in the stopwatch. Common durations and the associated maximum errors are shown in the table below.

Table 1. Allowable error for various time periods

Time Period (seconds)	Time Period (hours)	Maximum Allowable Error (seconds)
60	0.0167	±0.0167
1800	0.5	±0.5
3600	1	±1.0
14400	4	±4.0
28800	8	±8.0
43200	12	±12.0
86400	24	±24.0

iv. If the duration measured by the stopwatch differs by less than 0.028% of the duration observed on the GPS clock, the stopwatch is functioning properly and suitable for testing.

v. If the duration measured by the stopwatch differs by more than 0.028% of the duration observed on the GPS clock, the stopwatch is not suitable for testing.

I. Initial Set-Up

1. Required Supplies

1. Thermocouple with male connector
2. Data acquisition system including a TC module (Any Yokagowa main and sub unit)
3. Heat source (open flame, lighter, heat gun, etc)
4. If necessary, thermocouple extension wire with connectors

II. Start UP Procedures

1. Prior to the start of the first test in the series

1. The data acquisition unit shall be checked to confirm calibration.
2. Plug thermocouple into a TC module of data acquisition system.
    a. If TC extension wire is used, minimize the temperature gradient between the ends of the extension wire and any additional junctions.
3. Verify ambient temperature reading of thermocouple
4. Apply a heat source such as an open flame or heat gun to thermocouple junction and verify temperature rise.

2. Prior to each test in the series

1. Verify ambient temperature reading of thermocouple

III. Experiment Procedures

1. Record the thermocouple reading for the duration of the experiment.
    a. Exception- When the thermocouple must be removed prior to the end of the experiment due to experiment design or damage. The elapsed time at which the thermocouple was removed and the reason for removal shall be recorded.

IV. Shut Down Procedures

1. After the experiment, the thermocouples in locations where they could have been damaged shall be examined for visible damage. Perform functional verification if necessary.
    a. If damage has occurred, the instrument shall be taken out of service at the time of the damage. The laboratory engineer shall review the data to determine if there is a noticeable event that marked the damage to the instrument. If not, the thermocouple shall be taken out of service for the

entire test. After the thermocouple has been taken out of service, the calculations shall be redone.

V. Maintenance Procedures

1. Generally, there is no maintenance performed on a thermocouple. If a thermocouple becomes damaged or inoperable a replacement thermocouple is manufactured.

VI. Calibration Procedures

Due to the disposable nature of thermocouples, they undergo a functional verification procedure, rather than a calibration. The process for functional verification of a thermocouple is noted below:

1. Verify ambient temperature reading of thermocouple
2. Apply a heat source such as an open flame or heat gun to thermocouple junction and verify temperature rise.

VII. Best Practices

1. Make thermocouples no longer than 75 ft.
    a. Limit the length of thermocouple wire and extension wire to 100 ohms of resistance as recommended by Omega Engineering Inc.
    b. The resistance of 24 AWG thermocouple wire is approximately 0.75 Ohms/ft and 24 AWG extension wire at approximately 0.625 Ohms/ft.
    c. When using thermocouples longer than 75 ft., measure the resistance.
2. Be aware of radiative sources that could influence the accuracy of temperature reading. Shield thermocouples when practical or critical to the test results.
3. Use small gage wire and relatively long insertion lengths to minimize conduction error. Considering a 24 AWG wire with a diameter of 0.5 mm, the corresponding minimum insertion length is 2.5 cm.
4. Minimize the temperature gradient across any junctions
    a. Typically, run thermocouple wire outside of compartments before transitioning to extension wire.

1) **Initial Setup**

   a) ***Supplies Required***

      i) ***7.6 cm (3 inch) stainless steel braided hose for natural gas transport***

      ii) ***Tube burner***

      iii) ***115 VAC electrical power – single extension cord***

      iv) ***FireTOSS connectivity – single ethernet cable***

      v) ***FireTOSS client computer with LabView installed***

   b) ***Plumbing and Electrical / Data Connections***

      i) ***Connect stainless steel braided hose from gas main to burner***

      ii) ***Perform a leak check on all connections***

      iii) ***Connect burner to power outlet using extension cord. Confirm green power LED activated on left of burner electrical box.***

      iv) ***Connect burner electrical box to FireTOSS port using ethernet cable***

2) **Start-Up and Pre-Test**

   a) ***Check calibration status of NI FieldPoint modules inside tube burner electrical box and at mezzanine gas train***

   b) ***Position burner where needed***

   c) ***Launch LabVIEW tube burner control program on FireTOSS computer. Confirm communication between LabVIEW and FieldPoint modules*** *d) Verify functionality of pilot spark igniter PRIOR to turning natural gas ON*

i) If spark igniters do not function, check Fireye module in the burner electrical box. If the "Fire" LED is illuminated, press the RESET button on the module.

ii) After verifying functionality, turn spark igniter OFF.

e) Turn natural gas ON

i) In mezzanine, turn gas ball valve to ON position

ii) Turn control switch on gas train electrical box to LABVIEW position

iii) Pull out emergency shutoff "mushroom" button located on wall of burn room

f) Check pressures to verify adequate gas supply

g) Ignite pilot gas bank

i) Open ball valve on gas main

ii) Immediately after gas main has been opened, trigger "Switch 0" on LabVIEW control screen to activate spark igniter.

3) Experiment Procedure

a) During Test

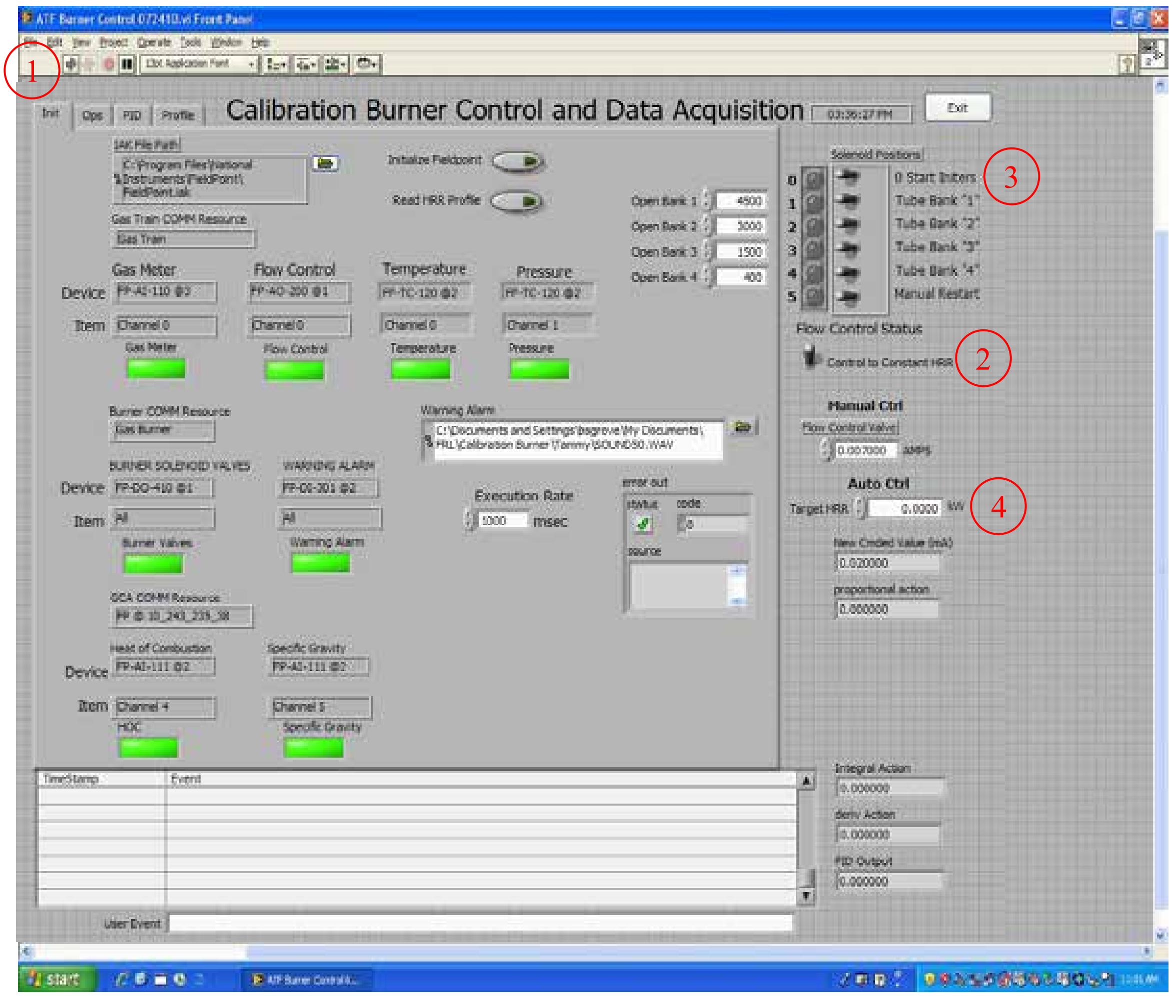
i) Monitor pressure in flow meter to ensure adequate supply of natural gas

ii) Monitor burner heat release rate to verify desired flow

b) Burner Control Through LabVIEW

i) Select "ATF Burner Control 072410.vi" from desktop

ii) The following screen should initialize:



NOTE: Red numbers are for reference only and do not appear on the actual burner control screen

iii) To start test, click on the arrow button located at reference number 1

iv) Verify "Flow Control Status" switch located at reference number 2 is set to "Control to Constant HRR"

v) To trigger spark igniters, toggle switch zero located at reference number 3

vi) Once pilot tubes are ignited, the burner HRR can be controlled using the "Auto Ctrl" field located at reference number 4.

- *(1)* ***To change burner HRR, type desired HRR value (in kW) into the field and press "Enter" key. The HRR will not change until "Enter" key is pressed (even if there is a new value in the field)***

- *(2)* ***There is no need to manually toggle the remainder of the tube bank toggles located at reference number 3. The "Auto Ctrl" field values will toggle the tube banks automatically as long as the "Flow Control Status" toggle is set to "Control to Constant HRR"***

- *(3)* ***NOTE: When first using the main banks of the tube burner there cab be a delay to achieve desired HRR due to gas transport times. Please take note of when desired HRR is achieved.***

vii) Clicking on the "Ops" tab located below the test Start/Stop buttons at reference number 1 will show the data being transmitted by the tube burner FieldPoint units. This includes desired and actual HRR, and gas train flowrate, pressure and temperature.

4) **Shut-Down and Post-Test**

   a) ***To end test, set "Auto Ctrl" field to 0.0000 kW and press "Enter" key. Then press the stop sign button at reference number 1.***

   b) ***Turn OFF natural gas.***

      i) ***Turn wall main ball valve to OFF position***

      ii) ***Allow gas in stainless steel line to burn off through pilot bank***

      iii) ***Push in emergency shutoff "mushroom" button located on wall of burn room***

      iv) ***In mezzanine, turn gas ball valve to OFF position and turn control switch to OFF position***

   c) ***Disconnect power and Ethernet cords if no other tests are being performed***

5) **Maintenance**

   a) ***Periodically check for leaks at connections***

   b) ***Make sure that spark igniters stay clean***

6) **Calibration - All instrumentation associated with the tube burner shall be calibrated according to FRL specifications. These instruments include:**

   a) ***NI FieldPoint modules – annual calibration***

   b) ***Pressure transducer in rotary flow meter – annual calibration***

I. Required Instrumentation

a. Determine the instrumentation required for the Fire Products Collector (FPC) Reported Quantity called out in the experiment design. A summary of the instrumentation required for each reported quantity is given in Table 1.

Table 1: Summary of instrumentation necessary for each FPC Reported Quantity

		Fire Product Collector Reported Quantity						
		Convective HRR	HRR	CFactor	Smoke Production	Species Production	Effective HOC	Mass Loss Rate
Instrumentation	Gas Analyzer		ü	ü		ü	ü	
	Velocity	ü	ü	ü	ü	ü	ü	
	Thermocouple	ü	ü	ü		ü	ü	
	Sand Burners(s)			ü				
	FPC ODM				ü			
	Laboratory Conditions		ü	ü			ü	
	Weighing Device(s)				✓ (yield)	✓ (yield)	ü	ü

II. Start-Up and Pre-Test

a. **Fire Lab Control System (FLCS)**

   i. Bring building into Test Mode.

   ii. Adjust the duct flow rate to the desired setting.

b. **Fire Products Collector (FPC)**

   i. Verify the functionality and/or calibration status of all instrumentation to be used in an experiment (Table 1). Requirements are described in each respective Standard Operating Procedure (SOP).

   ii. Set-up instrumentation according to the instructions provided in each SOP.

III. Experiment Procedures

a. Monitor data to ensure no anomalies occur.

b. The output of all instrumentation used in the experiment shall be recorded for the duration of the experiment.
c. Exception – When any instrument must be removed prior to the end of the experiment due to experiment design or impending damage, the elapsed time at which the instrument was removed and the reason for removal shall be recorded.
d. Operate the FPC according to the examiner's specifications and within operational limits.
   - **i.** The design flow rate for the 1 MW Square FPC is 6.8 kg/s (12,000 SCFM). Higher flow rates can be achieved however the flow rate should be set according to the anticipated peak heat release rate.
   - **ii.** The measured temperature at the instrumentation section should not exceed 300˚C.
      1. If the temperature exceeds this threshold, the test engineer shall decide whether to terminate the experiment, increase the flow rate in the duct or allow the experiment to continue.

IV. Shutdown and Post Test Procedures

a. If an instrument was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.
b. If conditions occurred, either during the test or following the test, that could potentially affect the performance of an instrument, a functional verification and / or maintenance shall be performed.
c. If no more tests are planned for that day,
   - **i.** Turn off the compressed air to the ODM purge.
   - **ii.** Bring the building out of Test Mode
   - **iii.** Shutdown the instruments according to the instructions provided in each SOP.

V. Calibration

a. Instrumentation
   - **i.** Calibration and / or functional verification for each instrument listed in Table 1 shall be performed according to instructions in the respective SOP.

b. Reported Quantities
   - **i.** Calibration of the FPC heat release rate shall be performed by calculating the calibration factor (C Factor).

1. A HRR calibration experiment shall be conducted prior to each series of FPC experiments, and within 30 days of any test within the series
2. The C Factor shall be calculated following an experiment in which a calibration burner(s) is used to produce a series of fires with varying size.
3. A calibration experiment shall include at least three (3) heat release rate steps.
4. The first HRR step shall be 0 kW.
5. The maximum HRR step shall be selected based on the anticipated fire size.
6. The calibration factor shall be between the values of 0.95 and 1.05.
7. The calibration factor shall not vary by more than ±5 percent from the previous calibration.
8. If the CFactor does not meet the requirements in (5) or (6), the system shall be checked for problems. Once the problems have been corrected, a new calibration experiment shall be conducted.

I. Initial Setup

a. Required Supplies

i. ODM System Components

1. Laser assembly equipped with 0.5 mW He-Ne laser, compensating photodiode, filter housing and beam splitter
2. Main detector assembly equipped with main photodiode, filter housing and beam splitter
3. Amplifier module
4. Power supply module
5. Laser power supply
6. Blank (zeroing) insert, 0.3 OD, and 0.8 OD Neutral Density Filters

ii. 115 VAC electrical power

iii. Data acquisition hardware

iv. Data acquisition connectivity

v. FireTOSS Client computer

vi. Compressed air source and plumbing to connect purge

b. Plumbing and Electrical/Data Connections

i. Plug the photodiode connections into the amplifier module and connect the amplifier module to the power supply module.

ii. Connect the amplified detector leads from the power supply module to the appropriate channels on the data acquisition system.

iii. Plug in the laser power supply and the detector power supply module.

iv. Turn the laser power supply on and allow the laser to stabilize. The laser power should be kept on to extend the life of the unit.

v. Connect the purge air source.

c. System Alignment

i. Align the laser to maximize the main detector signal.

ii. Perform a functional verification of the system.

1. Note: the 0.5 mW lasers are powerful enough to saturate the photodiode detectors. The supplied filters can be used to verify that the system is operating in the linear range. Placing a filter in the beam path should reduce the detector signal by a factor of 10^(-OD) where OD is the calibrated filter optical density. The filters have nominal optical densities of 0.3 and 0.8, which correspond to factors of roughly 0.5 and 0.15, respectively. If the signal is not reduced by the expected amount when a filter is put in place, the laser intensity may need to be reduced to bring the

photodiode into the linear range. Each detector module was shipped with an opal glass diffuser mounted in front of the photodiode. To further attenuate the laser intensity, a 1.6 mm (1/16 in.) thick PTFE (Teflon) disc was placed in front of the diffuser. Additional beam dissipation may be necessary to bring the photodiode into the linear range.

iii. Adjust the gain on the amplifier module until the main and compensating photodiodes have a signal output between 1.5V and 2.0V. Figure 1 shows the location of the amplifier adjustment screws.

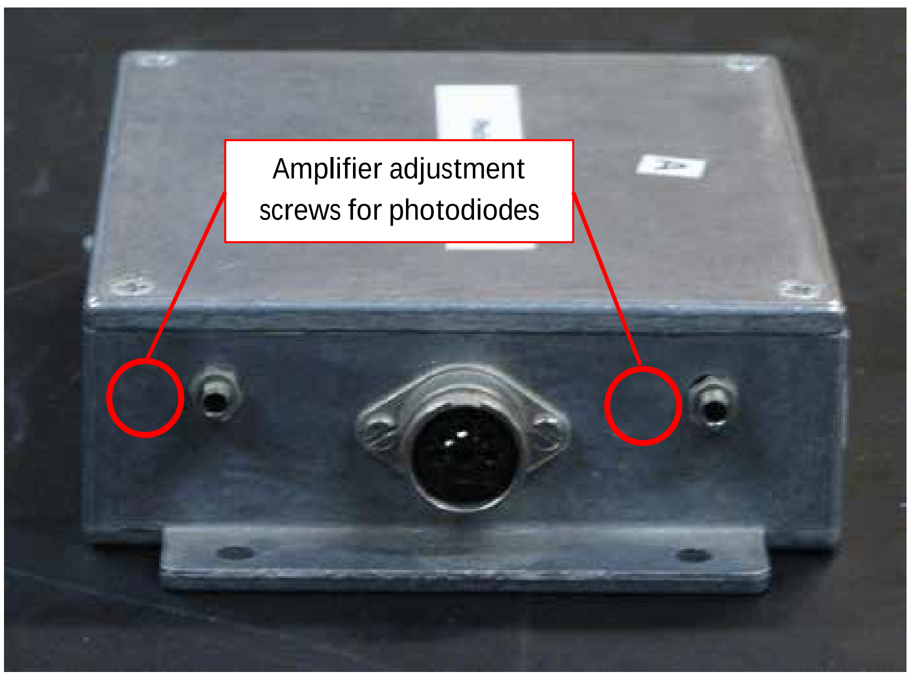


Figure 1: Location of screws for adjusting photodiode output on the amplifier

II. Experimental Procedure

a. Prior to First Test of Day

i. Ensure that the laser power supply is turned on. The laser system should be left on continuously to prolong the life of the laser.

1. If the power supply is not turned on, turn it on and allow the laser to stabilize.

ii. Ensure that the power supply module for the amplifier is plugged in.

iii. Verify that the main and compensating photodiodes to have a signal output between 1.5V and 2.0V.

1. If the signal is below 1.5V the following steps may be taken:
   a. Adjust the laser alignment. This should be done carefully as the phododiode surfaces are small and the detector output is very sensitive to laser alignment.
   b. Clean any excess dirt off the sight glass and the laser system optics.
   c. Check and, if necessary, adjust the amplification of the photodiodes.
2. Perform a system functional verification
3. Verify that the purge air is flowing. Purge air is activated through iFix on the Calorimeter Control Screen, shown in Figure 2.

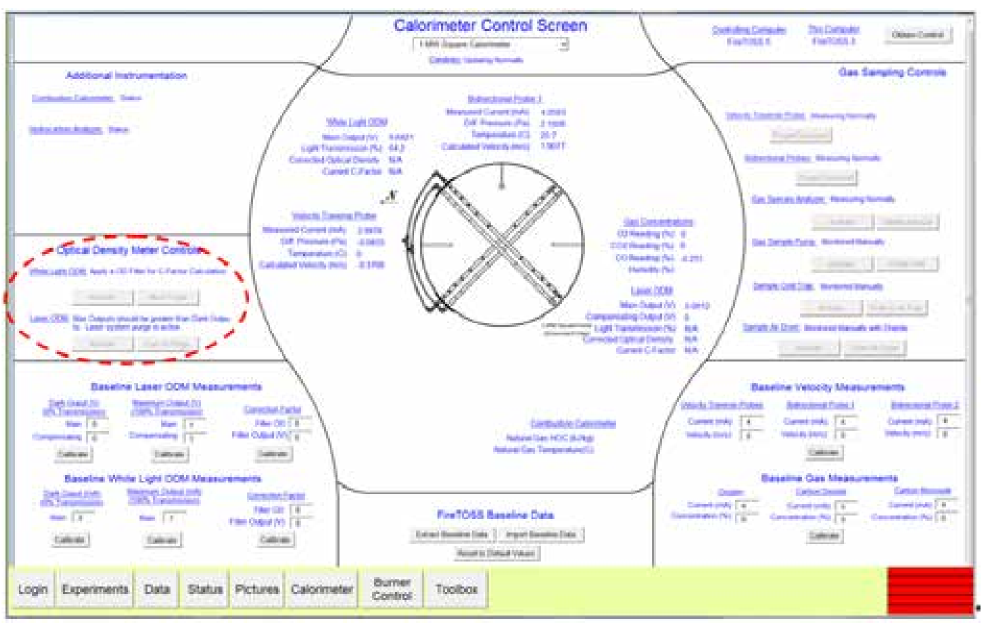


Figure 2: Calorimeter Control Screen

b. Prior to Each Test

i. Verify that the output of each photodiode is stable for a period of at least two minutes,

ii. System Balance

1. With no obstruction in the light path, record the signal outputs from the main and compensating photodiodes as $V_{1,main}$ and $V_{1,comp}$, respectively.
2. Block the laser by placing a blank insert into the filter housing adjacent to the compensating photodiode. Record the signal outputs from the main and compensating photodiodes as $V_{0,main}$ and $V_{0,comp}$, respectively.
3. Update the FireTOSS data sheet.
4. Ensure that the optical path is unobstructed prior to testing

iii. System Calibration (Optional)

1. Insert a neutral density filter into the slot in the main detector assembly.
2. Record the filter optical density on the FireTOSS data sheet.
3. Record the signal output from the main photodiode as $V_{filter,main}$.
4. Update the FireTOSS data sheet.
5. Remove filter from the slot and ensure that the optical path is unobstructed prior to testing.

c. During Test

i. Data Recording

1. The output of the main and compensating photodiodes shall be recorded for the duration of the experiment.
   a. Exception: When the ODM must be removed prior to the end of an experiment due to experiment design or system failure. The elapsed time at which the laser was removed and the reason for instrument removal shall be recorded on the data sheet.

III. Shut Down and Post Test

a. If an ODM was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.

b. If conditions occurred, either during the test or following the test, that could potentially affect the performance of the ODM, a functional verification shall be performed.

c. If it is determined that damage has occurred or that maintenance needs to be performed, the ODM shall be taken out of service until it has been repaired or replaced.

d. Unless the system needs to be shut down for maintenance or repair, power to the ODM components shall be left on.

IV. Maintenance and Safety

a. Laser windows on the FPC port should be checked periodically and cleaned as necessary.

b. The ODM uses a 0.5 mW helium neon laser. Care must be taken when performing any installation, maintenance or repair operations as eye damage can occur with exposure to the beam.

V. Functional Verification

a. Ensure that the laser system is turned on and has been given time to stabilize

b. Balance the system according to the procedure in section II.b.ii.

c. Insert the 0.3 OD filter in the filter slot of the main detector assembly.

i. Allow the system to stabilize and record the signal from the main and compensating photodiodes as $V_{filter,main}$ and $V_{filter,comp}$, respectively.

ii. Calculate the normalized signal for each photodiode according to:

$$V_n = \frac{V_{filter} - V_0}{V_1 - V_0}$$

iii. Calculate the optical density using the following equation:

$$OD_{meas} = \log_{10} \frac{V_{n,comp}}{V_{n,main}}$$

iv. If the calculated optical density agrees with the calibrated optical density of the filter ± 2%, proceed to step d.

v. If the calculated optical density varies from the calibrated optical density of the filter by more than 2 %, perform troubleshooting steps outlined in section II.a.iii.1. and repeat the functional verification. Also see the note in section 1.c.ii.1.

1. If these steps do not resolve the issue the ODM shall be taken out of service until the calculated OD is in agreement with the calibrated filter OD ± 2 %.

d. Repeat Step c using the 0.8 OD filter.

I. Initial Setup

a. Required Supplies

i. ODM System Components

1. White light control unit
2. White light transmitter
3. White light receiver
4. Three neutral density filters covering a range of optical density
   a. For example 0.1, 0.8 and 2.0

ii. 115 VAC electrical power

iii. Data acquisition hardware

iv. Data acquisition connectivity

v. FireTOSS Client computer

vi. Compressed air source and plumbing to connect purge

b. Plumbing and Electrical/Data Connections

i. Connect the light transmitter and receiver to the control unit.

ii. Connect the signal leads from the control unit to the appropriate channels on the data acquisition system.

iii. Plug in the control unit.

iv. Connect the purge air source.

c. System Alignment

i. Switch on the control unit and lamp.

ii. Adjust the damping control switch to zero.

iii. Align the light transmitter to center the beam on the window of the opposite side of the FPC duct.

iv. Verify that the light beam diameter is approximately 3 cm at the location of the light receiver.

v. Switch the control unit to “Calibrate” and use the adjusting screw on the light transmitter to give a reading of 1.5 V. The adjusting screw is shown in Figure 1.

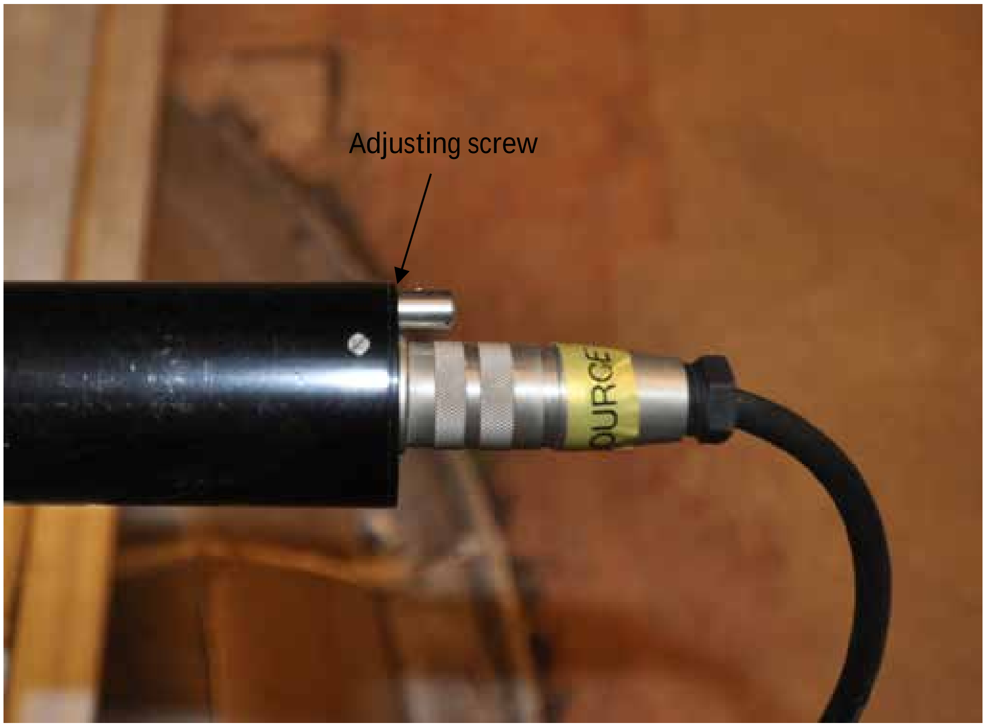


Figure 1: Location of adjusting screw on light transmitter

d. **System zero**
   i. Switch the control unit to "Measure."
   ii. Insert a blank in the filter slot or otherwise block light from the receiver.
   iii. Adjust the "Zero" potentiometer on the control unit until the control unit display reads "0.00."

e. **System span**
   i. Verify that the control unit is set to "Measure."
   ii. Unlock the "Span" potentiometer by moving the small latch counter-clockwise.
   iii. Verify that the light source is turned on and the path is unobstructed.
   iv. Adjust the "Span" potentiometer on the control unit until the control unit display reads "100.0."
   v. Lock the "Span" potentiometer by moving the small latch clockwise. If you accidentally move the "Span" potentiometer, then span the system again.

f. Perform a system functional verification.
g. Remove filters and ensure that the optical path is unobstructed.
h. **Turn off the power to the lamp and control unit when the system is not in use**.

II. Experimental Procedure

a. Prior to First Test of Day

i. Turn on the power to the control unit and allow the system to stabilize.
ii. Turn on the lamp power.
iii. Zero and span the system.
iv. Perform a system functional verification.
v. Verify that the purge air is flowing. Purge air is activated through iFix on the Calorimeter Control Screen, shown in Figure 2.

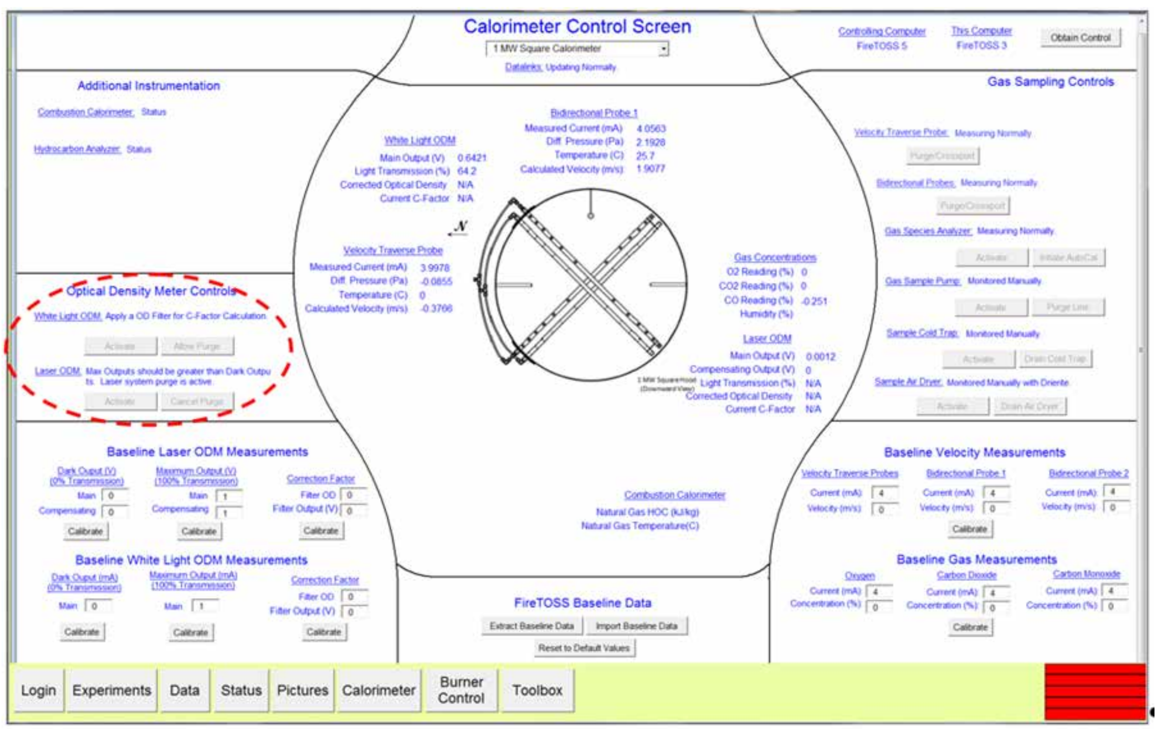


Figure 2: Calorimeter Control Screen

b. Prior to Each Test

- **i.** Verify that the output from the light receiver is stable for a period of at least two minutes.
- **ii.** Zero the system and record the light receiver signal.
- **iii.** Span the system and record the light receiver signal.
- **iv.** Update the FireTOSS data sheet.
- **v.** Ensure that the optical path is unobstructed.
- **vi.** System Calibration (Optional)
  1. Insert a neutral density filter into the filter slot.
  2. Record the light receiver signal.
  3. Update the FireTOSS data sheet.
  4. Remove filter from the slot and ensure that the optical path is unobstructed prior to testing.

c. During Test

- **i.** Data Recording
  1. The output of light receiver shall be recorded for the duration of the experiment.
     a. Exception: When the ODM must be removed prior to the end of an experiment due to experiment design or system failure. The elapsed time at which the ODM was removed and the reason for instrument removal shall be recorded on the data sheet.

III. Shut Down and Post Test

a. If an ODM was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.

b. If conditions occurred, either during the test or following the test, that could potentially affect the performance of the ODM, a functional verification shall be performed.

c. If it is determined that damage has occurred or that maintenance needs to be performed, the ODM shall be taken out of service until it has been repaired or replaced.

d. The control unit power should be switched off overnight.

e. The lamp power should be switched off between tests.

IV. Maintenance and Safety

a. Windows on the FPC ports should be checked periodically and cleaned as necessary.

V. Functional Verification

a. Verify that the control unit is turned on and has been given time to stabilize.
b. Verify that the light source power is on.
c. Insert a neutral density filter in the filter slot.
d. Verify that the measured transmission value agrees with the calibrated transmission of the filter. The filter transmission (T) can be calculated from the optical density (OD) according to:

$$T = 10^{-OD}$$

e. Repeat steps c and d for two additional filters with different OD values.
f. If the measured transmission varies from the calculated transmission from the calibrated filter by more than 2 %, perform troubleshooting steps and repeat the functional verification.

Scope

This instruction covers the use, design, and specifications of thermocouples used at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

A thermocouple is a temperature measurement sensor that consists of two dissimilar metals joined at one end (a junction) that produces a small thermo-electrical voltage when the wire is heated. The change in voltage is interpreted as a change in temperature. [1]

Although there are many configurations of thermocouples, there are five important factors to consider when using thermocouples for fire applications: temperature range, ruggedness, response time, wire tolerance limit, and grounded or ungrounded.

<u>Temperature Range</u> : The temperature range of a thermocouple is defined by the type and thickness of the metals used in their construction. The type of thermocouple is described using a letter nomenclature. Typical thermocouple types are J, K, T and E. For most fire applications, Type-K thermocouples with a maximum temperature range of approximately 1250 ºC (2282 ºF) are used. [1]

<u>Ruggedness</u>: The resistance of a thermocouple to environmental conditions is largely dependent on the type of junction and the wire insulation. Typically, thermocouples have either exposed or sheathed junctions. Exposed junction thermocouples have a faster response time but the junction is unprotected from the environment. Sheathed junction thermocouples are protected inside of a metal sheath, commonly constructed of Inconel, that provides environmental and abrasion resistance. However, sheathed thermocouples have a slower response time and a lower maximum temperature range because thinner wires are used within the metal sheathing. The ruggedness of thermocouples is mainly a function of the wire insulation material. Glass braid insulation has a temperature range of -73 ºC to 260 ºC and Nextel braid insulation has a temperature range of -73 ºC to 1204 ºC. Inconel is listed with a maximum temperature of 1150 ºC. [1, Page H-5-7]

<u>Response Time</u>: The response time of a thermocouple is characterized by its "time constant" that is defined as the time required to achieve 62.3% of an instantaneous change. Factors that affect response time are wire gage, sheathed versus exposed junction, and grounding. For a 0.015 mm (0.001 inch) gage wire, the response time in a "still" air environment is approximately 0.05 sec [1, Table 2, Page A-18].

<u>Wire Tolerance Limit</u>: Thermocouple wire is generally available in more than one grade. The grade of wire refers to the tolerance limit specified for a particular thermocouple type. For

example, one manufacturer sells two grades: standard and special limits of error (SLE) [1]. Unless otherwise specified, Type-K SLE thermocouple wire is used at the ATF Fire Research Laboratory which has a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. When there is a specific experiment requirement for a different level of accuracy, the actual measured thermocouple accuracy shall be documented in the "TC Type" FireTOSS input field.

Grounded Thermocouples: The difference between grounded and ungrounded thermocouples is that the junction of a grounded thermocouple is welded directly to the protective sheathing where as an ungrounded thermocouple junction is isolated from the sheathing. Grounded thermocouples are recommended for measurements of corrosive substances or in high pressure environments. Because the junction of a grounded thermocouple is welded to the sheath, the response time is faster than ungrounded thermocouples. However, a concern with grounded thermocouples is that many instruments can have ground loop problems.

Uncertainty and Accuracy

In a thermocouple measurement, the reported temperature is that of the junction, or bead. Generally, however, the temperature of the thermocouple junction is different from the temperature of interest. In fire tests, the temperature of interest is typically that of the gases surrounding the thermocouple junction. The uncertainty associated with the measured junction temperature can be estimated based on specifications for a particular thermocouple and an analysis of the measurement system. The difference between the junction temperature and the temperature of the surrounding gases can be significant and is highly dependent on conditions associated with a particular experiment. The analysis that follows is divided into two sections: first, an analysis of the uncertainty associated with the junction temperature measurement (measurement error) and second, an analysis of the error associated with the differences between junction temperature and environment temperature (insertion error).

MEASUREMENT ERROR

The uncertainty associated with the measured junction temperature is a primarily a function of the thermocouple/extension wire and any additional junctions such as when the thermocouple wire transitions to extension wire. The measurement system illustrated in Figure 1 is a common set-up used at the FRL. The analysis provided here is based on manufacturer specifications for Type-K thermocouples [1].

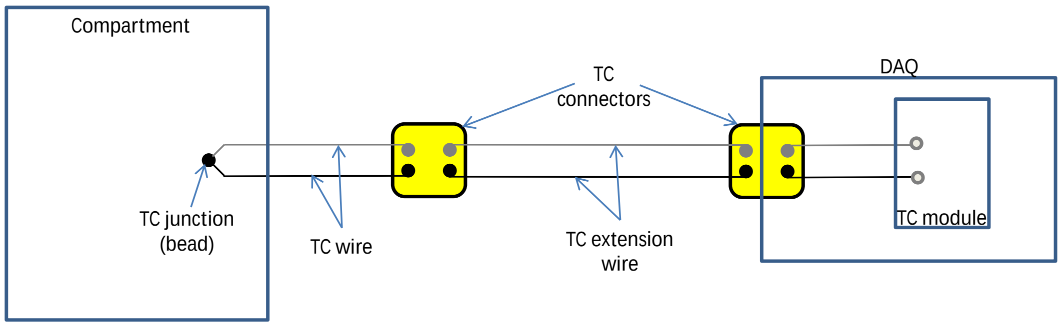


Figure 1. Thermocouple measurement system

Thermocouple wire can be specified as having either standard or special limits of error. The limit of error for standard Type-K thermocouples is the greater of 2.2°C or 0.75% of the temperature reading over 0°C. Special limit of error (SLE) Type-K thermocouples can be specified with a corresponding error limit that is the greater of 1.1°C or 0.4% of the temperature reading over 0°C. The maximum specified temperature of a Type-K thermocouple is 1250°C. At this temperature, the error associated with standard and SLE type-K thermocouples is 9.38°C and 5°C, respectively. [1, page H4] The FRL uses SLE thermocouple wire.

Thermocouple extension wire is fabricated from the same material as the thermocouple wire, and is also available in standard or SLE grades. The error associated with standard and SLE grades are, respectively, ±2.2°C and ±1.1°C. This error is valid in a temperature range is between 0°C – 200°C. The error due to extension wire is only considered if there is a temperature gradient across the length of the extension wire.

Thermocouple connectors are commonly used to transition from the thermocouple to extension wire or extension wire to the data acquisition system. These junctions introduce uncertainty in the measurement if there is a temperature gradient across the junction and the junction is made of a different material than the thermocouple wire. This error is approximately the same as the temperature difference across the junction [2]. Junctions are generally small and are often insulated. The connectors used at the FRL are made of the same material as the thermocouple wire and are therefore ignored in this analysis.

Excessive wire lengths and the data acquisition system are other sources of error. However, these errors are generally small and are not considered in this analysis.

This analysis considers two scenarios. In the first scenario a SLE Type-K thermocouple is placed in a high temperature environment (1000°C), such as inside a compartment fire. The thermocouple lead extends outside the compartment where it is connected to standard Type-K extension wire that runs to the data acquisition system, shown in Figure 1. In this scenario the environment outside the compartment is between 0°C – 200°C and is conditioned such that there is no temperature gradient between the TC/extension connection and the data acquisition system.

In this scenario, because there is no temperature gradient at any of the junctions or across the extension wire, the connections and extension wire can be ignored in the uncertainty analysis. The measurement error is only associated with the error of the thermocouple wire.

For SLE K-type wire at 1000°C, the corresponding error is 0.4%, or 4°C. Assuming a square probability distribution, the standard uncertainty is obtained by dividing by $\sqrt{3}$. The result is a standard uncertainty of, u_{TC} = 2.3°C.

The second scenario is identical to the first, with the exception that there is a temperature gradient between the ends of the extension wire. In this case, the error associated with the extension wire must be considered. This is accomplished by combining the errors from the thermocouple wire and extension wire in quadrature:

$$u_c(T) = \sqrt{u_{TC}^2 + u_{EX}^2} \quad (1.1)$$

Where $u_c(T)$ is the combined standard uncertainty, and u_{TC} and u_{EX} are, respectively, the standard uncertainties of the thermocouple wire and extension wire. Assuming that the extension wire is standard grade, the standard uncertainty is u_{EX} = 1.27°C. The combined standard uncertainty is then, $u_c(T)$ = 2.64°C.

INSERTION ERROR

Insertion errors are those that arise from differences between the thermocouple junction temperature and the temperature of the surrounding fluid. The two types of errors considered are conduction errors and radiation errors.

Conduction Error

Conduction error, as the name suggests, results when heat is conducted away from the thermocouple junction through the wire, causing a reduction in the junction temperature. Conduction errors are minimized by using small gauge wire and relatively long insertion lengths. For wire diameter, D, and insertion length, L, a general rule is that conduction errors can be neglected in conditions for which L/D > 50 [3]. Considering 24 AWG wire with a diameter of 0.5 mm, the corresponding minimum insertion length is 2.5 cm.

Radiation Error

In fire environments, radiation error can be significant. Radiation error can be quantified by considering a thermocouple junction in a fluid environment that exchanges energy through convection with the local medium and through thermal radiation with the surroundings. A First Law analysis simplifies to:

$$T_g \quad T_j = \frac{}{h_c}\left(T_j^4 \quad T_s^4\right) \quad (1.2)$$

Where T_g is the gas temperature, T_j is the junction temperature, T_s is the temperature of the surroundings, is the probe emissivity, is Boltzmann's constant and h_c is the convective heat transfer coefficient [4]. The left hand side of Eqn. 1.2 is the difference between the gas temperature and the junction temperature, which represents the error. This error is highly dependent on the conditions of a particular experiment. In conditions where the gas and surrounding temperature are in equilibrium, the net radiant exchange is zero and the radiation error is eliminated. Fire experiments tend to be highly transient, particularly in the developing stage, and the T^4 dependence in the radiation term can drive significant errors in the temperature measurement.

The largest errors are encountered with thermocouples in low temperature regions that are exposed to an intense radiant flux. This is a condition often encountered in a developing enclosure fire in which cool air is drawn into a compartment through the lower area of a door and a sooty, hot upper layer is developing below the ceiling. Radiation from the hot upper layer heats the thermocouple junction, resulting in temperature readings that can be significantly higher than the actual temperature of the gases in the lower layer. One study documented errors as high as 225°C in extreme cases [4].

Radiation errors are greatest in the lower region where the gas temperature is lower than the temperature of the surroundings. The error decreases with a reduction in the temperature of the surroundings and as the gas temperature increases. Errors are typically reduced in the upper layer where gas temperatures are higher than the temperature of the surroundings. However, even in the upper layer, errors can be on the order of 25% [4]. Figure 1 shows a chart of calculated radiation errors for a range of conditions assuming an idealized bare bead thermocouple with a diameter of 1.5 mm [4].

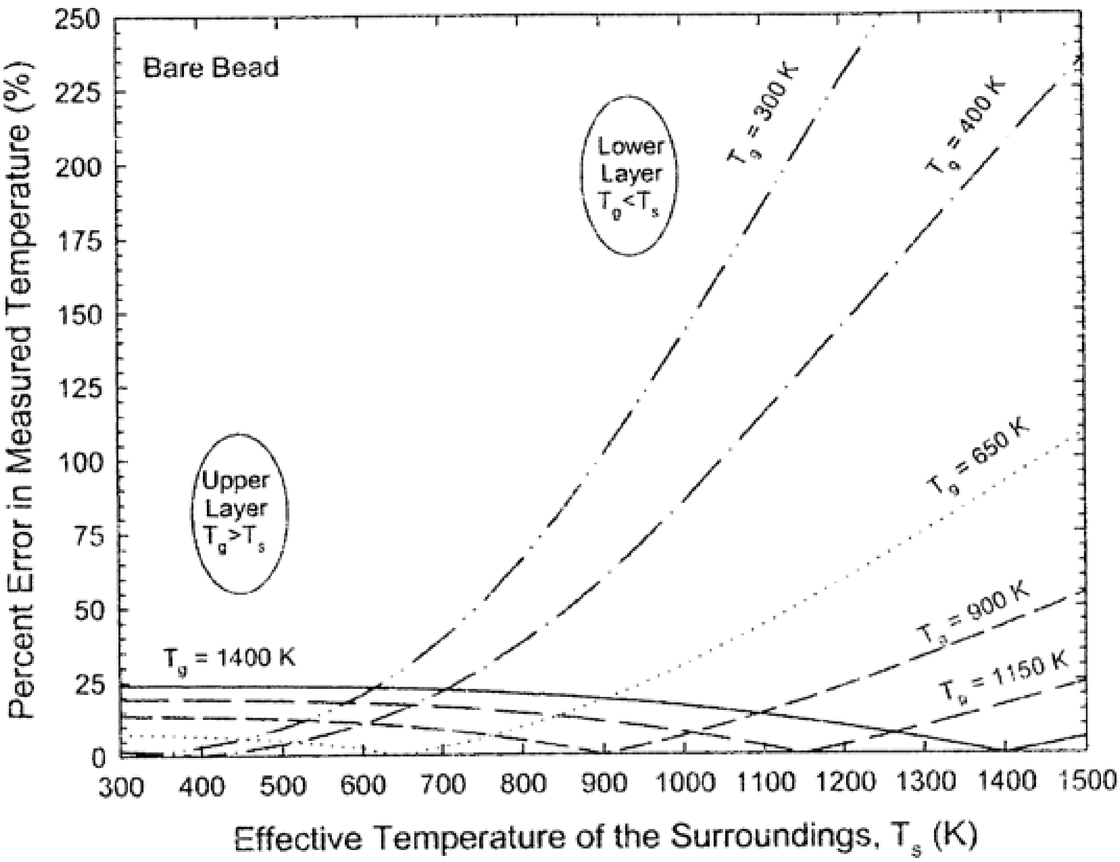


Figure 2: Calculated percentage errors for an idealized bare-bead thermocouple with 1.5 mm diameter bead [4].

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition instrumentation shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. All thermocouples shall be constructed from thermocouple wire with a minimum accuracy of the greater of 1.1°C or 0.4% of the temperature reading over 0°C.
   3.1. Exception: When there is a specific experiment requirement for a different level of accuracy, the actual measured thermocouple accuracy shall be documented in the "TC Type" parameter in FireTOSS laboratory report.
4. If thermocouple extension wire is used, the wire shall be used in the range specified.

4.1. The minimum accuracy of Type-K extension wire shall be 2.1 C between 0 ºC and 200 ºC.
4.2. The temperature gradient between the ends of the extension wire and any additional junctions shall be minimized.

PROCEDURE

1. Prior to the first test in a series
1.1. Operation of the thermocouples shall be verified in two ways.
1.1.1. The thermocouple reading shall be verified against ambient temperature
1.1.2. A heat source shall be applied and the resulting rise in temperature verified.

2. Before each test in a series
2.1. The thermocouple reading shall be verified against ambient temperature to ensure operability.

3. **During the Test**
3.1. The output of the thermocouple shall be recorded for the duration of the experiment.
3.1.1. Exception – When the thermocouple must be removed prior to the end of the experiment due to experiment design or damage. The elapsed time at which the thermocouple was removed and the reason for removal shall be recorded.

4. **Post Test**
4.1. After the experiment, the thermocouples in locations where they could have been damaged shall be examined for visible damage. Perform functional verification if necessary.
4.1.1. If damage has occurred, the instrument shall be taken out of service at the time of the damage. The laboratory engineer shall review the data to determine if there is a noticeable event that marked the damage to the instrument. If not, the thermocouple shall be taken out of service for the entire test. After the thermocouple has been taken out of service, the calculations shall be redone.

Figure 3 shows a flowchart of the procedure that should be used for thermocouples.

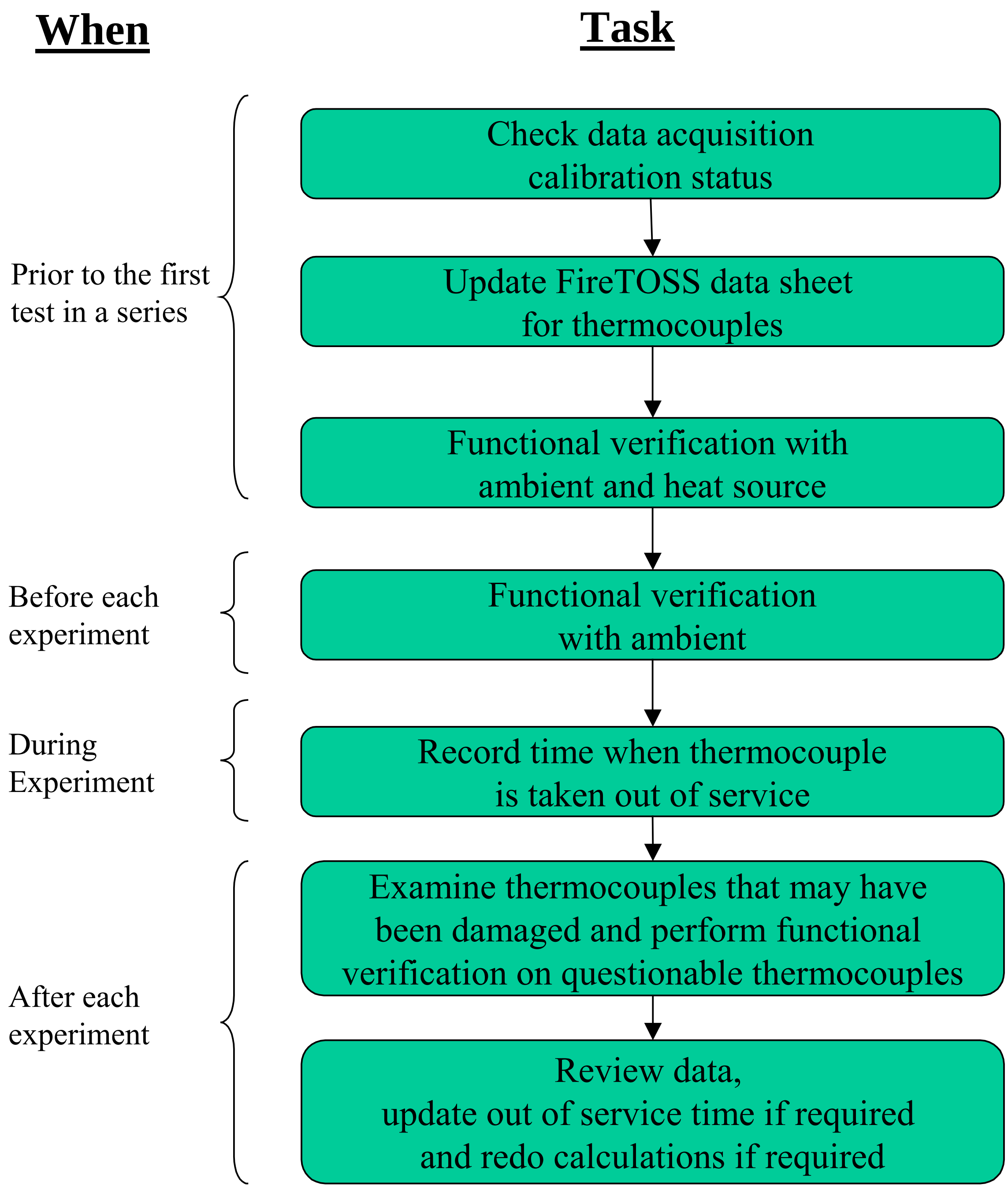


Figure 3. Thermocouple Process Flow Chart

Thermocouple Documentation Requirements

Thermocouples shall be documented using the FireTOSS experiment design program. The information that the user can document about the thermocouples is shown in Table 1. The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and column three provides a description of the information to be supplied for the parameter.

Table 1. Data Acquisition Input Parameters

Parameter	Required	Parameter Description
Description	True	Description of the location of the thermocouple
Location X	False	X axis location of thermocouple
Location Y	False	Y axis location of thermocouple
Location z	False	Z axis location of thermocouple
TC Type	True	Identifies the type of thermocouple. Required information includes, thermocouple type, diameter, Inconel or beaded, grounded or ungrounded. Thermocouple accuracy shall be documented if required by the design of the experiment or if the accuracy is less than the FRL standard. Also, indicate if TC extension wire was used.
Tree ID	False	In conjunction with a diagram of the experiment set-up, this parameter is used to identify a horizontal or vertical traverse of instruments.
Room Number	False	Cross reference of instrument location
Chart	False	Allows the user to group instrument data onto different charts. If this parameter is left empty, data for similar instruments will be put on one chart.
Out of service time	False	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.
Out of service reason	False	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design
Initial Change Amount	False	Used in standardized testing to mark an event
Discontinuity threshold value	False	Value used to mark a discontinuity in the data. Typically, an data acquisition error has occurred.

References

1. Omega Temperature Measurement Handbook, 6th edition, Omega Engineering, Stamford, CT, 2007.

2. Nakos, J. T., "Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant Heat Facility and Lurance Canyon Burn Site," SAND2004-1023, Sandia National Laboratories, Albuquerque, NM, 2004.

3. Figliola, R. S., and Beasley, D. E., *Theory and Design for Mechanical Measurements, Second Edition*, John Wiley and Sons, New York, 1995.

4. Pitts, W. M., Braun, E., Peacock, R. D., Mitler, H. E., Johnsson, E. L., Reneke, P. A., and Blevins, L. G., "Temperature Uncertainties for Bare Bead and Aspirated Thermocouple Measurements in Fire Environments," *Thermal Measurements: The Foundation of Fire Standards," ASTM STP 1427*, L. A. Gritzo and N. J. Alvares, Eds., ASTM International, West Conshohocken, PA, 2002.

Scope

This laboratory instruction covers the use of Schmidt-Boelter Heat Flux Transducers in FRL custom experiments.

Instrument Description

GENERAL

A heat flux transducer is a device that measures the rate of absorbed incident energy, and expresses it on a per unit area basis. The operating principle of most heat flux transducers is based on one-dimensional heat conduction through a solid. Temperature sensors are placed on a thin, thermally conductive sensor element, and applying heat establishes a temperature gradient across the element. The heat flux is proportional to the temperature difference across the element according to Fourier's Law.

There are many configurations of heat flux transducers, but for fire applications the choice revolves around five decisions: (1) type, (2) range, (3) size, (4) mode and (5) cooling.

<u>Transducer Type</u>: Two primary types of transducers in use are circular foil (Gardon) and thermopile (Schmidt-Boelter). Schmidt-Boelter transducers are recognized as being the most appropriate for fire applications.

In a Schmidt-Boelter transducer, a constantan wire is wrapped around an electrically insulating sensor element and the turns on one side are plated with copper, producing (T-type) thermocouple junctions on both faces of the sensor [1,2]. The number of thermocouple junctions determines the sensitivity, as there is an additive effect of the potential for each junction.

The time constant of a heat flux transducer is the time required for the sensor to reach 62.5 % of a step input. Time constants vary based on sensor range, however for Schmidt-Boelter transducers they are typically less than 250 milliseconds [3].

<u>Range</u>: The range of a heat flux transducer is determined by the sensitivity of the element to an applied heat flux. Transducers are typically designed to provide a signal of nominally 10 mV at the range peak. Heat flux transducers are classified according to the peak flux for which they are calibrated to read. For Schmidt-Boelter transducers, standard ranges vary from 2 kW/m^2 – 50 kW/m^2, however ranges as high as 1100 kW/m^2 are available. In fire applications, a range from 25 kW/m^2 – 150 kW/m^2 will cover most applications. Sensors have an over range capability of up to 150 % of the peak specified heat flux [3].

<u>Size</u>: The size of transducer that is appropriate for use depends on the application. A typical size that is used in fire applications is a 2.5 cm (1 in.) diameter body with a 1 cm (3/8 in.) diameter sensor. When finer spatial resolution is required, 1.3 cm (1/2 in.) or 3 mm (1/8 in.) transducers can be used.

Transducer Mode: Transducers are designed for use as radiometers to measure the radiative flux, or as total flux transducers in which the sum of radiative and convective components are measured. A radiometer isolates the radiative component by placing an IR-transmitting window in front of the sensor element, eliminating the effect of convective heat transfer on the sensor. Some transducers use two sensors, a total heat flux sensor and a radiometer so that the magnitude of the individual components can be determined. Care must be taken, as window materials do not transmit 100% throughout the IR spectrum. The FRL uses Zinc Selenide window material, as it provides a relatively high and consistent transmittance throughout the relevant spectral range.

Transducer cooling: Some transducers come equipped with the capability for water cooling. In this configuration, water flows through the transducer, removing heat from the backside of the sensor. Water-cooling is recommended for conditions in which the temperature of an uncooled transducer will exceed 204ºC (400ºF) [3].

UNCERTAINTY AND ACCURACY

The uncertainty of the heat flux measurement has two parts: the uncertainty of the instrument and the uncertainty associated with fluctuations over time. The uncertainty in the instrument is a function of the linearity, repeatability and calibration of the instrument. The combined uncertainty of the measurement is estimated by combining the standard uncertainty of each component in quadrature.

Medtherm gives the linearity of the heat flux transducer as ± 2 % full scale [3]. The repeatability is listed as ± 0.5 % and the calibration uncertainty is ± 2 % for ranges up to 3000 kW/m^2. It can be assumed that these errors have a rectangular probability distribution, in which case the standard uncertainty is computed by dividing each component by $\sqrt{3}$ [4]. For a 50 kW/m^2 transducer, the standard uncertainties of these components are then, respectively, 0.58 kW/m^2, 0.14 kW/m^2, and 0.58 kW/m^2.

The uncertainty over time can be calculated using a sample standard deviation. NIST [4] states that for a sample of data, the uncertainty of the samples is:

$$Us = \sigma/\sqrt{n}n$$

where:

U_s = Standard uncertainty of the samples
σ = Standard deviation of the samples
n = Number of samples

Using this formula, the uncertainty of the heat flux can be determined. Over a sample of 40 data points, the standard deviation was 0.227 kW/m^2, which yields a standard uncertainty of 0.036 kW/m^2.

The uncertainty components are combined in quadrature to estimate the combined uncertainty of the heat flux measurement. The result is $U_{HF} = \mathrm{u}(\mathrm{SG}_{\mathrm{NG}}) =$0.83 kW/m^2. For a 50 kW/m^2 transducer this is equivalent to ± 1.7 %

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. Heat flux transducers shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
4. Transducers size, range and mode shall be selected to represent the test conditions.

PROCEDURE

1. Set up

1.1. The calibration marking on the transducer shall be checked to confirm that the instrument is calibrated.

1.2. Transducers shall be connected to the data acquisition hardware using the smallest voltage input range that will bound the output range of the transducer. This is usually the 20 mV range.

1.3. All heat flux transducers shall be connected to a constant temperature flowing water source.

1.4. Water lines and wires connected to the heat flux transducer shall be protected if it is anticipated that they will be exposed to excessive heat during the experiment.

2. Pre-Test

2.1. It shall be verified that water is flowing through each transducer.

2.2. The water temperature used to cool the transducer shall be a minimum of 5°C above ambient. This temperature shall be recorded on the data sheet.

2.3. A baseline reading shall be recorded with the transducer prior to conducting experiments. The baseline value shall be the average heat flux measured during a period with a minimum 2-minute duration.

2.4. During the baseline reading, the water temperature will be stable.

3. **Test**
   3.1. Water shall be supplied continuously at the required temperature.
   3.2. The output of the heat flux transducer shall be recorded for the duration of the experiment.
   3.3. Exception – When the heat flux transducer must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the transducer was removed and the reason for instrument removal shall be recorded on the data sheet.

4. **Post Test**
   4.1. After the experiment, heat flux transducers in areas where they may have been damaged shall be examined for visible damage or surface dirt.
   4.2. If damage or surface dirt is observed the instrument shall be cleaned and/or repaired according to manufacturer's documentation.
   4.3. If the heat flux exceeded 150% of the maximum transducer range during any point of a test, the instrument shall be taken out of service until its correct operating condition is confirmed.

Heat Flux Transducer Documentation Requirements

Heat flux transducer usage shall be documented using the FireTOSS experiment design program. The information that the user shall document about the heat flux transducers is shown in Table 1. The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and column three provides a description of the information to be supplied for the parameter.

Table 1: Data Acquisition Input Parameters

Parameter	Required	Parameter Description
Calibration Factors	True	(m, b) Taken directly from the calibration data sheet or sticker.
Description	True	Description of the location of the heat flux transducer or a description of what it is pointing at.
Location – X	False	X – Location of transducer based on defined coordinate system (m)
Location – Y	False	Y – Location of transducer based on defined coordinate system (m)
Location – Z	False	Z – Location of transducer based on defined coordinate system (m)
Orientation	False	Orientation of transducer based on defined coordinate system
Room Number	False	Identification of transducer location in a compartment
Type	True	Description of transducer type.
Range	True	Peak range (kW/m^2)
OverRange	False	
Mode	True	Total or Radiative
Serial number	True	Manufacturer's serial number
Status	True	
Bar code	True	FRL Equipment identification number (asset number)
Path length	False	Distance in meters from the measuring surface of the flux transducer to the item of interest. A diagram of the test set up typically supports this

Parameter	Required	Parameter Description
		measurement.
Water temperature	True	Temperature of the cooling water supplied to the heat flux transducer
Chart	False	Allows the user to group instrument data onto different charts. If this parameter is left empty, data for similar instruments will be put on one chart.
Baseline Experiment ID	False	Experiment ID where baseline data is stored for a particular instrument.
Baseline Heat Flux	False	Offset applied to heat flux readings to account for measured background heat flux due to the cooling water. If a value for the 'Baseline Experiment ID' is input in the data sheet this value will be automatically inserted from the calculated 'Average Uncorrected Heat Flux' otherwise the user input value will be used. (kW/m²)
Out of service time	False	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.
Out of service reason	False	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design

List of Standards

The following standards apply to the use of heat flux transducers.

ISO/TS 14934-1:2010 "Fire tests -- Calibration and use of heat flux meters -- Part 1: General principles"

ISO/TS 14934-2:2006 "Fire tests -- Calibration and use of heat flux meters – Part 2: Primary calibration methods

ISO/TS 14934-3:2006 "Fire tests -- Calibration and use of heat flux meters – Part 3: Secondary calibration method

ISO/TS 14934-4:2007 "Fire tests -- Calibration and use of heat flux meters – Part 3: Guidance on the use of heat flux meters in fire tests

References

1. Barnes, A., "Heat Flux Sensors Part 1: Theory," Sensors, January 1999.
2. Technical Data Sheet, "Schmidt-Boelter Heat Flux Sensor," Vatell Corporation, www.vatell.com/SB.htm
3. Medtherm Corporation, Technical Data Sheet.

4. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD 1993.
5. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, Gaithersburg, MD 2003.
6. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.

Scope

This instruction covers the use of digital cameras for experiments at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Digital Cameras are used within the FRL to record digital still photographs during experiments. The following gives a brief description of the factors effecting digital camera image quality. [1]

Pixels

Though a digital photograph looks smooth and continuous just like a regular photograph, it's actually composed of millions of tiny squares called pixels.

Each pixel in an image has a numerical value and is made up of three color channels with values ranging from 0 to 255. Each color in this scheme can be represented by an 8-bit number (byte), so the color of each pixel is defined by three color bytes.

Aspect Ratio

The aspect ratio of a camera is the ratio of the length of the sides of the images. For example, a 35 mm film frame is approximately 36 mm wide and 24 mm high which equates to an aspect ratio of 3:2. Most digital SLR (single lens reflex) cameras use the same aspect ratio for their digital images. However, video monitors typically use a 4:3 aspect ratio and most consumer level digital cameras use a 4:3 aspect ratio for their images.

Sensor Size

A 35mm film frame is 24 mm high by 36 mm wide but most digital cameras use sensors much smaller than this. For a given pixel count, the larger the sensor, the better the image quality and the lower the noise level.

White Balance

With digital you can pick your white balance to suit your light source, so that white looks white, not yellow or blue. Normally there is an automatic setting and the camera decides what white balance setting to use. However if you know what your light source is you can usually set the camera to it and this may give better results. Most digital cameras have settings for sunlight, shade, electronic flash, fluorescent lighting and tungsten lighting. Some have a manual or custom setting where you point the camera at a white card and let the camera figure out what setting to use to make it white.

Sensitivity

Sensitivity settings on digital cameras are the equivalent of ISO ratings on film. Most digital cameras will have settings with a sensitivity equivalent to ISO 100 film and ISO 200 film. Many will have an ISO 400 setting, but above that the images from cameras with small sensors gets noisy. The more expensive digital SLRs with much larger sensors have higher sensitivity settings. At ISO 400 they are virtually noise free and some can go as high as ISO 3200. Very few cameras have ISO setting lower than ISO 100 because noise levels are so low at ISO 100 there would be no real advantage in a slower setting. Quite a few digital cameras have an "auto" ISO setting, where the camera will pick the ISO setting depending on the light level and the mode in which the camera is operating.

Digital Zoom and Optical Zoom

Most cameras have both optical zoom and digital zoom. Optical zoom works just like a zoom lens on a film camera. The lens changes focal length and magnification as it is zoomed. Image quality stays high throughout the zoom range. Digital zoom simply crops the image to a smaller size, then enlarges the cropped portion to fill the frame again. Digital zoom results in a significant loss of quality.

JPEG, TIFF and RAW

The size of the digital file corresponding to the image which the camera produces depends on the pixel count. In most digital cameras each pixel generates 3 bytes of data (so called "8-bit data"). This means that a 3 MP camera generates 9 MB per image. A few cameras can generate extra data for extra quality, and some of these cameras generate files which correspond to 2 bytes of data for each color ("16-bit"), so a 3 MP camera which is capable of generating 16-bit data will produce an 18 MB image file.

JPEG (Joint Photo Experts Group) is an algorithm designed to work with continuous tone photographic images that takes image data and compresses it in a lossy manner. The more you compress, the smaller the file but the more information you lose. However, you can reduce file size by a factor of 10 or more and still get a very high quality image, just about as good as the uncompressed image for most purposes.

There are also lossless ways of saving files using TIFF (Tagged Image File Format) . These keep all the original information, but at the cost of much bigger files. TIFF files can be compressed in a non-lossy way, but they don't get very much smaller.

Some cameras can save the actual data generated by the sensor in a proprietary format. Nikon calls these files "NEF". These files are compressed, but in a non-lossy manner. They are significantly smaller than equivalent TIFF files, but larger than JPEGs. Typically they achieve a compression of around 6:1 using 16-bit data, so files are 1/6 the size of equivalent TIFF files. The disadvantage of these formats is that the image must be converted to either JPEG or TIFF for most software to be able to display them. Since NEF formats contain more information than JPEGs, some degree of exposure compensation and white balance corrections can be done.

Uncertainty and Accuracy

The accuracy requirement for the clock on the digital camera is 1 second over a 24 hour period. In addition, before taking the first picture of a test series each day, the clock on the camera must be synchronized with the clock on the data acquisition computer.

SYNCHRONIZING CAMERA CLOCKS

FireTOSS uses the date and time embedded in the digital picture file to determine the time that the photo was taken in relation to the start of the experiment. For this reason, the digital camera's date and time must be set to the same date and time as the computer taking the data. The process of setting the date and time on the camera to be the same as the date and time on the computer is called synchronizing the camera clock.

Nikon Transfer 2 software is used to synchronize the camera clock to the computer clock, which is in turn regulated by the secure FireTOSS database. The camera must be connected to the computer via USB cable to use this synchronization method. This is the preferred method of camera synchronization.

If the previous method is not possible, a second, manual method of synchronization is possible. To synchronize the camera manually, the user must open the computer clock program and the camera date/time menu and manually set the camera time to the computer time.

Operating Instructions

REQUIREMENTS

1. Digital cameras used for laboratory experiments shall be capable of having their clocks synchronized with the data acquisition system
2. The photographer shall be proficient with the camera.
3. Digital photographs shall be uploaded into FireTOSS immediately after the conclusion of each test or immediately after completion of post-test photographs are taken, where applicable.

PROCEDURE

1. **Prior to taking the first test picture of the day**
   a. Check camera battery status.
   b. The digital camera clock shall be synchronized with the data acquisition system before the first test of the day.

2. **During experiment**
   a. Take photographs
3. **At the conclusion of each test**
   a. Digital photographs shall be uploaded to the data acquisition system.

Figure 1 shows a flowchart of the procedure that should be used for digital cameras.

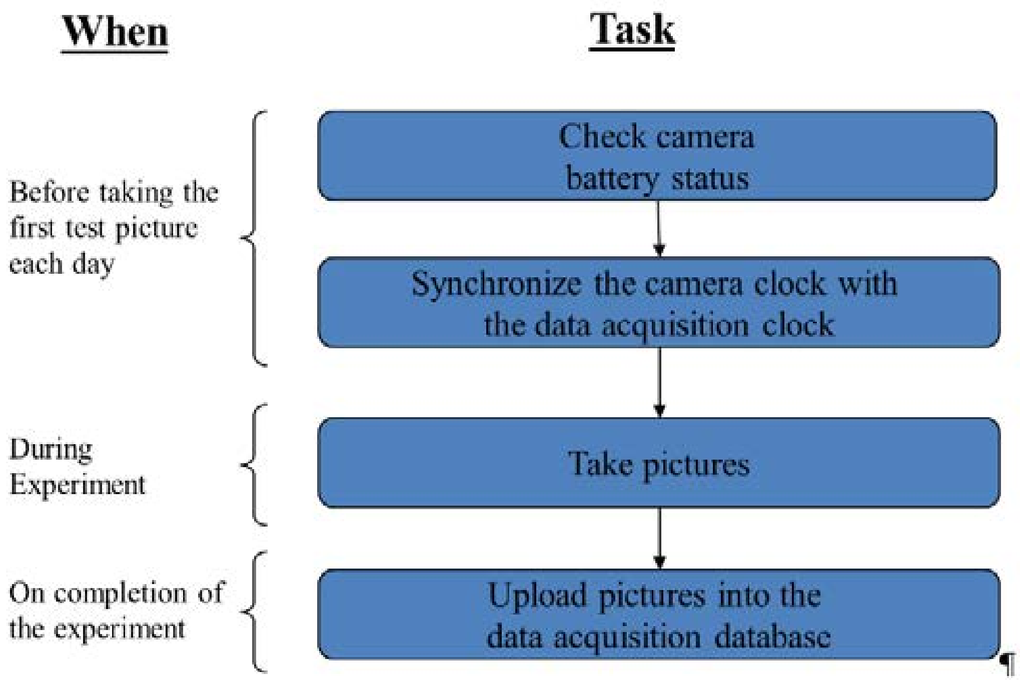


Figure 1. Digital Camera Process Flow Chart

Digital Camera Documentation Requirements

Digital photographs taken during an experiment shall be documented using the FireTOSS experiment design program. The required information that the user must document when using the digital camera in an experiment is shown in Table 1. The first column provides the input parameter and the second column provides a brief description of that parameter. The third column lists whether the parameter is required in all cases. The fourth column lists how the parameter is entered into the FireTOSS design program.

Table 1. Data Acquisition Input Parameters

Parameter	Parameter Description	Required	Input Method
Description	Description of what the image shows	FALSE	User
Cleared for General Public	All requirements have been met to share this for public dissemination.	FALSE	User
Picture poster status	Usually, many pictures are taken during an experiment. This parameter is used to identify pictures that are the best representation of a test.	FALSE	User
Use in report	Determines whether the image will be inserted into the default test record document. This option is often used to choose the best image out of a series images taken of the same subject with different camera settings.	FALSE	User
File Upload Verified	Indicates that the existence of the file in the archive has been verified.	TRUE	Automatic
Picture test time	The elapsed time from the start of the experiment	FALSE	Automatic
Photographer	Identification of the person that took the picture.	TRUE	User
Upload date time	Date and time when the file was uploaded into FireTOSS	TRUE	Automatic
Synchronized with FireTOSS	Specifies if the camera had been synchronized to the data acquisition system	TRUE	User
Original file date	Date of the file that was uploaded into the archive. This date is taken from the file system of the device from which the file was uploaded.	TRUE	Automatic
Time Offset	The time difference between the camera clock and the data acquisition clock	FALSE	User
Time Offset Units		FALSE	User
Filename	################	TRUE	Automatic
Thumbnail file name	Name of the low resolution picture file stored in the archive	FALSE	Automatic
File Size	Specifies the size of the file. This value is automatically calculated by the FireTOSS upload programs.	FALSE	Automatic
Original file name	File name of the file that was uploaded into the data acquisition system. This file name is taken from the file system of the device from which the file was uploaded.	TRUE	Automatic
Use on web	Determines whether the image will be inserted into the default web page for the experiment.	FALSE	User
File Path	Alternate location for files not stored in the default archive location	FALSE	User

References

1. "D90 User's Manual," Nikon, 2008.

Scope

This instruction covers the use of stopwatches used by the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL) Examiners.

Instrument Description

GENERAL

A stopwatch is a manually operated device that measures and displays the duration of a specific event or test. Though many stopwatches contain additional functions, the functions primarily utilized by FRL Examiners are the start, stop, and reset functions on the stopwatch. Refer to the stopwatch manufacturer's documentation for detailed information concerning additional stopwatch functions.

Accuracy Requirements

FRL stopwatches are required to maintain time with a loss of no more than 1 second over a 1 hour period. This results in an accuracy of 0.028%. The stopwatches shall be functionally verified in accordance with FRL Stopwatch Functional Verification Procedures.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The assigned operator shall verify the functionality of the stopwatch prior to testing

PROCEDURE

The following is a general procedure for operation of a stopwatch.

1. Set up

1.1 Ensure that stopwatch has been functionally verified

2. Pre-Test

2.1 Ensure that operator is familiar with test procedures to ensure appropriate stopwatch operation.

3. Test

3.1 Operate the stopwatch in accordance with the test examiner's specifications.

3.2 The operability of the stopwatch shall be monitored during the test. If the stopwatch operation is in question, verify the functionality of the stopwatch before continuing use in a test.

4. Post Test

4.1 If testing is complete, reset the time displayed on the stopwatch.

Stopwatch Documentation Requirements

None

References

None

Scope

This laboratory instruction covers the use of differential pressure probes for velocity measurements in FRL experiments.

Instrument Description

GENERAL

Velocity measurements can be separated into two categories: external and internal. External velocity measurements are generally point measurements conducted in the open or near a surface. Internal velocity measurements are conducted inside pipes or ducts where the total volumetric flow rate is an important parameter. Internal velocity measurements can be performed at individual points within a pipe or duct, in which case the flow rate can be determined if the velocity profile is known. Alternatively, the average internal velocity can be measured using a probe with an array of pressure taps spaced at precise locations throughout a cross section of the duct.

Point Measurements

For point measurements in fire applications two common probe types are Pitot static tubes and bidirectional probes. Pitot static tubes are the standard probe used for many velocity measurements in clean flow environments where the direction of flow is known and consistent. Bi-directional probes, as the name suggests, can be used to measure flows in two directions and are relatively insensitive to alignment as long as the probe axis is oriented within ± 50 degrees of the direction of flow [1]. Bidirectional probes can also be used in dirty flow environments because the pressure measuring ports are larger than those in Pitot static tubes and as such are less prone to blockage from the accumulation of soot particles. These features make bidirectional probes well suited for measurements in fire environments. See TR009a for more detailed technical reference regarding point measurements.

Averaging Measurements

Averaging pressure probes are used for internal measurements and are designed to span the cross section of a pipe or duct. This type of probe is characterized by multiple pressure taps spaced at precise intervals in order to deliver a measurement that represents the average differential pressure for flow in a duct. The advantage of this type of probe is that the average velocity, and hence the flow rate, can be calculated without requiring knowledge of the velocity profile. See TR009b for more detailed technical reference regarding averaging measurements.

THEORY

Differential pressure velocity measurements are based upon Bernoulli's Equation [2]:

$$P_1 + \frac{1}{2} \quad V_1^2 + \quad gZ_1 = P_2 + \frac{1}{2} \quad V_2^2 + \quad gZ_2 \qquad (1)$$

where P is static pressure,   is density of the flowing fluid, V is velocity, g is acceleration due to gravity, and Z is the elevation. This equation can be applied to two points along a streamline as in Figure 1. If one point is taken upstream of a blunt body, where the velocity is equal to the free stream velocity, and the second point is taken as the stagnation point (where the velocity is reduced to zero), a velocity term in Eqn. (1) can be eliminated.

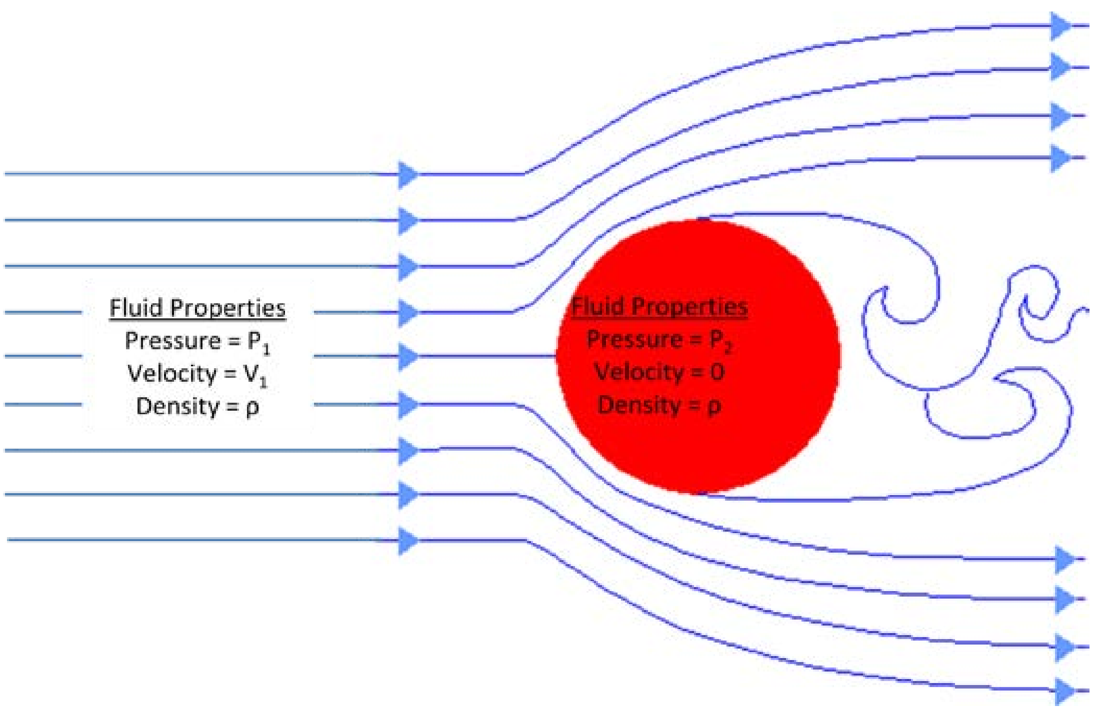


Figure 1: Flow along a streamline to a stagnation point.

Further, for a velocity probe, the assumption can be made that pressure induced by elevation difference is negligible. Under these conditions, Eqn. (1) can be reduced to:

$$P \;= \frac{1}{2} \quad V^2 \qquad (2)$$

Solving for the velocity as a function of the pressure yields:

$$V = \sqrt{\frac{2\ \ P}{\ }} \qquad (3)$$

FireTOSS Calculations

VELOCITY CALCULATION

In practice, it is desirable to express velocity in terms of readily measurable quantities such as temperature. For fluids that conform with the ideal gas law, the density,   , at any temperature, T, can be calculated from the density at a reference temperature as follows:

$$_0T_0 = \ \ T \qquad (4)$$

or, rearranging terms:

$$= \frac{_0T_0}{T} \qquad (5)$$

Substituting Eqn. (5) into Eqn. (3) yields:

$$V = \sqrt{\frac{2\ \ PT}{_0T_0}} \qquad (6)$$

or

$$V = C\sqrt{\ \ PT} \qquad (7)$$

where   *P* is the measured differential pressure, *T* is the measured temperature at the velocity probe, and *C* is calculated from $\sqrt{2/\ \ _0T_0}$ where T_0 is the reference temperature and $_0$ is the fluid density at the reference temperature. The differential pressure measured using a bidirectional probe is slightly greater than the dynamic pressure given in Eqn. (2) and a correction to C is required. Details associated with this correction can be found elsewhere [3].

UNCERTAINTY AND ACCURACY

The velocity uncertainty is a combination of the uncertainty of its components, including temperature, pressure and the correction factor, C, and is given by the following equation [4 - 6]:

$$u_C(\mathrm{V}) = \sqrt{\sum \mathrm{s_i^2 u(x_i)^2}} \qquad (9)$$

where:

$u_c(V)$ = Combined standard uncertainty of the velocity
$\mathrm{u(x_i)}$ = Standard uncertainty of each velocity component
$\mathrm{s_i}$ = Sensitivity coefficient $(\partial y/\partial x_i)$

Applying Eqn. (9) to Eqn. (7) yields:

$$u_c(V) = \left[\left(\frac{\mathrm{C}}{2}\sqrt{\frac{\mathrm{T}}{\Delta\mathrm{P}}}\right)^2 \left(\mathrm{u}(\Delta\mathrm{P})\right)^2 + \left(\frac{\mathrm{C}}{2}\sqrt{\frac{\Delta\mathrm{P}}{\mathrm{T}}}\right)^2 \left(\mathrm{u(T)}\right)^2 + \left(\sqrt{\Delta\mathrm{PT}}\right)^2 \left(\mathrm{u(C)}\right)^2\right]^{1/2} \qquad (10)$$

where:

$\mathrm{u}(\Delta\mathrm{P})$ = Standard uncertainty of differential pressure
$\mathrm{u(T)}$ = Standard uncertainty of temperature
$\mathrm{u(C)}$ = Standard uncertainty of correction factor

The velocity uncertainty calculated using Eqn. (10) is specific to a given type of probe, instrumentation and experimental configuration. Temperature uncertainty is primarily a function of the temperature sensor. For a thermocouple with special limits of error the accuracy is 1.1ºC or 0.4 % [7]. For a bidirectional probe, uncertainty in the value of C is ± 5 % [1]. Uncertainty in the pressure measurement is a function of several factors, including transducer uncertainty and probe alignment. The stated error of a MKS Baratron pressure transducer is ± 0.15 % of the reading [8]. The accuracy of a Setra model 267 pressure transducer is ± 0.4 % of full scale [9]. Probe alignment has a potential for introducing 10 % error in the velocity in extreme cases [1]. A more reasonable estimate of this error is ± 3 % for alignment within ± 15º of the flow direction.

Detailed uncertainty analyses specific to probe – transducer combinations are given in the Technical Reference documents [3,10].

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. Pressure transducers shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
4. Thermocouples shall be constructed from thermocouple wire with a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. If there is a specific experiment requirement for a different level of accuracy, then the actual measured thermocouple accuracy shall be documented in the "TC Type" input field of the data sheet.

PROCEDURE

1. Set up

1.1. The calibration marking on the pressure transducer shall be checked to confirm that the instrument is calibrated.
1.2. Pressure transducers shall be connected to the data acquisition hardware using the smallest voltage input range that will bound the output range of the transducer.
1.3. Pressure lines connected to the velocity probe shall be protected if it is anticipated that they will be exposed to excessive heat or pressure during the experiment.
1.4. Perform functional verification of:
1.4.1. Thermocouple with ambient and heat source
1.4.2. Pressure transducer with positive pressure source

2. Prior to First Test of Series

2.1. A zero pressure baseline shall be recorded with the pressure transducer prior to conducting experiments. During the baseline reading the high and low pressure ports of the pressure transducer shall be directly connected. The baseline value shall be the average pressure measured during a period with a minimum 2-minute duration.
2.2. Following the baseline test, the ports on the pressure transducer shall be opened to each of the two probe fittings.
2.3. Verify that the zero pressure baseline has been recorded on the FireTOSS data sheet.

3. Prior to each Test

3.1. Perform functional verification of the pressure transducer and thermocouple with ambient.
3.2. Update FireTOSS data sheet.

4. Test

4.1. The output of the pressure transducer and the thermocouple shall be recorded for the duration of the experiment.

4.2. When the velocity probe must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the probe was removed and the reason for instrument removal shall be recorded on the data sheet.

5. Post Test

5.1. If an instrument was taken out of service during a test, update the out of service time and out of service reason fields on the FireTOSS data sheet and redo the calculations.

5.2. After the experiment, velocity probes located in areas where they may have been damaged shall be examined for visible damage or surface dirt.

5.3. If surface dirt is observed, the accumulated soot shall be removed and lines shall be blown out with compressed air. If the probe is physically damaged, it shall be taken out of service until it has been repaired.

5.4. If conditions occurred, either during the test or following the test, that could potentially affect the performance of the instrument, a functional verification shall be performed on the pressure transducer and thermocouple.

Velocity Probe Documentation Requirements

Velocity probe usage shall be documented using the FireTOSS experiment design program. For velocity probes used with a Fire Product Collector (FPC), the required information is automatically entered when the FPC is selected in the FireTOSS experiment design program. For

The information that the user shall document for external velocity measurements using a velocity probe is shown in Table 1, which is for the . The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and column three provides a description of the information to be supplied for the parameter.

Table 1: Data Acquisition Input Parameters

Parameter	Parameter Description	Required	Input Method
Calibration Status	Automatically updated status of the pressure transducer calibration	True	Automatic
Description	Description of the location of the velocity probe.	True	User
Bar Code	FRL unique identifier for pressure transducer.	True	User
Baseline Experiment	This is the experiment ID number that contains baseline average data for this instrument. If this is specified, and a serial number is entered corresponding to a serial number in the Baseline test, the baseline pressure will be taken from that test.	False	User
Serial Number	The manufacturer provided pressure transducer serial number.	True	Automatic
Velocity Probe Description	Identifies the type of velocity probe. The coefficients used in the velocity calculations are determined by the probe type. Typical probe types are bidirectional and Pitot.	True	User Selectable
Velocity Probe Diameter	For a bidirectional probe this is inner diameter.	True	
Thermocouple Type	Identifies the type of thermocouple. Required information includes, Thermocouple type, diameter, Inconel or beaded, grounded or ungrounded.	True	
Location X	In conjunction with a diagram of the experiment set up, this parameter is used to identify the X location of the instrument.	False	User
Location Y	In conjunction with a diagram of the experiment set up, this parameter is used to identify the Y location of the instrument.	False	User
Location Z	The elevation of the probe in meters. This parameter is recommended for probes within compartments.	False	User
Orientation	Direction probe is facing.	True	User
Time Out of Service	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.	False	User
Out of Service Reason	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design	False	User
Tree ID	In conjunction with a diagram of the experiment set	False	User

Parameter	Parameter Description	Required	Input Method
	up this parameter is used to identify a horizontal or vertical traverse of instruments		
Chart	Integer, Allows the user to group instrument data onto different charts. If this parameters is left empty all the charts will contain data for all instruments. A value of -1 indicates that the data will not be shown on a chart.	False	User
Room Number	This is an integer number indicating the room number. It is used as a cross reference for instrument location.	False	User

References

1. McCaffrey, B.J., and Heskestad, G., "A Robust Bidirectional Low-Velocity Probe for Flame and Fire Applications", Combustion and Flame, 26, 125 – 127, 1976.
2. Fox, R. W., and McDonald, A. T., *Introduction to Fluid Mechanics, 3rd Edition*, Wiley, 1985.
3. ATF FRL Technical Reference, "TR009a – Differential Pressure – Point Velocity Probes."
4. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD 1993.
5. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, 2003.
6. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.
7. The Temperature Handbook, 2nd edition, Omega Engineering, Stamford, CT, 2000.
8. MKS Baratron Technical Data Sheet.
9. Setra 267 Pressure Transducer, Technical Data Sheet.
10. ATF FRL Technical Reference, "TR009b – Differential Pressure – Averaging Velocity Probes."

Scope

This Laboratory Instruction covers the use of calibration burners used in FRL experiments.

Instrument Description

GENERAL

Burners are used in experiments to produce fires of known size and configurations. Burners consist of three main components as shown in Figure 1: a fuel supply, fuel flow monitoring and controlling instrumentation (sometimes referred to as the gas train), and a generic burner. All instrumentation must be calibrated according to manufacturer and ATF specifications.

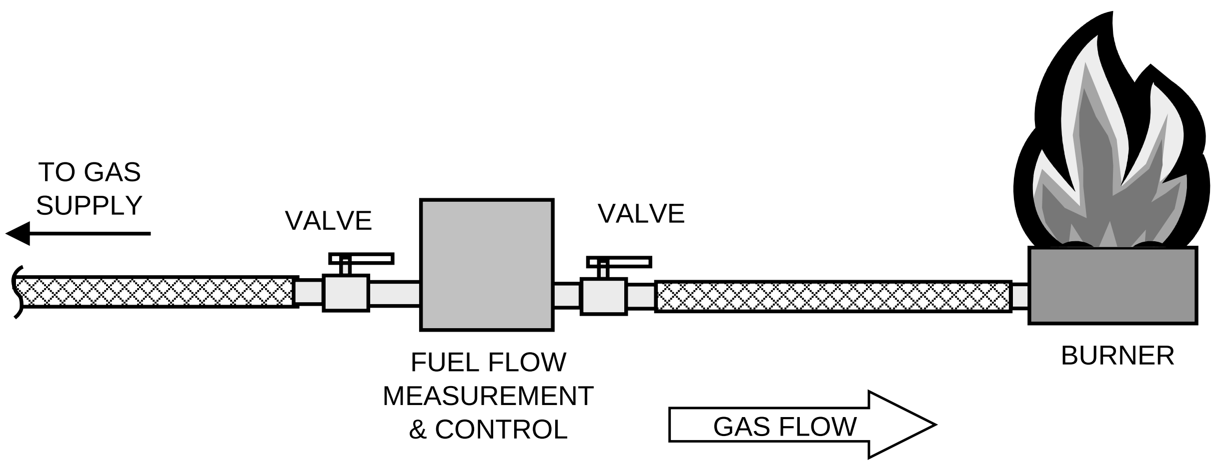


Figure 1. General Burner Components

Fuel

The primary types of fuel used in the ATF FRL are heptane liquid and natural gas, which is composed primarily of methane. Other types of fuel are equally acceptable as long as the proper gas measurement equipment and burners are used. The properties of n-heptane can be taken from relevant literature. Alternatively, properties can be measured using appropriate test methods. The properties of natural gas are calculated by the ATF FRL using a combustion calorimeter [1].

Gas Train

A gas train consists of a minimum of a flow controller and a flow rate measurement instrument. Gas trains may also contain instrumentation for measuring fluid temperature and pressure as well as various filters and valves.

There are several types of flow measurement instruments used for burners. Flow measurement instruments are not universal and must be chosen based upon the type of fuel being used.

Flow rate measurement instruments output flow rates using several different methods.

1) The flow rate can be output as an electronic signal that can be monitored by a data acquisition system
2) The instrument can have a visual flow rate indicator so that the flow rate must be recorded manually, or
3) The flow measurement instrument may have a total flow counter from which the average flow rate can be calculated by dividing by the duration between recorded measurements.

Four basic types of flow meters are described as follows:

Variable Area Flow Meters (rotameter)
Variable area flow meters, also known as rotameters, are used for both liquid and gaseous fuels. A rotameter consists of a tapered tube with an indicator inside that is pushed up by flow and pulled down by gravity. At a higher flow rate more area (between the indicator and the tube) is needed to accommodate the flow, so the indicator rises. The location of the indicator is visually compared with graduations on the tube to measure the flow rate of the fluid.

The accuracy of rotameters depends on the specific model, and is typically in the range of 2% to 5%.

Diaphragm Meters
Diaphragm meters, also known as dry test meters, are used for gaseous fuels. Diaphragm meters are positive-displacement devices that have fixed-volume measurement compartments formed by a two-sided convoluted diaphragm. A small pressure drop across the meter causes it to cycle. The compartments then alternately fill with gas at the inlet and empty at the outlet. By counting the number of cycles, the meter provides a measure of gas volume [2].

The accuracy of these flow indicators depends on the specific model, and is typically on the order of 1% [2].

Laminar Flow Elements
Laminar flow elements are typically used for gas flow measurements. In these types of meters, the volumetric flow rate is determined by creating a pressure drop across a unique internal restriction, known as a Laminar Flow Element (LFE), and measuring differential pressure across it. The restriction is designed so that the gas molecules are forced to move in parallel paths along the entire length of the passage; hence laminar (streamline) flow is established for the entire range of operation of the device. Unlike other flow measuring devices, in laminar flow meters the relationship between pressure drop and flow is linear [3].

The accuracy of these flow indicators depends on the specific model, and is typically on the order of 0.5% to 1%. [3].

Ultrasonic Flow Meters
Ultrasonic flow meters are used for liquids and gases. These types of meters measure transit times of ultrasonic pulses passing through a fluid. Transmitters and receivers are located in multiple locations, enabling measurement of both upstream and downstream transit times. The difference in transit times of the downstream-directed pulses and the upstream-directed pulses is directly proportional to the velocity of the fluid being measured.

The accuracy of these flow indicators depend on the specific model, and are typically on the order of 1% [4].

Flow Controllers
Manual and automated flow controllers are used at the FRL. Manual flow controllers are often simple gate valves placed in line with the gas train or they can be pressure regulating devices. Automated flow controllers consist of a remote controlled flow controller whose position is regulated based upon feedback from the flow rate measurement. Automated flow controllers can be integral to flow measurement device as in the case of mass flow controllers, or they can be separate devices that are controlled by a computer program that adjusts the flow controller based upon readings from the flow meter.

The accuracy of these controllers depends on the specific model, and is typically on the order of 0.5% to 1%. [3].

Burners

Burners are designed in a wide variety of shapes and sizes depending on the intended purpose. Burners consist of a minimum of a connection to a fuel supply and a means for distributing the fuel. The following provides a brief description of the three primary types of burners used at FRL.

Sand Burners
Sand burners are used for gaseous fuels. Sand burners are constructed from open top noncombustible containers filled with an aggregate such as sand, gravel, or ceramic chips. A gas supply is located within the aggregate in a location such that the gas flux at the open surface is uniform. See technical reference TR010A for further information regarding sand burners.

Tube Burners
Tube burners are used for gaseous fuels. They are constructed from metal tubing with a fuel supply attached to one end and one or more holes at the locations where flame is desired. See technical reference TR010B for further information regarding tube burners.

Atomizing Spray Burners
Atomizing spray burners are used for liquid fuels. The function of the spray burner is to transform the liquid into a flammable mist composed of small droplets of flammable liquid that will burn efficiently. Each spray burner is typically rated for a narrow range of flow rates. Therefore, the number of burners used in a test will depend upon the desired fire size.

FireTOSS Calculations

HEAT RELEASE RATE CALCULATION

The heat release rate (HRR) of the fire is calculated using the flow rate of the fuel and the combustion properties of the fuel. Equation (1.1) expresses the HRR in terms of the mass flow rate of the fuel.

$$\dot{Q} = \times \dot{m} \times H_{C,net} \qquad (0.1)$$

Equation (1.2) expresses the HRR in terms of the volumetric flow rate of the fuel.

$$\dot{Q} = \times \times \dot{V} \times H_{C,net} \qquad (0.2)$$

where

$\dot{Q}$ = heat release rate of the burner (kW)
= combustion efficiency of the fuel (assumed to be 1 for gaseous fuels).
$\dot{m}$ = mass flow rate of the fuel (kg/s)
$H_{C,net}$ = net heat of combustion of the fuel (kJ/kg)
= density of the fuel (kg/m³)
$\dot{V}$ = volumetric flow rate of the fuel (m³/s)

Uncertainty and Accuracy

The heat release rate uncertainty is a combination of the uncertainty of its components, including flow, density and heat of combustion, among other factors, and is given by the following equation [5 - 7]:

$$u_C(\dot{Q}) = \sqrt{\sum s_i^2 u(x_i)^2} \quad (0.3)$$

where:

$u_c(\dot{Q})$ = Combined standard uncertainty of the burner heat release rate
$u(x_i)$ = Standard uncertainty of each heat release rate component
s_i = Sensitivity coefficient $(\partial y/\partial x_i)$

Applying Eq. 1.3 to Eq. 1.2 yields:

$$u_c(\dot{Q}) = \begin{bmatrix} (\eta\rho_{NG}\Delta H_{c,net})^2 \left(u(\dot{V}_{NG})\right)^2 + (\eta\dot{V}\Delta H_{c,net})^2 \left(u(\rho_{NG})\right)^2 \\ +(\eta\rho_{NG}\dot{V})^2 \left(u(\Delta H_{c,net})\right)^2 + (\rho_{NG}\dot{V}\Delta H_{c,net})^2 \left(u(\eta)\right)^2 \end{bmatrix}^{1/2} \quad (0.4)$$

where:

$u(\eta)$ = Standard uncertainty of Combustion Efficiency
$u(\dot{V}_{NG})$ = Standard uncertainty of Natural Gas Volumetric Flow Rate
$u(\rho_{NG})$ = Standard uncertainty of Natural Gas Density
$u(\Delta H_{c,net})$ = Standard uncertainty of Natural Gas Heat of Combustion

The heat release rate uncertainty calculated using Equation 1.4 is specific to a given burner configuration. The uncertainty in the fuel's net heat of combustion is dependent on the fuel type and the fuel source. The burning efficiency of the fuel is dependent on many factors including the burner configuration, the fuel type, and the fuel flow rate. To calculate a burner's burning efficiency an analysis must be done using as inputs the carbon monoxide and soot generation rates and a measure of the unburned hydrocarbons. The uncertainty of the flow rate measurement is dependent on the measuring instrument and is often not a constant but instead a function of several factors including the flow rate.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. Fuel flow rate instrument shall be calibrated and the calibration status shall be marked in accordance with FRL calibration procedures.
3. If data acquisition is used, the data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
4. If pressure transducers are used in the heat release rate calculation, the transducers shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
5. The fuel flow rate instrument shall be selected to represent the test conditions.

PROCEDURE

The following is the general procedure that shall be followed for all burners regardless of type.

1. Set up

1.1 The calibration marking on the fuel flow measurement instrument shall be checked to confirm that the instrument is calibrated.

1.2 If data acquisition is used, the fuel flow measurement instrumentation shall be connected to the data acquisition hardware using the smallest input range that will bound the output range of the instrument.

1.3 Connect the flow controller to the fuel supply and outlet (i.e. burner, nozzle, etc.)

1.4 Verify that there are no leaks in the fuel supply lines.

1.5 Ensure that adequate fuel is available.

2. Pre-Test

2.1 The functionality of the fuel igniter (pilot) shall be confirmed.

3. Test

3.1 The burner ignition status shall be monitored and a person shall be in a position to shut off the fuel flow if the burner does not ignite or if the burner is extinguished during the test.

3.2 The fuel flow rate shall be monitored.

4. Post Test

4.1 Shut off valves from the fuel supply shall be closed.

Burner Documentation Requirements

When using a calibration burner during an experiment, there are two instruments in FireTOSS that must be used: a Gas Train and a Burner. Selecting one instrument automatically selects the other. Each instrument has its own input parameters, which are listed below in Table 1 and Table 2.

Table 1 – Gas Train Data Acquisition Input Parameters

Parameter	Required	Input Method
Status - Calibration	TRUE	Automatically Updated
Description	TRUE	User Input from List
Heat release rate E factor description	TRUE	User Input from List
Time out of service (s)	FALSE	User Input
Out of service reason	FALSE	User Input
Baseline time	FALSE	Automatically Updated
Fuel Heat of Combustion	TRUE	Automatically Updated
Fuel Density	TRUE	Automatically Updated
Mezzanine Pressure Baseline value	FALSE	Automatically Updated
Mezzanine Temp Baseline value	FALSE	Automatically Updated
NG Specific Gravity Baseline value	FALSE	Automatically Updated
Mezzanine Pressure data (Pa)	FALSE	Automatically Updated
NG Pipe Pressure data (Pa)	FALSE	Automatically Updated
Mezzanine Temperature Data (C)	FALSE	Automatically Updated
NG Temperature Data (C)	FALSE	Automatically Updated
Specific Gravity Data	FALSE	Automatically Updated
Pipe Fuel Density Data (kg/m^3)	FALSE	Automatically Updated
Average Pipe Fuel Density	FALSE	Automatically Updated
Volumetric Flow Rate Data (m^3/s)	FALSE	Automatically Updated
Heat Release Rate Data (kW)	FALSE	Automatically Updated
Cumulative Heat Release (kJ)	FALSE	Automatically Updated
MFC Bar Code	TRUE	Automatically Updated
MFC Serial number	TRUE	Automatically Updated
WS Bar Code	TRUE	Automatically Updated
WS Serial number	TRUE	Automatically Updated
CC Bar Code	TRUE	Automatically Updated
CC Serial number	TRUE	Automatically Updated
PT Bar Code	FALSE	Automatically Updated
PT Serial Number	FALSE	Automatically Updated

Table 2 – Burner Data Acquisition Input Parameters

Parameter	Required	Input Method
Burner Type	TRUE	User Input from List
Burner Dimensions	TRUE	Automatically Updated

References

1. ATF FRL Instruction, “Laboratory Instruction LI018: Combustion Calorimeter.”
2. American Meter Company, http://www.elster-americanmeter.com/en/diaphragm_meters.html
3. “16 Series Mass and Volumetric Flow Controllers, Operating Manual,” Alicat Scientific, Tucson, Arizona.
4. “Field Manual: System 1010N NEMA 4X Clamp-On Multi-Function Flowmeter,” Controlotron Corp., 2003.
5. Taylor, B. N., & Kuyatt, C. E., “NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results,” National Institute of Standards and Technology, Gaithersburg, MD 1993.
6. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., “Special Publication 1007,” National Institute of Standards and Technology, 2003.
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Scope

This Laboratory Instruction covers use of the ATF FRL's large-scale fire products collectors (FPCs).

Instrument Description

GENERAL

A large-scale FPC collects smoke and other products of combustion generated during fire experiments. Generally, a FPC consists of a collection hood connected to an exhaust duct, with air drawn through the duct by one or more variable speed fans. A FPC serves two purposes:

1) To remove combustion products from a laboratory space, and
2) To optimize the flow field for measurement and quantitative analyses of the combustion products.

INSTRUMENTATION

The FPCs in the ATF FRL are equipped with instrumentation to measure gas species concentrations, velocity, and smoke concentration. Additional instruments, not located in the FPCs exhaust ducts, are used to measure the mass of the burning item and the ambient conditions in the laboratory.

Gas Species Concentration Measurement

Gas species concentrations are measured by extracting a continuous sample from the exhaust duct, conditioning the sample by removing particulates and moisture, and delivering the sample at the required pressure and flow rate to a set of gas analyzers. Sample extraction is performed using a gas sampling probe located in the FPC exhaust duct; the sample conditioning equipment and gas analyzers are located in a remote instrument rack.

Gas Sampling Probe

The gas sampling probe is used to draw samples from across the full diameter of the exhaust duct. For large diameter ducts two probes, positioned at 90° spacing, may be used. The sampling probe is positioned downstream of an orifice where the gases and other product species are well mixed. The probe consists of a stainless steel tube with 2–4 mm diameter sampling holes positioned at regular intervals across the length of the duct. The sampling probe(s) is installed with the sampling holes facing downstream. The gas sample is drawn from both ends of the probe(s) and transported to the gas analysis rack through a single gas sampling line. Details on the layout of the gas sampling probes are provided in the Technical Reference for each FPC.

Gas Analysis Rack

The gas analysis rack contains instrumentation to draw a continuous sample from the duct, condition the sample, and measure the concentrations of oxygen (O_2), carbon dioxide (CO_2) and carbon monoxide (CO) in the gas sample. The gas sample is pre-treated prior to reaching the analyzers to remove particulate materials and moisture that can damage the analyzers. This pre-treatment is accomplished through a series of particulate filters and sample driers (including cold traps, desiccant columns and / or membrane dryers). The concentrations of O_2, CO_2, and CO are measured by the gas analyzer [1, 2].

Velocity Measurement

Gas velocity measurements in the FPCs are performed with differential pressure probes [3] because of their ruggedness and simplicity. Differential pressure probes are based on the Bernoulli Principle, which relates velocity to the difference between the total and static pressure in a flow field [4]. Velocity is calculated based on measured differential pressure and the temperature of the gases at the probe location. The ATF FRL uses both bi-directional probes [5] and averaging pressure probes [6].

Bi-Directional Probe

A bi-directional probe is used to make point velocity measurements in the exhaust duct [5]. The probe is positioned at a fixed radial location in the duct with the axis of the probe in line with the flow direction. Due to the fact that the velocity profile is generally not flat across the duct cross section, a correction factor is applied to determine the average velocity based on the value measured at a single location. The average velocity is then used to calculate both the volumetric flow rate and the mass flow rate of the gases in the exhaust duct.

Averaging Pressure Probe

Averaging pressure probes are designed to span the cross section of a pipe or duct [6]. This type of probe is characterized by multiple pressure taps spaced at precise intervals in order to deliver a measurement that represents the average differential pressure for flow in a duct. The advantage of this type of probe is that the average velocity, and hence the flow rate, can be calculated without requiring knowledge of the velocity profile.

Differential Pressure Transducers

Differential pressure transducers are used to measure the differential pressure between the high and low pressure sides of the velocity probes. The pressure measurement is corrected for the zero pressure differential offset, which is measured by cross porting the high and low pressure ports and measuring the transducer output.

Thermocouple

In addition to differential pressure, temperature measurements are required to calculate velocity. The FPCs use Inconel-sheathed, K-type thermocouples to measure temperature at the differential pressure probe locations [7].

Smoke Measurement

Smoke is measured in the FPCs using optical density meters (ODMs) [8, 9]. An ODM uses an optical technique in which a beam of light is passed across the exhaust duct and attenuated by smoke particles in the flow field. The smoke concentration is calculated based on the reduced light intensity across the fixed path. Smoke is measured with both laser and white-light ODMs in the FPCs. The ODM access port is located downstream of the velocity and gas sampling probes. The laser ODMs for the FPCs use low-power Helium-Neon (HeNe) lasers that emit continuous light at 632 nm. The white-light ODMs for the FPCs use broad-band visible (white) light source.

Mass Measurement

Additional quantitative data, such as the effective heat of combustion, the species yields (CO and CO_2), and smoke yield, can be obtained from a FPC by measuring the mass of an object as it burns. A range of weighing devices may be used with a FPC depending on the mass of the object and the desired measurement sensitivity [10].

Ambient Conditions Measurement

Ambient conditions within the laboratory space are monitored so that the moisture content of the ambient air can be calculated. The mole fraction of water in the ambient air is an input used for the calculation of heat release rate (HRR). Weather stations located throughout the ATF FRL monitor and record ambient conditions of temperature, barometric pressure and relative humidity [11].

REPORTED QUANTITIES

Fire Products Collectors are designed to provide four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production. When used in conjunction with a weighing device, such as a load cell, the mass loss rate (MLR) of the burning object can be calculated. Gas species yields, smoke yield, and the effective heat of combustion of a burning item can then be calculated based on the MLR.

Heat Release Rate

The heat release rate (HRR) is a measure of the amount of heat evolved from an item per unit of time. HRR measurements are based on the principle of oxygen consumption calorimetry [12]. The principle is based on the fact that the chemical energy released in a fire, per unit mass of oxygen consumed for complete combustion, is relatively constant for many organic fuels [13, 14]. The ATF FRL calculates HRR based on the oxygen consumption principle using measurements of oxygen, carbon monoxide, and carbon dioxide [12].

Convective Heat Release Rate

The convective heat release rate (CHRR) of a fire is the rate at which energy is transferred to the gases that flow through the FPC. The CHRR is an important parameter in correlations for fire plumes and sprinkler / detector activation. It can also be used to determine the radiative fraction of a fire. The CHRR is calculated as the enthalpy rise of gases flowing through the FPC and is based on the temperature and velocity measurements in the exhaust duct.

Mass Loss Rate

The mass loss rate (MLR) is a measure of the decrease in mass of an object as it burns. The MLR is used in conjunction with other measurements to calculate gas species yields, smoke yield, and the effective heat of combustion of a burning item.

Gas Species Production

The gas species released during a fire can be expressed in various ways, including total mass production (kg), mass production rate (kg/s), or in terms of a yield (kg/kg specimen burned). These metrics are calculated based on the measured concentrations of the combustion gas species and the mass flow rate in the FPC exhaust stream. The yield for a particular combustion gas is the ratio of the mass of the gas species produced to the mass lost by the burning object [12]. The total mass of combustion gas released, and the rate of gas release, are important parameters for fire hazard analyses. Gas species yields are important parameters for fire modeling applications.

Smoke Production

Similar to gas species production, smoke production can be expressed in various ways, including the total smoke released (TSR, m^2), rate of smoke release (RSR, m^2/s), or in terms of a yield (kg/kg specimen burned). RSR is calculated as the product of the light extinction coefficient, k (m^{-1}), and the FPC volumetric flow rate, $\dot{V}$ (m^3/s). TSR is an integration of the RSR over the test duration. RSR and TSR are used to compare the smoke production from burning items and determine the associated fire hazard. Smoke yield is the ratio of the mass of smoke produced to the mass lost by the burning object. Smoke yield is an important parameter for fire modeling applications. Optical density per meter (D, m^{-1}) is proportional to the extinction coefficient.

Effective Heat Of Combustion

The effective heat of combustion is the amount of heat generated by an object per unit mass lost during a fire [15]. It is calculated by dividing the HRR calculated by the FPC by the mass loss rate (MLR) of the burning object.

CALIBRATION

Calculation of HRR relies on the use of a calibration factor, or C Factor [16]. The C Factor is determined by placing a calibration burner [17] beneath the FPC and controlling the fuel flow to the burner through a series of well-characterized steps. The type of calibration burner is selected based on the desired maximum HRR needed for the calibration. The C Factor is defined as the ratio of the burner HRR to the calculated HRR based on the FPC measurements.

FireTOSS Calculations

HEAT RELEASE RATE

The HRR is calculated using the oxygen consumption principle based on the measurement of oxygen, CO and CO_2 concentrations, in addition to velocity [12]:

$$HRR = C\left[E\phi - \left(E_{CO} - E\right)\frac{1-\phi}{2}\frac{X_{CO}}{X_{O_2}}\right]\left(\frac{\dot{m}}{1+\phi(\alpha-1)}\right)\left(\frac{MW_{O_2}}{MW_{air}}\right)\left(1 - X_{H_2O}^0\right)X_{O2}^0 \quad \textbf{(1)}$$

where

C	= FPC calibration factor or “C Factor”
HRR	= measured heat release rate (kW)
	= oxygen depletion factor; a measure of the amount of oxygen that has been removed from the ambient air by the combustion process; Eq. (2)
E	= net heat release per unit of O_2 consumed (a property of the fuel being burned); Values of *E* for various fuels are provided in Table 1; Appendix A explains how these values were determined.
E_{CO}	= net heat release per unit of mass of O_2 consumed for combustion of CO to CO_2, E_{CO} = 17,600 kJ/kg [12]
$\dot{m}$	= mass flow rate through the exhaust duct (kg/s); Eq. (5)
	= gas volumetric expansion factor (a property of the fuel being burned); Values of for various fuels are provided in Table 1; Appendix A explains how these values were determined.
MW_{O_2}	= molecular weight of oxygen; MW_{O_2} = 32.00 kg/kmol [12]
MW_{air}	= molecular weight of air; Eq. (8)
X_{O_2}	= measured mole fraction of oxygen
X_{CO}	= measured mole fraction of carbon monoxide
$X_{O_2}^0$	= ambient mole fraction of oxygen
$X_{H_2O}^0$	= ambient mole fraction of water; Eq. (6)

Table 1. Properties of Fuel Gases

Fuel	**E** (kJ/g O_2)	( )
Default	13.10	1.105
Methane	12.54	1.105
Propane	12.77	1.040
Natural Gas	12.55	1.084

The oxygen depletion factor ( ) is calculated as:

$$= \frac{X^0_{O_2}\left(1 \quad X_{CO_2} \quad X_{CO}\right) \quad X_{O_2}\left(1 \quad X^0_{CO_2}\right)}{X^0_{O_2}\left(1 \quad X_{O_2} \quad X_{CO_2} \quad X_{CO}\right)} \qquad \textbf{(2)}$$

where

X_{CO_2} = measured mole fraction of CO_2

$X^0_{CO_2}$ = ambient mole fraction of CO_2

Mass Flow Rate

The mass flow rate ($\dot{m}$) in the exhaust duct is calculated based on the velocity of the gas through the duct [3]. The velocity of the exhaust gases is used to determine the volumetric flow of the gases ($\dot{V}$) from

$$\dot{V} = k_f vA \qquad \textbf{(3)}$$

where

k_f = empirical velocity profile shape factor that relates the average velocity across the exhaust duct to the measured velocity; see the Technical Reference for each FPC for the appropriate value.
A = area of the exhaust duct (m^2)
v = measured velocity in the exhaust duct (m/s)

The exhaust mass flow rate ($\dot{m}$) is calculated as

$$\dot{m} = \dot{V} \quad \textbf{(4)}$$

Using the Ideal Gas Law, assuming dry air at 1 atm, the mass flow rate equation becomes

$$\dot{m} = \dot{V}\frac{353.05}{T} \quad \textbf{(5)}$$

<u>Water Vapor</u>

The ambient mole fraction of water in ambient air ($X^0_{H_2O}$) is calculated from [12]:

$$X^0_{H_2O} = \frac{RH}{100}\frac{P_s(T_0)}{P_0} \quad \textbf{(6)}$$

where

RH = relative humidity (%)
P_s = saturation pressure of water at T_0 (Pa); Eq. (7)
T_0 = ambient temperature (K)
P_0 = atmospheric pressure (Pa)

The saturation pressure of water as a function of the ambient temperature is calculated from:

$$\ln(P_s) = 23.2 \quad \frac{3816}{(\quad 46 + T_0)} \qquad \text{-or-} \qquad P_s = e^{23.2 \quad \frac{3816}{(\quad 46+T_0)}} \quad \textbf{(7)}$$

The molecular weight of air is corrected for the moisture content according to:

$$MW_{air} = MW_{air,dry}\left(1 - X^0_{H_2O}\right) + MW_{H_2O}X^0_{H_2O} \quad \textbf{(8)}$$

where

MW_{air} = molecular weight of air; used in Eq. 1
$MW_{air,dry}$ = molecular weight of dry air (29 g mol^{-1}) [12]
MW_{H_2O} = molecular weight of water (18 g mol^{-1}) [12]
$X^0_{H_2O}$ = ambient mole fraction of water; calculated from Eq. (6)

CONVECTIVE HEAT RELEASE RATE

The CHRR of a fire is the rate at which energy is transferred to the gases that flow through a control volume surrounding the fire. This can be expressed mathematically by the First Law of Thermodynamics for a control volume. For a system with a single inlet and exit under steady state conditions, with no work and negligible changes in kinetic and potential energy, the CHRR can be expressed as [18]:

$$\dot{Q}_c = \dot{m}\left(h_2 - h_1\right) \quad \textbf{(9)}$$

where

$\dot{Q}_c$ = convective heat release rate (kW)
$\dot{m}$ = mass flow rate in the exhaust duct (kg/s); Eq. (5)
h_2 = enthalpy at the exit of the control volume; Eq. (11)
h_1 = enthalpy at the inlet of the control volume; Eq. (11)

The enthalpy of air is calculated from the measured temperature using a polynomial expression [19, 20]:

$$h(T) = \left(\alpha T + \beta\frac{T^2}{2} + \gamma\frac{T^3}{3} + \delta\frac{T^4}{4} + \varepsilon\frac{T^5}{5}\right) \quad \textbf{(10)}$$

where

h(T) = enthalphy of air (kJ/kg)
T = air temperature (K)
a = 1.0595
b = -4.8068E-4
g = 1.234E-6
d = -8.9161E-10
e = 2.1957E-13

The inlet enthalpy, h_1, is characterized by the average temperature measured prior to the start of the test. It is assumed that this is the condition of the air entering the control volume throughout the duration of experiment. The exit enthalpy, h_2, is computed using the FPC exhaust temperature measurement.

MASS LOSS RATE

When a weighing device is used, the mass loss rate (MLR) of a burning object can be calculated as an average value for the entire test duration (or a portion thereof), or as a time-varying value. The average MLR for the test duration is computed as follows:

$$\dot{m}_{f,avg} = \frac{m_n - m_0}{t_d} \quad \textbf{(11)}$$

where

$\dot{m}_{f,avg}$ = average mass loss rate of burning object (kg/s)
m_n = final mass of burning object (kg)
m_0 = initial mass of burning object (kg)
t_d = test duration (s)

Anomalies at the beginning or end of a test may cause the average mass loss rate for the test duration to be skewed. For example, if a test is allowed to continue for an extended time after mass loss of the burning object has ceased, the average mass loss rate calculated in Eq. (11) will be artificially low. To address this potential issue, an average mass loss rate is also computed during the period when 10 percent to 90 percent of the total mass loss has occurred. ASTM E1354 uses this approach to report the mass loss rate from small-scale oxygen consumption calorimeter experiments [21]. The average mass loss rate of a burning object during the period when 10 percent to 90 percent of the total mass loss occurred is calculated as follows:

$$\dot{m}_{f,avg,1090} = \frac{m_{10} - m_{90}}{t_{90} - t_{10}} \qquad \textbf{(12)}$$

where

$\dot{m}_{f,avg,1090}$= average mass loss rate of burning object during the period when 10 percent to 90 percent of the total mass loss occurred (kg/s)
m_{10} = mass of burning object when 10 percent of total mass loss occurred (kg)
m_{90} = mass of burning object when 90 percent of total mass loss occurred (kg)
t_{10} = time at which 10 percent of total mass loss occurred (s)
t_{90} = time at which 90 percent of total mass loss occurred (s)

The time varying mass loss rate is calculated using a least-squares linear regression through the given point and a total of *n* surrounding points:

$$\dot{m}_f(t) = -\frac{(\sum t * \sum m) - (n * \sum m * t)}{(\sum t * \sum t) - (n * \sum t * t)} \qquad \textbf{(13)}$$

where

$\dot{m}_f(i)$ = mass loss rate of burning object at time *t* (kg/s)
m = mass of burning object (kg)
t = time (s)
n = number of data points used in the linear regression calculation

GAS SPECIES PRODUCTION

The gas species mass production rate is calculated as [16 ,22]:

$$\dot{m}_x = \dot{m}(X - X_0)\left(\frac{M_x}{M_a}\right) \quad \textbf{(14)}$$

where

$\dot{m}_x$ = mass production rate of species *x* (kg/s)
$\dot{m}$ = mass flow rate through the exhaust duct (kg/s); Eq. (5)
X = species mole fraction during an experiment
X_0 = species mole fraction pre-test baseline value.
M_x = molecular weight of species *x* (kg/kmol)
M_a = molecular weight of air (29 kg/kmol)

The total mass produced is calculated by integrating the mass production rate over the test duration:

$$m_x = \int \dot{m}_x \, dt$$

where

m_x = total mass of species *x* produced (kg)

The gas yield can be calculated as an average value for the entire test duration, or as a time-varying value. The average gas yield is computed as follows:

$$f_{x,avg} = \frac{m_x}{m_0 - m_n} \quad \textbf{(15)}$$

where

$f_{x,avg}$ = average gas yield for species *x* (kg/kg)
m_n = final mass of burning object (kg)
m_0 = initial mass of burning object (kg)

The time-varying gas yield $(f_x(t))$ is calculated as the ratio of the gas species mass production rate and the time-varying MLR of the burning object:

$$f_x(t) = \frac{\dot{m}_x(t)}{\dot{m}_f(t)} \qquad \textbf{(16)}$$

where

$f_x(t)$ = gas yield of species *x* at time *t* (kJ/kg)
$\dot{m}_x(t)$ = mass production rate of species *x* at time *t* (kg/s);
$\dot{m}_f(t)$ = mass loss rate of burning item at time *t* (kg/s); Eq. (13)

SMOKE PRODUCTION

Smoke production is quantified based on optical smoke measurements, which measure the attenuation of light as it passes through a particulate and gaseous medium. Light absorption by gas molecules is characterized by an absorption coefficient; light scattering by particulates is characterized by a scattering coefficient. These combine to produce an extinction coefficient, k . The extinction coefficient is a proportionality coefficient that relates the differential change in light intensity as it passes through a medium [23]:

$$dI = k\ I\ dL \qquad \textbf{(17)}$$

where

I = spectral light intensity
k = extinction coefficient (m^{-1})
L = path length that the light passes through a medium (m)

Equation (17) can be rearranged and integrated to produce:

$$\ln \frac{I_{\lambda,L}}{I_{\lambda,0}} = -\int_0^L k_\lambda dL \qquad \textbf{(18)}$$

In a uniform medium, in which k does not vary along the path, Eq. (18) simplifies to:

$$k = \frac{1}{L} \ln \frac{I_{,0}}{I_{,L}} \qquad \textbf{(19)}$$

In this expression $I_{,0}$ is the intensity of the light at its source, and $I_{,L}$ is the intensity of the light reaching a detector at the end of the path. Equation (19) applies strictly to monochromatic (laser) light, however it is often generalized for use with broadband light sources, such as white light, by removing the spectral dependence. Additionally, a correction factor, f, is applied to account for nonlinearities in the measurement system:

$$k = f\frac{1}{L}\ln\frac{I_0}{I_L} \quad \textbf{(20)}$$

The correction factor f is calculated from the measured intensity I_L through a filter with known optical density [24]. The optical density per meter, *D*, (sometimes referred to as simply the optical density) is calculated as follows:

$$D = f\frac{1}{L}\log_{10}\frac{I_0}{I_L} \quad \textbf{(21)}$$

The optical density per meter is related to the extinction coefficient according to D = k/2.3.

Equation (20) is used to calculate the extinction coefficient for both laser and white light measurements. The rate of smoke release (RSR, m^2/s) is then calculated as the product of the extinction coefficient and the air volumetric flow rate [16, 22]:

$$RSR = k\dot{V} \quad \textbf{(22)}$$

By integrating Eq. (21) over the entire test duration, the total smoke released (TSR) is obtained [16, 22]:

$$TSR = \int RSR\ dt \quad \textbf{(23)}$$

The average smoke yield ($f_{s,avg}$) is used to quantify smoke production in terms of a mass ratio, similar to the gas species yields, when mass loss of the burning object is known [25]:

$$f_{s,avg} = \frac{m_s}{m_f} = \frac{\frac{1}{\sigma_s}TSR}{m_0 - m_n} \quad \textbf{(24)}$$

where the integral is taken over the entire test duration, and

σ_s = specific extinction coefficient, 8.7E3 m^2/kg [26]
m_n = final mass of burning object (kg)
m_0 = initial mass of burning object (kg).

The time-varying smoke yield is calculated as follows:

$$f_s(t) = \frac{\frac{1}{\sigma_s}RSR}{\dot{m}_f(t)} \quad \textbf{(25)}$$

where

$\dot{m}_f(t)$ = mass loss rate of burning item at time *t* (kg/s); Eq. (13).

EFFECTIVE HEAT OF COMBUSTION

The effective heat of combustion is expressed by the following general relationship between the HRR and the MLR of a burning item [15]:

$$\Delta h_c = \frac{HRR}{MLR} \quad \textbf{(26)}$$

where

Δh_c = effective heat of combustion (kJ/kg)
HRR = measured heat release rate (kW)
MLR = mass loss rate (kg/s)

The effective heat of combustion can be computed as an average value for the entire test duration, or as a time-varying value. The average effective heat of combustion is computed as follows:

$$\Delta h_{c,avg} = \frac{\int HRR\, dt}{m_0 - m_n} \quad \textbf{(27)}$$

where the integral is taken over the entire test duration, and

$\Delta h_{c,avg}$ = average effective heat of combustion for the test (kJ/kg)
HRR = measured heat release rate (kW)
m_n = final mass of burning object (kg)
m_0 = initial mass of burning object (kg)

The time-varying effective heat of combustion is computed as follows:

$$\Delta h_c(t) = \frac{HRR(t)}{\dot{m}_f(t)} \quad \textbf{(28)}$$

where

$\Delta h_c(t)$ = effective heat of combustion at time *t* (kJ/kg)
$HRR(t)$ = measured heat release rate at time *t* (kW); Eq. (1)

$\dot{m}_f(t)$ = mass loss rate of burning item at time t (kg/s); Eq. (13)

CALIBRATION FACTOR

The calibration factor, or C Factor, is determined by calculating the average HRR of the calibration burner and the FPC during each step. The HRR of the calibration burner is calculated according to its Laboratory Instruction [17] and the HRR of the FPC is calculated according to Equation (1).

A least squares linear regression analysis is performed on the average heat release rates of the burner and FPC. The burner data is plotted with respect to the measured FPC data; the C Factor is the slope of the linear regression line. Appendix B contains an example C Factor determination.

Uncertainty and Accuracy

The uncertainty of the FPCs was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [27], NIST Technical Note 1297 [28], and the NIST Uncertainty Workshop [29]. The combined standard uncertainty of a FPC is a combination of the uncertainty of its components given by the following equation:

$$u_c = \sqrt{\sum \mathrm{s_i^2 u(x_i)^2}} \qquad \textbf{(29)}$$

where:

u_c = Combined standard uncertainty
$\mathrm{u(x_i)}$ = Standard uncertainty of each component
$\mathrm{s_i}$ = Sensitivity coefficient $(\partial/\partial \mathrm{x_i})$

Uncertainty is specific to the instrumentation used in each FPC, and is therefore documented in the Technical Reference for the FPC.

Operating Instructions

A FPC is a system of instruments, and the requirements and procedures for the individual instruments apply to the FPC [1, 3, 7, 8, 10, 11, 17]. These requirements and procedures will not be repeated in this Laboratory Instruction.

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. All FPC instruments used in the experiment shall be calibrated or functionally verified and marked with the calibration/verification status in accordance with FRL procedures.
3. The laboratory condition station selected for the experiment shall be in close proximity to the FPC.

4. The FPC shall be selected based on the anticipated fire size and the desired accuracy of the measurement.
5. A HRR calibration experiment shall be conducted prior to each series of FPC experiments, and within 30 days of any test within the series.

PROCEDURE

1. **Setup**
   a. The calibration/functional verification marking on all FPC instruments used in the experiment shall be checked to confirm that the instrument is calibrated / verified.
   b. All FPC instruments shall be connected to the data acquisition hardware utilizing the smallest voltage input range that will bound the output range of the instrument.

2. **Calibration**
   a. A calibration experiment shall include at least three (3) heat release rate steps.
   b. The first HRR step shall be 0 kW.
   c. The maximum HRR step shall be selected based on the anticipated fire size.
   d. The calibration factor (C Factor) shall be between the values of 0.95 and 1.05.
   e. The calibration factor (C Factor) shall not vary by more than ±5 percent from the previous calibration.
   f. If the CFactor does not meet the requirements in (d) or (e), the system shall be checked for problems. Once the problems have been corrected, a new calibration experiment shall be conducted.

3. **Prior to Each Test**
   a. Perform functional verification of any FPC instrument for which it is required.

4. **During the Test**
   a. The output of each FPC instrument used in the experiment shall be recorded for the duration of the experiment.
   b. Exception – When any FPC instrument must be removed prior to the end of the experiment due to experiment design or impending damage, the elapsed time at which the instrument was removed and the reason for removal shall be recorded.

5. **Post Test**
   a. If an instrument was taken out of service during an experiment, the out of service time and reason shall be recorded. Calculations shall be repeated with the updated out of service time.
   b. If conditions occurred during or following the experiment that could potentially affect the performance of a FPC instrument, a functional verification of that instrument shall be performed.

Documentation Requirements

Use of the FPCs shall be documented using the FireTOSS experiment design program. The information that the user shall document about the FPC is shown in Table 2. The first column in Table 2 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 2 shows whether the parameter is required in all cases, and column three describes the method by which the field for each parameter is filled.

Table 2: FPC Data Acquisition Input Parameters

Parameter	Required	Input Method
Description	TRUE	User Input from List
Fuel Type	TRUE	User Input from List
HRR_Calc	FALSE	User Input from Checkbox
CHRR_Calc	FALSE	User Input from Checkbox
CFACTOR_Calc	FALSE	User Input from Checkbox
Gas Calc	FALSE	User Input from Checkbox
SMOKE_Calc	FALSE	User Input from Checkbox
YIELDS_Calc	FALSE	User Input from Checkbox
Baseline Experiment	FALSE	User Input
C Factor Experiment ID	FALSE	User Input
Heat release rate - C Factor	TRUE	User Input
Calorimeter-Time out of service time	FALSE	User Input
Calorimeter- Out of service reason	FALSE	User Input
Expansion factor	TRUE	Automatically Updated
E factor	TRUE	Automatically Updated
Time baseline	FALSE	Automatically Updated
Duct diameter	TRUE	Automatically Updated
Flow shape factor	TRUE	Automatically Updated
Velocity Probe Diameter	TRUE	Automatically Updated
Velocity Probe Description	TRUE	Automatically Updated
Pressure Transducer 1 Bar Code	TRUE	Automatically Updated
Pressure Transducer 1 Serial Number	TRUE	Automatically Updated
Pressure Transducer 2 Bar Code	FALSE	Automatically Updated
Pressure Transducer 2 Serial Number	FALSE	Automatically Updated
Gas Analyzer Bar Code	TRUE	Automatically Updated
Gas Analyzer Serial number	TRUE	Automatically Updated
Delay Time Oxygen	TRUE	Automatically Updated
Delay Time CO/CO2	TRUE	Automatically Updated
Baseline Value Pressure Transducer 2	FALSE	User Input
Smoothing algorithm	FALSE	Automatically Updated

Parameter	Required	Input Method
Smoothing algorithm parameter 1	FALSE	Automatically Updated
Baseline Value Pressure Transducer 1	FALSE	User Input
Delay Time Temperature	FALSE	Automatically Updated
Smoke - Main detector Span	FALSE	User Input
Smoke- Main Detector Zero	FALSE	User Input
Smoke - Comp Detector Span	FALSE	User Input
Smoke- Comp Detector Zero	FALSE	User Input
Smoke- White Detector Zero	FALSE	User Input
Smoke- White Detector Span	FALSE	User Input
Smoke- Laser OD Filter	FALSE	User Input
Smoke- White OD Filter	FALSE	User Input
Smoke- Main Laser Detector Filter Signal	FALSE	User Input
Smoke- White Detector Filter Signal	FALSE	User Input
Smoke- Laser Pathlength	FALSE	Automatically Updated
Smoke- White Pathlength	FALSE	Automatically Updated
Smoke- Delay Time	FALSE	Automatically Updated
Procedure for Out of Range Values Max	FALSE	User Input from List
Procedure for Out of Range Values Min	FALSE	User Input from List

List of Standards

The following table lists the applicable standards for the FPC.

Table 3. List of Standards

Standard	Description	Ref
NFPA 289	Standard Method of Fire Test for Individual Fuel Packages	16
ASTM E2067	Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests	22

References

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7. ATF FRL Laboratory Instruction, Thermocouple, ATF-LS-FRL-LI001.
8. ATF FRL Laboratory Instruction, Optical Density Meter, ATF-LS-FRL-LI014.
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Appendix A – Fuel Property Determination

VOLUMETRIC EXPANSION FACTOR ( )

The volumetric expansion factor accounts for the expansion of the incoming air molecules into combustion products based on a complete combustion reaction (all carbon is converted to carbon dioxide). To calculate the volumetric expansion factor, the ratio is taken between the total moles of combustion products and the total moles of air (oxygen and nitrogen). One mole of air is 21% oxygen and 79% nitrogen. Trace amounts of argon and other gases are neglected. This relates to 3.76 moles of nitrogen for every one mole of oxygen. Although nitrogen is inert and does not take part in the combustion reaction the volume of the nitrogen must be conserved through the reaction. An example of a volumetric expansion factor calculation is provided below.

In the following chemical equation for the combustion of propane (C_3H_8), 5 moles of oxygen are needed to completely oxidize one mole of propane. The volume of air required to contain five moles of oxygen will also contain 18.8 moles of nitrogen, which will be conserved through the reaction. The volume of air will contain a total of 23.8 moles, which expands to 25.8 moles of combustion products. This results in a volumetric expansion factor of = 25.8 / 23.8 or = 1.084.

$$C_3H_8 + \underbrace{5O_2 + 18.8N_2}_{23.8\ \text{moles}} \quad \underbrace{3CO_2 + 4H_2O + 18.8N_2}_{25.8\ \text{moles}}$$

NET HEAT RELEASED PER UNIT MASS OF OXYGEN CONSUMED (E)

The basis of oxygen consumption heat release measurements is founded on the net heat released per unit mass of oxygen consumed during the combustion process. If the chemical formula of the fuel being burned is known, the value for E can be determined based on the chemical reaction, the molecular weight of the fuel and the net heat of combustion of the fuel ($H_{C,\,net}$).

For the combustion reaction described, the net heat of combustion of propane is 46.34 kJ/g and the molecular weight is 44.094 g/mol. Therefore, for each mole of propane burned, 2,043.3 kJ of heat are released. Since this one mole of propane reacts with 5 moles of oxygen (total mass of 160 g), the net heat released per unit mass of oxygen is E = 204.3 kJ/160 g or E = 12.77 kJ/g O_2. When the chemical reaction is unknown, a default value of 13.1 kJ/g O_2 can be used and is accurate to within ± 5 % for most fuels [13, 14].

Appendix B – Calibration Factor Determination

This Appendix contains informative, non-mandatory information on how the calibration factor, or C Factor, is determined for a Fire Products Collector (FPC). Figure 1 shows an example of a calibration burner experiment using nine (9) heat release steps ranging from 0 to 1100 kW. The average heat release rate output of the gas burner and the average heat release rate measured by the FPC are determined at each step. The averages are calculated during the steady-state period of each step.

Once the average heat release rate is calculated for the burner and the FPC at each step, the data is plotted as shown in Figure 2. A least squares linear regression analysis is performed with the y-intercept forced through zero. The C Factor is the slope of the least squares linear regression line. When the measured heat release rate data is corrected with the calculated C-Factor, the data from Figure 1 is transformed into the data in Figure 3.

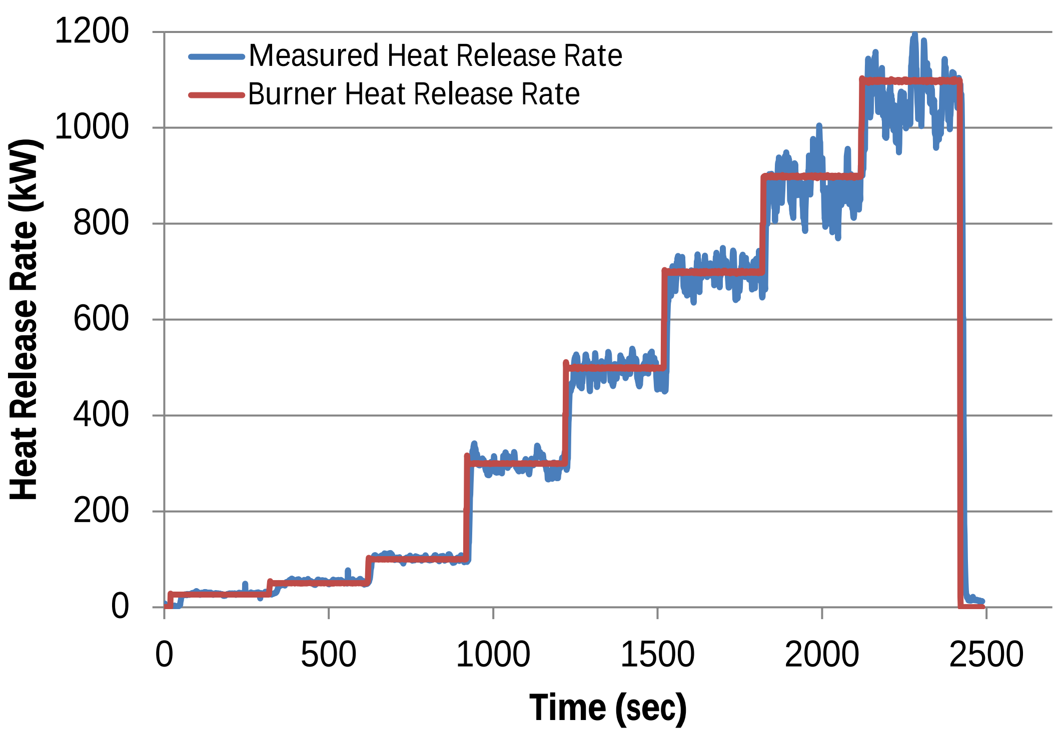

Figure 1. Example of a Nine-Point Burner Calibration Experiment

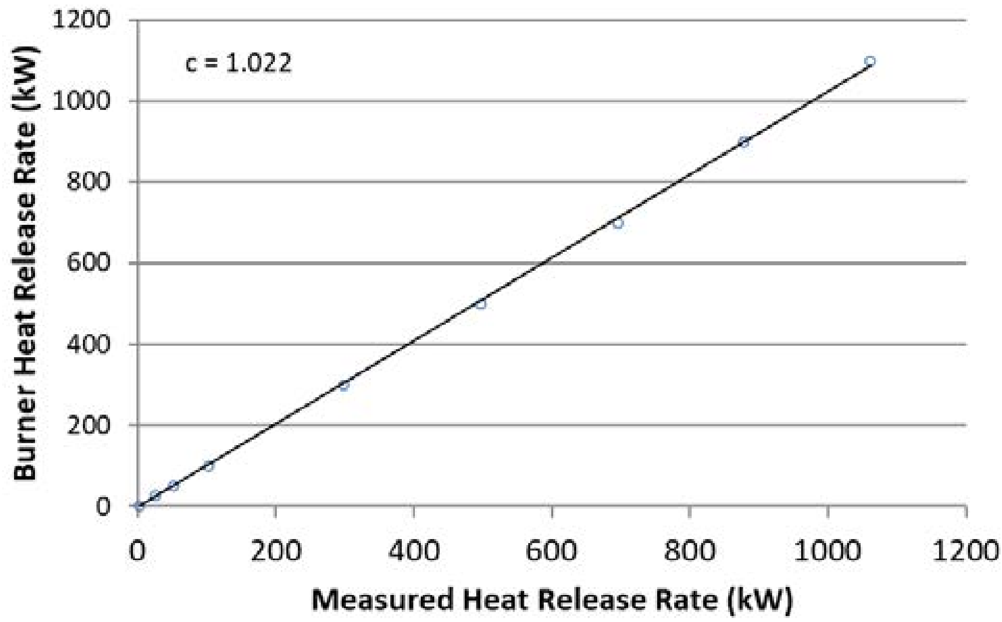

Figure 2. Example of a Nine-Point Burner C-Factor Determination

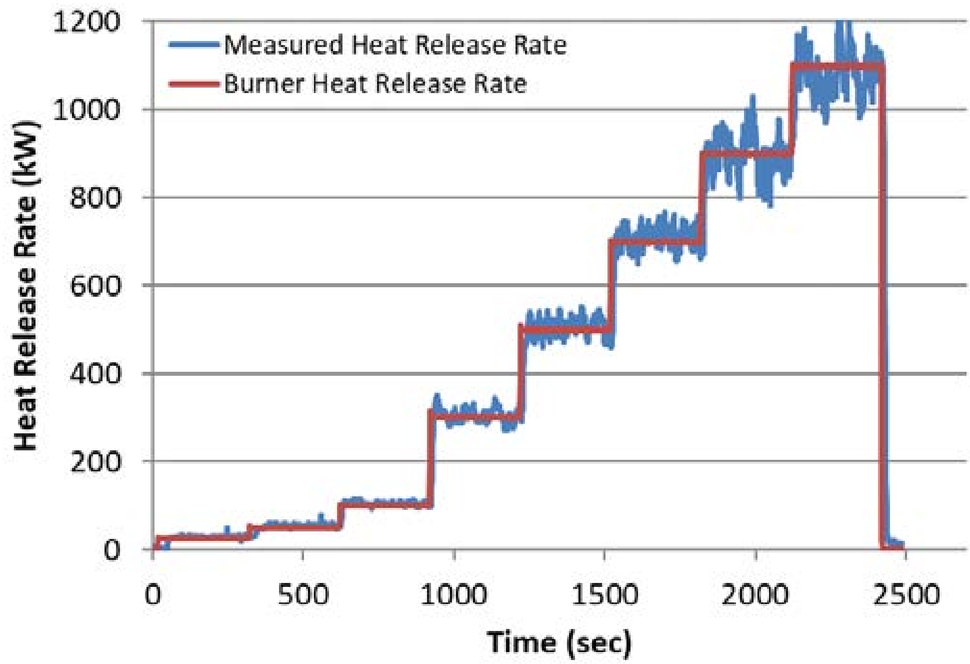

Figure 3. Measured Heat Release Rate Corrected with C-Factor

Scope

This Laboratory Instruction covers the use, design and specifications of optical density meters (ODMs) for smoke measurement in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Smoke measurements in fires are performed for a variety of reasons including toxicity assessment, visibility calculation, and model validation. Measurements are inherently difficult to perform in high temperature environments due to instrument limitations; however smoke data can be obtained downstream of a fire where reduced temperatures allow for use of sensitive instruments. The ATF FRL uses optical density meters to perform smoke measurements; these allow for good time resolution, they can be performed non-intrusively, and are not as labor intensive relative to other smoke measurement techniques.

OPERATING PRINCIPLE

Fires generate a range of products including gaseous species, aerosols and particulates. Optical smoke measurements are based on the attenuation of light as it passes through a particulate and gaseous medium. Light attenuation can be measured using a two part instrument comprised of a light source and a photo-detecting transducer. The photo-detecting transducer is designed such that it responds when subjected to the intensity of the light source. The transducer produces an output that is linear with the amount of light it receives. When a light source and transducer are arranged across a fixed path length, quantitative information can be inferred from the measured output.

METER APPLICATION

The operating principle for all optical density meters is generally the same, however the instrumentation used and the calculations performed depend on the application. The FRL uses ODMs for two primary applications: custom experiments and fixed location.

Custom Experiments

In custom experiments the instrument placement is scenario dependent. Often times ODMs are used in experiments involving a compartment or structure; the ODM can be placed in an area removed from the fire that is not expected to have high temperature exposure. This application provides a local smoke measurement where multiple ODMs can be used in a single experiment [1].

Fixed Location

Fixed location refers to applications where the ODM is mounted to a duct and measurements are performed on the sample passing through the duct. The FRL Fire Product Collectors and Cone Calorimeter are equipped with ODMs mounted to the duct several diameters downstream of the collection hood [2]. This application provides an integrated measurement of the smoke produced by the experiment.

THEORY

Light absorption by gas molecules is characterized by an absorption coefficient; light scattering by particulates is characterized by a scattering coefficient. These combine to produce a spectral extinction coefficient, k , that represents the total attenuation of light by a given medium. The extinction coefficient can be viewed as a proportionality coefficient in the expression that relates the differential change in light intensity as it passes through a differential medium [3]:

$$dI = k\ I\ dL \qquad (1.1)$$

In this expression, I is the spectral light intensity and L is the path length that the light passes through a medium. Equation 1.1 can be rearranged and integrated to produce:

$$\ln \frac{I_{\lambda,L}}{I_{\lambda,0}} = -\int_0^L k_\lambda dL \qquad (1.2)$$

In a uniform medium, in which k does not vary along the path, Equation 1.2 simplifies to:

$$k = \frac{1}{L} \ln \frac{I_{,0}}{I_{,L}} \qquad (1.3)$$

In this expression $I_{,0}$ is the intensity of the light at its source, and $I_{,L}$ is the intensity of the light reaching a detector at the end of the path. Equation 1.3 applies strictly to monochromatic (laser) light, however it is often generalized for use with broadband light sources, such as white light, by removing the spectral dependence ( ). Additionally, a correction factor, f, is sometimes applied to account for nonlinearities in the measurement system:

$$k = f \frac{1}{L} \ln \frac{I_0}{I_L} \qquad (1.4)$$

The correction factor f is calculated from the measured intensity I_L through a filter with known optical density [4]. The optical density per meter, *D*, (sometimes referred to as simply the optical density) is calculated as follows [5]:

$$D = f \frac{1}{L} \log_{10} \frac{I_0}{I_L} \qquad (1.5)$$

The optical density per meter is related to the extinction coefficient according to D = k/2.3.

FireTOSS Calculations

FIRE PRODUCT COLLECTOR

The relation generalized in Equation 1.4 is used to calculate the extinction coefficient for both laser and white light measurements. The rate of smoke release (RSR) is then calculated as the product of the extinction coefficient and the product volumetric flow rate in the duct:

$$RSR = k\dot{V} \qquad (1.6)$$

A third quantity that is of interest is the total smoke released (TSR). This is obtained by integrating the RSR rate over time [4].

CUSTOM EXPERIMENTS

Percent obscuration, O, is used in visibility calculations and is calculated as follows [6]:

$$O = 100\%\left[1 - \frac{I_L}{I_0}\right] \qquad (1.7)$$

Percent obscuration per unit length is used in detector design and is compared against manufactures' specifications for the detectors. Percent obscuration per meter is calculated according to [6]:

$$O_{u,meters} = 100\%\left[1 - \left(\frac{I}{I_0}\right)^{1/L_{meters}}\right] \qquad (1.8)$$

Uncertainty and Accuracy

The uncertainty of the ODMs was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [7], NIST Technical Note 1297 [8], and the NIST Uncertainty Workshop [9]. The combined standard uncertainty of a ODM is a combination of the uncertainty of its components given by the following equation:

$$u_c = \sqrt{\sum s_i^2 u(x_i)^2} \qquad \textbf{(29)}$$

where:

u_c = Combined standard uncertainty
$u(x_i)$ = Standard uncertainty of each component
s_i = Sensitivity coefficient $(\partial/\partial x_i)$

The FRL utilizes ODMs which have different light sources and photo detecting transducers. The uncertainty of each ODM varies depending on the instruments used and the path length measurement. Uncertainty calculations discussed in the appropriate Technical Reference.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition instrumentation shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. Optical density meters shall be functionally verified in accordance with FRL procedures.

TEST PROCEDURE

1. Setup

1.1. All ODM instruments shall be connected to the data acquisition hardware utilizing the smallest input range that will bound the output range of the instrument.

2. Prior to the First Test in a Series

2.1. Operation of the ODM shall be verified using the appropriate functional verification procedure.

3. Prior to Each Test

3.1. The output of the ODM shall be verified to be stable.

4. **During the Test**

4.1. The output of the ODM shall be recorded for the duration of the experiment.

4.2. Exception – When the ODM must be taken out of service prior to the end of an experiment due to experiment design or impending damage, the elapsed time at which the instrument was removed and the reason for instrument removal shall be recorded.

5. **Post Test**

5.1. If an instrument was taken out of service during an experiment, the out of service time and reason shall be recorded. Calculations shall be repeated with the updated out of service time.

5.2. If conditions occurred during or following the experiment that could potentially affect the performance of an ODM, a functional verification of that instrument shall be performed prior to its use in future experiments.

Optical Density Meter Documentation Requirements

Optical density meter usage during experiments shall be documented using the FireTOSS experiment design program. The information that the user can document about the optical density meter is shown in Table 1 and Table 2, depending on the type of ODM used. The first column shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column shows whether the parameter is required in all cases, and column three describes the method by which the field for each parameter is filled.

Table 1. Data Acquisition Input Parameters for Custom Experiment White Light ODM

Parameter	Required	Input Method
Description	TRUE	User Input
Bar Code	TRUE	User Input
X	FALSE	User Input
Y	FALSE	User Input
Z	FALSE	User Input
Light Source Type	FALSE	User Input from List
Extinction Beam Path Length	TRUE	User Input
C Factor	TRUE	User Input
Smoke Main Detector Zero	FALSE	User Input
Time Out of Service	FALSE	User Input
Out of Service Reason	FALSE	User Input
Chart Number	FALSE	User Input
Procedure for Out of Range Values Max	FALSE	User Input from List
Procedure for Out of Range Values Min	FALSE	User Input from List
Maximum Allowable measurement	FALSE	User Input
Minimum Allowable Measurement	FALSE	User Input

Table 2. Data Acquisition Input Parameters for Fire Product Collector ODM

Parameter	Required	Input Method
Smoke - Main detector Span	FALSE	User Input
Smoke- Main Detector Zero	FALSE	User Input
Smoke - Comp Detector Span	FALSE	User Input
Smoke- Comp Detector Zero	FALSE	User Input
Smoke- White Detector Zero	FALSE	User Input
Smoke- White Detector Span	FALSE	User Input
Smoke- Laser OD Filter	FALSE	User Input
Smoke- White OD Filter	FALSE	User Input
Smoke- Main Laser Detector Filter Signal	FALSE	User Input
Smoke- White Detector Filter Signal	FALSE	User Input
Smoke- Laser Pathlength	FALSE	Automatically Updated
Smoke- White Pathlength	FALSE	Automatically Updated
Smoke- Delay Time	FALSE	Automatically Updated
Smoke – Laser time out of service	FALSE	User Input
Smoke – Laser out of service reason	FALSE	User Input
Smoke – White light time out of service	FALSE	User Input
Smoke – White light out of service reason	FALSE	User Input

References

1. ATF FRL Technical Reference, Optical Density Meter Custom Experiments, ATF-LS-FRL-TR014b.
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8. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, 1993.
9. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.

Scope

This instruction covers the use, design, and specifications of Hot Wire Anemometers (HWA) used at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Hot wire anemometers are used for a wide range of applications for both internal and external velocity measurements. HWA are commonly used to measure velocity inside of ducts or pipes to calculate volumetric or mass flow rate. HWA are also used for point velocity measurements of external flows and have better sensitivity to low speed flows than differential pressure probes. These characteristics make HWA well suited for use in convective flows associated with fires, however they are typically restricted to low temperature environments.

A HWA consists of one or more resistive thermal device (RTD) elements that each constitute one active leg of a Wheatstone bridge circuit. The RTD sensors are electrically heated wire elements which are controlled by one of two types of solid- state electronics: constant temperature or constant power. Constant- temperature anemometers are more prevalent because they have a quick response time and low electronic noise, are compatible with liquids and gases, and are immune from sensor burnout when there is a sudden drop in flow. The FRL uses HWA that operate in constant-temperature mode.

HWA use the principles of convective heat transfer to determine fluid velocity. In a constant-temperature anemometer the RTD sensor is heated to maintain a constant temperature above that of the surrounding fluid. As a fluid flows past, the sensor is cooled convectively. The amount of power required to maintain the constant temperature is measured and converted to an electrical signal proportional to the fluid velocity.

The electrical output varies depending on the model of HWA. Some models produce a DC voltage signal, while others produce a current output. A current output can be converted to a voltage by using a resistor in parallel with the signal. For example, a 250 Ohm resistor can be used to convert a 4 – 20 mA output to a 1 – 5 V signal based Ohm's Law:

$$V = R * I \tag{1.1}$$

where:

V = Voltage
R = Resistance
I = Current

Uncertainty and Accuracy

The uncertainty and accuracy of HWA's are dependent on the manufacturer, model, operating temperature, range, and output type. The uncertainty analysis provided here is based on two models from the same manufacturer [1, 2]. The analysis is approached differently for each model because of the output types. Both are constant temperature anemometers, however one produces a current output and the other produces a voltage output. The current output model has an additional component, the resistor, which has an effect on the overall uncertainty of the velocity measurement. In both cases, it is reasonable to assume that the errors, stated by manufacturer literature, have a rectangular probability distribution, in which case the standard uncertainty of each component is computed by Equation 1.2 [3].

$$u(x) = \frac{e}{\sqrt{3}} \quad \textbf{(1.2)}$$

where:

$u(x)$ = Standard uncertainty
e = Error/accuracy of the measurement

When more than one source of uncertainty is present for a measurement, the values can be combined in quadrature to achieve a combined standard uncertainty, using Equation 1.3 [3-5]:

$$u_C(\mathrm{X}) = \sqrt{\sum \mathrm{s}_\mathrm{i}^2 \mathrm{u}(\mathrm{x}_\mathrm{i})^2} \quad (1.3)$$

where:

$u_c(X)$ = Combined standard uncertainty
$u(x_i)$ = Standard uncertainty component
s_i^2 = Sensitivity coefficient $(\partial \mathrm{y}/\partial \mathrm{x}_\mathrm{i})$

The specifications for each model are found in the User's Guides [1, 2].

For the current output model [1], the accuracy is listed as ±1.5% of full scale at room temperature, plus ±0.5% of reading from 0 to 50 °C (32 to 122 °F), plus 1% of full scale if the velocity measurement is below 5.1 meters per second (m/s) (1000 SFPM). For a 1 m/s (200 SFPM) anemometer operating under typical conditions in the FRL, the worst case accuracy (assuming full scale flow) is then ±3 %. The repeatability is listed as ±0.2% of full scale.

Using Equation 1.2, the accuracy and repeatability at 1 m/s (200 SFPM) yield standard uncertainties of ±0.018 m/s (±3.46 SFPM) and ±0.001 m/s (±0.23 SFPM), respectively. These values combined in quadrature result in a combined standard uncertainty for the instrument of ±0.018 m/s (±3.47 SFPM). In terms of raw current, the combined standard uncertainty correlates to ±0.2776 mA.

An additional source of error is a resistor that converts the current output to a voltage. For a 250 Ohm resistor with an accuracy of ±0.1% the standard uncertainty is ±0.144 Ohms.

The total uncertainty in the final voltage signal can be calculated by applying Equation 1.3 to Equation 1.1 yielding Equation 1.4.

$$u_c(V) = \sqrt{(R)^2\big(u(I)\big)^2 + (I)^2\big(u(R)\big)^2} \tag{1.4}$$

$$u_c(V) = \sqrt{(250)^2(0.0002776)^2 + (0.02)^2(0.144)^2} = \pm 0.069 \text{ Volts}$$

This correlates to a combined standard uncertainty of ±0.018 m/s (3.47 SFPM).

For the voltage output anemometers [2], the accuracy is listed as ±1.5% of full scale which equates to ±0.08 m/s (±15 SFPM) for HWA with a 5.1 m/s (1000 SFPM) range. Applying Equation 1.2, the standard uncertainty is ±0.044 m/s (±8.7 SFPM).

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. Hot wire anemometers shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.

PROCEDURE

1. Set up

1.1 The calibration marking on the HWA shall be checked to confirm that the instrument is calibrated.

1.2 HWA shall be connected to the data acquisition hardware using the smallest voltage input range that will bound the output range of the transducer.

1.3 HWA must be exposed to the environment for a period of at least five minutes prior to the start of the test.

1.4 Align sensor probe with the air flow. The air flow shall be perpendicular to the sensor window.

1.5 A type-K SLE thermocouple shall be installed near the HWA.

2. **Pre-Test**
   2.1 The surfaces of the temperature and velocity sensor elements shall be inspected for soot and or debris. All soot and debris shall be removed according to manufacturer instructions.
   2.2 The signal output of the HWA and thermocouple shall be verified using the DAQ.

3. **Test**
   3.1 The output of the HWA shall be recorded for the duration of the experiment.
   3.2 Exception I- When the HWA must be removed prior to the end of the experiment due to experiment design or impending damage to the instrument. The elapsed time at which the probe was removed and the reason for instrument removal shall be recorded.
   3.3 Exception II- The gas temperature surrounding the HWA shall be measured. If the gas temperature exceeds the temperature limit as set by the HWA's manufacturer, the HWA shall be taken "Out of Service" for the duration of the experiment. The elapsed time at which the HWA was removed and the reason for the instrument removal shall be recorded.

4. **Post Test**
   4.1 After the experiment, velocity probes in areas where they may have been damaged shall be examined for visible damage or surface dirt.
   4.2 If damage or surface dirt is observed on the velocity/ temperature sensing probe, the instrument shall be taken out of service until it has been cleaned according to manufacturer's instructions.
   4.3 If damage has occurred to the electronics casing, the instrument shall be taken out of service and sent in for recalibration.

Hot wire Anemometer Documentation Requirements

HWA usage shall be documented using the FireTOSS experiment design program. The information that the user shall document about the HWA is shown in Table 1. The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and column three provides a description of the information to be supplied for the parameter.

Table 1: Data Acquisition Input Parameters

Parameter	Required	Parameter Description
Conversion Factors	True	(m, b) Taken directly from the FRL calibration database.
Description	True	Description of the location of the HWA.
Type	True	Description of probe type.
Serial number	True	Manufacturer's serial number
Bar code	True	FRL Equipment identification number (asset number)
Over Range	True	The maximum temperature exposure range of the HWA

Parameter	Required	Parameter Description
Range	True	Input the maximum flow velocity
Manufacturer	True	Manufacturer of the HWA
Model	True	Manufacturer's model number
Chart	False	Allows the user to group instrument data onto different charts. If this parameter is left empty, data for similar instruments will be put on one chart.
Out of service time	False	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.
Out of service reason	False	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design

References

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Scope

This instruction covers the use of gas concentration measurements using gas analyzers utilizing either a paramagnetic or infrared absorption principle. This laboratory instruction covers the use of gas analyzers as a standalone instrument or as part of a system with a collection of instruments such as the cone calorimeter or Fire Product Collectors (FPC).

Instrument Description

GENERAL

Gas analyzers determine the concentration of a gas species in a mixture of gases through the unique properties of that gas. For analyzers that utilize a paramagnetic principle, the response of the gas in a varying magnetic field is utilized to determine the presence and concentration of a paramagnetic species, like oxygen, in the mixture. For analyzers that utilize an infrared absorption principle, the absorption of infrared light over a wavelength range is utilized to determine the presence and concentration of species, like carbon dioxide or carbon monoxide, in a gas mixture.

Gas analyzers are utilized remotely from the measurement location with a continuous sample drawn from the measurement location and pumped through the analyzers via tubing. The sample is pre-treated prior to reaching the analyzers to remove particulate materials and moisture that can damage the analyzers. This pre-treatment is accomplished through a series of filters, cold traps and desiccant filters. To reduce the transit time between the sampling point and the analyzer, a by-pass flow is incorporated into the sampling apparatus.

Some types of gas analyzers require a reference gas to flow through the analyzer as well as the sample gas.

UNCERTAINTY AND ACCURACY

The uncertainty and accuracy of the gas analyzer varies with make and model. Typical analyzer specifications consist of combined instrument accuracy, linearity of response and repeatability representing errors less than 3% of the full scale concentration range for which it is calibrated.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.

PROCEDURE

1. Set-up
   a. Analyzer output signals shall be connected to the data acquisition hardware utilizing the smallest voltage input range that will bound the output range of the analyzer.
   b. Tubing through which the gas will flow to the analyzer will be of the appropriate size and construction for the environment and flows to be encountered.
   c. If deemed necessary, the exhaust flow from the analyzer will be returned to the test chamber.
   d. All required gasses will be connected to the analyzer. This may include but is not limited to a reference gas, a zero gas and a span calibration gas.
   e. Delay time in analyzer response will be measured and sample line checked for leaks.

2. Pre-Test
   a. Desiccant filter will be changed and particulate filters cleaned/replaced.
   b. Sample line blown down to remove any clogs.
   c. Reference gas flow initiated, if necessary.
   d. Analyzer turned on and allowed to warm up.
   e. Analyzer calibrated with both a zero and span.
   f. Sample gas flow initiated with flow rate set for the analyzer and by-pass flows.

3. Test
   a. The output of the analyzer shall be recorded for the duration of the experiment

4. Post-Test
   a. Analyzer shall be checked for any damage
   b. Flow rate to the analyzer shall be checked to determine whether sample lines became clogged during the test.
   c. Gas sample flow shall be secured

Gas Analyzer Documentation Requirements

Gas analyzer usage shall be documented using the FireTOSS experiment design program. When using a gas analyzer, there are two instruments that need to be added to FireTOSS. For oxygen analysis, the “Oxygen Analyzer” instrument must be added. For carbon dioxide and carbon monoxide analysis, the “CO CO2 Analyzer” instrument must be added. The FireTOSS input parameters for the Paramagnetic O_2 analyzer and NDIR CO CO_2 analyzers are shown in Table 1 and Table 2, respectively.

Table 1 – "Paramagnetic O_2" Data Acquisition Parameters

Parameter	Parameter Description	Required	Input Method
Calibration Status	Determines if the instrument was in calibration for the experiment.	True	Automatic
Bar Code	The FRL provided bar code for the instrument.	True	User
Serial number	The manufacturer provided serial number.	True	Automatic
Description	Description of the location of the sample probe.	True	User
Location X	In conjunction with a diagram of the experiment set up, this parameter is used to identify the X location in meters of the sample probe	False	User
Location Y	In conjunction with a diagram of the experiment set up, this parameter is used to identify the Y location in meters of the sample probe	False	User
Location Z	In conjunction with a diagram of the experiment set up, this parameter is used to identify the height, in meters, of the sample probe	False	User
Manufacturer	Manufacturer	False	Automatic
Model number	The manufacturer provided model number	False	Automatic
Status-Gas Sample Exhaust Return Line	Description of where the exhaust line vents: To Ambient Laboratory or To Test Chamber.	True	User Selectable
Time out of service time	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.	False	User
Out of service reason	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design	False	User
O_2 Analyzer Full Scale Range	Full scale range that measurements were made on; default value = 0.25	True	User
O_2 Analyzer Span Value	Span gas concentration, usually taken as the oxygen in ambient air; default value = 0.2095	True	User
Delay Time Oxygen	The amount of time it takes for the analyzer to respond to a change in oxygen levels.	True	User

Table 2. "NDIR CO CO2" Data Acquisition Parameters

Parameter	Parameter Description	Required	Input Method
Calibration Status	Determines if the instrument was in calibration for the experiment.	True	Automatic
Bar Code	The FRL provided bar code for the instrument.	True	User
Serial Number	The manufacturer provided serial number.	True	Automatic
Description	Description of where the exhaust line vents: To Ambient Laboratory or To Test Chamber.	True	User
Location X	In conjunction with a diagram of the experiment set up, this parameter is used to identify the X location in meters of the sample probe	False	User
Location Y	In conjunction with a diagram of the experiment set up, this parameter is used to identify the Y location in meters of the sample probe	False	User
Location Z	In conjunction with a diagram of the experiment set up, this parameter is used to identify the height, in meters, of the sample probe	False	User
Status-Gas Sample Exhaust Return Line	Description of where the exhaust line discharges.	True	User Selectable
Manufacturer	Manufacturer	False	Automatic
Model number	The manufacturer provided model number	False	Automatic
Delay Time CO/CO2	This value is calculated by the calculation program as the test time when the value changed by at least 'initial change amount' from the initial value.	True	User
CO- Time OOS	Indicates the elapsed test time that the instrument was removed. All calculations for the data on the instrument cease at this time.	False	User
CO- Reason OOS	Specifies the reason that the instrument was removed. Reasons typically include damage, impending damage, or test design.	False	User
CO2- Time OOS	Indicates the elapsed test time that the instrument was removed. All calculations for the data on the instrument cease at this time.	False	User
CO2- Reason OOS	Specifies the reason that the instrument was removed. Reasons typically include damage, impending damage, or test design.	False	User
CO Analyzer Full Scale Range	Full scale range that CO measurements were made on	True	User
CO Span Gas Value	CO span gas concentration value (mole/mole) obtained from calibration gas; Default Value = 0.045	True	User

Parameter	Parameter Description	Required	Input Method
CO2 Analyzer Full Scale Range	Full scale range that CO2 measurements were made on	True	User
CO2 Span Gas Value	CO2 span gas concentration value (mole/mole) obtained from calibration gas; Default Value = 0.225	True	User

Scope

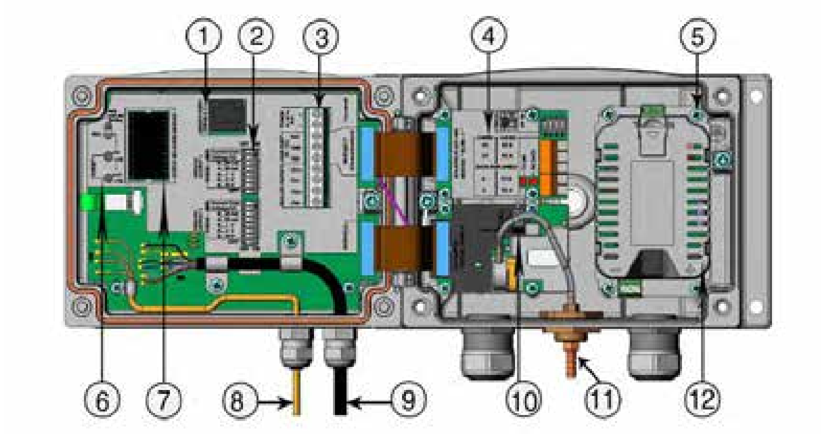
This Laboratory Instruction covers the use, design, and specifications of the Laboratory Conditions stations that utilize the Vaisala PTU300 Combined Pressure, Humidity and Temperature transmitter with a PTU303 probe. The Laboratory Conditions stations are used by the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

The Vaisala PTU300 transmitter and PTU303 probe measure the ambient pressure, temperature and humidity simultaneously. Figure 1 shows a Vaisala PTU300 transmitter with the PTU303 probe attached beneath the unit. Figure 2 shows an illustration of the interior of the transmitter. The transmitter communicates with the FireTOSS network using Modbus TCP/IP (Ethernet) communication.

Figure 1. Vaisala PTU300 transmitter and PTU303 probe



1 = Service port (RS-232)
2 = DIP switches for analog output settings
3 = Power supply and signal wiring screw terminals
4 = Relay, RS-422/485, data logger, LAN, WLAN, or analog output module (optional)
5 = Grounding connector for power supply module
6 = Adjustment buttons (chemical purge buttons) with indicator LED
7 = Galvanic isolation module (optional)
8 = Temperature probe cable
9 = Humidity probe cable
10 = BARO-1 module
11 = Pressure port
12 = Power supply module.

Figure 2. Interior of the Vaisala PTU300 transmitter [1]

The Laboratory Conditions station using the Vaisala hardware contains three sensors that measure pressure, humidity, and temperature simultaneously. Barometric pressure measurement is accomplished using a silicon capacitive absolute sensor developed by Vaisala (BAROCAP). The micromechanical sensor uses dimensional changes in its silicon membrane to measure pressure [2]. Humidity measurement is achieved using a capacitive humidity sensor developed by Vaisala (HUMICAP). The capacitance of the thin-film polymer sensor changes as the relative humidity changes [3]. Temperature measurement is attained using a platinum Resistance Temperature Detector (RTD) sensor. The RTD contains a resistor that changes resistance as the temperature changes [4]. The Laboratory Conditions station using the Vaisala hardware requires annual calibration.

Uncertainty and Accuracy

The uncertainty in the pressure, temperature, and relative humidity measured by the Laboratory Conditions stations are estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [5] and the NIST Uncertainty Workshop [6]. Information about the errors and accuracy of each measurement is obtained from Vaisala, the manufacturer of the Laboratory Condition station hardware [1].

The error for each measurement is assumed to have a rectangular probability distribution, in which case the standard uncertainty is computed by the following equation [5]:

$$u(x) = \frac{e}{\sqrt{3}} \tag{1.1}$$

where,

$u(x)$ = Standard uncertainty
e = Error/accuracy of the measurement

Where more than one type or uncertainty is present for a measurement, the values can be combined in quadrature to achieve a combined uncertainty, using the following equation [5-6]:

$$u_C(\mathrm{X}) = \sqrt{\sum \mathrm{u}(\mathrm{x_i})^2} \tag{1.2}$$

where,

$u_c(X)$ = Combined standard uncertainty
$u(x_i)$ = Standard uncertainty component

PRESSURE

Vaisala [1] lists the following values for the error associated with the pressure measurement for a pressure senor with a range of 500 hPa to 1100 hPa and Class B accuracy:

Linearity:	±0.10 hPa
Hysteresis:	±0.03 hPa
Repeatability:	±0.03 hPa
Calibration Uncertainty:	±0.15 hPa
Accuracy at +20°C:	±0.20 hPa
Temperature dependence:	±0.1 hPa

Total accuracy (-40°C to +60°C) ±0.25 hPa

Long-term stability/year: ±0.1 hPa

Using Equation 1.1, these errors yield a standard uncertainty for each error/accuracy of measurement as 0.058 hPa, 0.017 hPa, 0.017 hPa, 0.087 hPa, 0.115 hPa, 0.058 hPa, 0.144 hPa, and 0.058 hPa, respectively. The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty for the pressure measurement. The result is a combined standard uncertainty of 22.9 Pa.

$$u_C(\mathrm{P}) = \sqrt{0.058^2 + 0.017^2 + 0.017^2 + 0.087^2 + 0.115^2 + 0.058^2 + 0.144^2 + 0.058^2}$$

$$u_C(\mathrm{P}) = 0.229 \text{ hPa or } 22.9 \text{ Pa}$$

RELATIVE HUMIDITY

Vaisala [1] lists the following values for the error of the relative humidity measurement:

Accuracy: ±1% RH for 0-90% RH (+15°C to 25°C)
±1.7% RH for 90-100% RH (+15°C to 25°C)
±(1.0% + 0.008 x reading)% RH (-20°C to 40°C)
±(1.5% + 0.015 x reading)% RH (-20°C to 40°C)

Calibration Uncertainty: ±0.6% RH (0 to 40% RH)
±1.0% RH (40 to 97% RH)

It is assumed that under normal operating conditions, the temperature inside the testing area will fall between -20°C to 40°C and that the maximum relative humidity will be 90%. Therefore, the error associated with the accuracy will be ±1.72% RH and the calibration uncertainty will be ±1.0% RH.

Using Equation 1.1, the standard uncertainty for the accuracy and calibration uncertainty are of 0.993% RH and 0.577C, respectively. These values are combined in quadrature to calculate the combined standard uncertainty of the relative humidity measurement. The result is a combined standard uncertainty of 1.1% RH.

$$u_C(\mathrm{RH}) = \sqrt{0.993^2 + 0.577^2} = 1.1\ \%\ \mathrm{RH} \tag{1.3}$$

TEMPERATURE

Vaisala [1] lists the following value for the error associated with the accuracy of the temperature measurement:

Accuracy: ±0.2°C at + 20°C

For temperatures other than 20°C, Vaisala provides a chart for the accuracy, as shown in Figure 3. Therefore, assuming a maximum laboratory temperature of 35°C (95°F), the accuracy of the temperature measurement would be approximately ± 0.25°C.

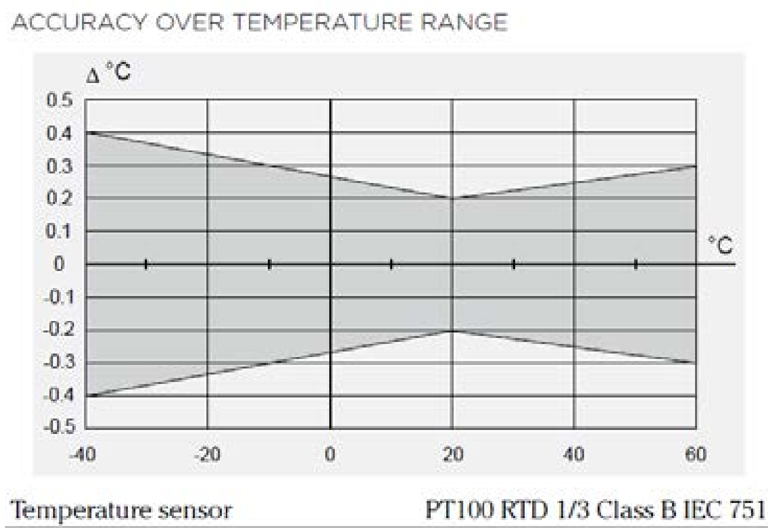


Figure 3. Accuracy of temperature measurement [1]

Using Equation 1.1, the standard uncertainty is calculated to be 0.14°C. Because there is only one value listed for the error in the temperature measurement, the combined standard uncertainty is equal to the standard uncertainty of 0.14°C.

$$u_C(\mathrm{T}) = \sqrt{0.14^2} = 0.14°\mathrm{C} \qquad (1.4)$$

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The Laboratory Conditions station shall be calibrated and marked with the calibration status in accordance with FRL calibration procedures.
3. The measuring probe shall be clean and free of debris.
4. The pressure port on the bottom of the unit shall be free of any obstructions.

PROCEDURE

The following is the general procedure that shall be followed for using the Laboratory Conditions station.

1. **Set up**
   - 1.1 The calibration status of the Laboratory Conditions station shall be checked to confirm that the instrument is calibrated.
   - 1.2 The Laboratory Conditions station shall be connected to the FireTOSS network.
2. **Pre-Test**
   - 2.1 Verify that the Laboratory Conditions station is free of debris or any obstacle that would prevent an accurate measurement of the surrounding conditions.
3. **Test**
   - 3.1 The measurements of the Laboratory Conditions station shall be monitored.
4. **Post-Test**
   - 4.1 Verify that the data has been collected and that there are no issues with the data collected.
   - 4.2 The laboratory condition station shall remain powered and connected to the FireTOSS network.

Laboratory Conditions Documentation Requirements

The use of a Laboratory Conditions station shall be documented using the FireTOSS experiment design program. Table 1 lists the FireTOSS input parameters for laboratory conditions. The first column provides the input parameter and the second column provides a brief description of that parameter. The third column lists whether the parameter is required in all cases. The fourth column lists how the parameter is entered into the FireTOSS design program.

Table 1. Data Acquisition Input Parameters

Parameter	Description	Required	Input Method
Calibration Status	Determines if the instrument was in calibration for the experiment.	TRUE	Automatic
Description	Description of the location of the laboratory condition station	TRUE	User Input from List
Bar Code	FRL asset number for the laboratory condition station	TRUE	Automatic
Manufacturer	Manufacturer of hardware	TRUE	Automatic
Model	Manufacturer provided model number	TRUE	Automatic
Time Out of Service	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.	FALSE	User
Out of Service Reason	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design	FALSE	User

References

1. "User Guide: Vaisala Combined Pressure, Humidity, and Temperature Transmitter PTU300", M210796EN-H, Vaisala 2015
2. BAROCAP Technology Description, Ref. B210845EN-B, Vaisala 2012
3. HUMICAP Technology Description, Ref. B210781EN-C, Vaisala 2012
4. Morris, Alan, *Measurement & Instrumentation Principles*, Butterworth-Heinemann, Woburn, MA, 2001.
5. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, 1993.
6. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.

Scope

This Laboratory Instruction covers the use, design, and specifications of the CWD 2000 Combustion Calorimeter from Union Instruments. The Combustion Calorimeter is used to measure the heat content and specific gravity of natural gas that is used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL) experiments.

Instrument Description

GENERAL

The purpose of the Combustion Calorimeter is to measure the calorific value and specific gravity of the natural gas entering the building. Figure 1 shows a photograph of the instrument.

Figure 1: Combustion Calorimeter Mounted to Wall in 1 Megawatt Shed

The Combustion Calorimeter has a built in specific gravity measurement cell. Sample gas flows through the measuring chamber where a membrane vibrates at a constant frequency. Oscillations are transferred through the gas to a transducer. The amplitude of these oscillations is directly proportional to the density of the gas.

The calorific value is measured by way of a thermopile measuring system. Sample gas passes through a Wobbe range orifice and is burned at atmospheric pressure. The hot gases are mixed with a cooling airflow and the temperature of the mix is measured by thermopile hot junctions. The cold junction of the thermopile measures the temperature of the incoming cool air flow, which results in a pressure difference that is proportional to the Wobbe Index of the gas. To calculate the calorific value, the following relation is used by the Combustion Calorimeter [1]:

$$\text{Calorific Value} = \text{Wobbe Index}\sqrt{\text{Specific Gravity}}$$

Additional technical information regarding the theory behind the use of the Combustion Calorimeter can be found in the "*Users Manual – CWD 2000 Combustion Calorimeter – For high speed measurement of fuel gases*". [1]

SYSTEM COMPONENTS

The major components of the Combustion Calorimeter are listed below and are indicated in Figure 2. Note that components with as asterisk (*) are not shown in the figure. See the Combustion Calorimeter user's manual for a diagram showing their location. [1]

1. Differential pressure for density cell (positive)
2. Differential pressure for density cell (negative)
3. Differential pressure for air (negative)
4. Differential pressure for air (positive)
5. Gas pressure at range orifice (Wobbe jet)
6. Power supply*
7. PC 104type processor circuit board*
8. Disk drive
9. Filter element for air supply*
10. Pt 100 temp correction
11. Pt 100 temp correction
12. Ignition electrode
13. Burner
14. Electrical noise filter
15. Air fan
16. Frequency controller for air fan

17 - Discharge (exhaust) pipe
18 - Solenoid valve for calibration gas
19 - Solenoid valve for process gas
20 - Specific gravity cell
21 - Pressure regulator for process gas
22 - Precision pressure regulator
23 - Pressure regulator, specific gravity cell differential pressure
24 - Range orifice (Wobbe jet) location
25 - Primary air supply tube
26 - E/A internal
27 - Temperature sensor
28 - Door switch
29 - Terminal block for line power supply
30 - Output signal PG cord connector
31 - Line power PG cord connector
32 - E/A Extern

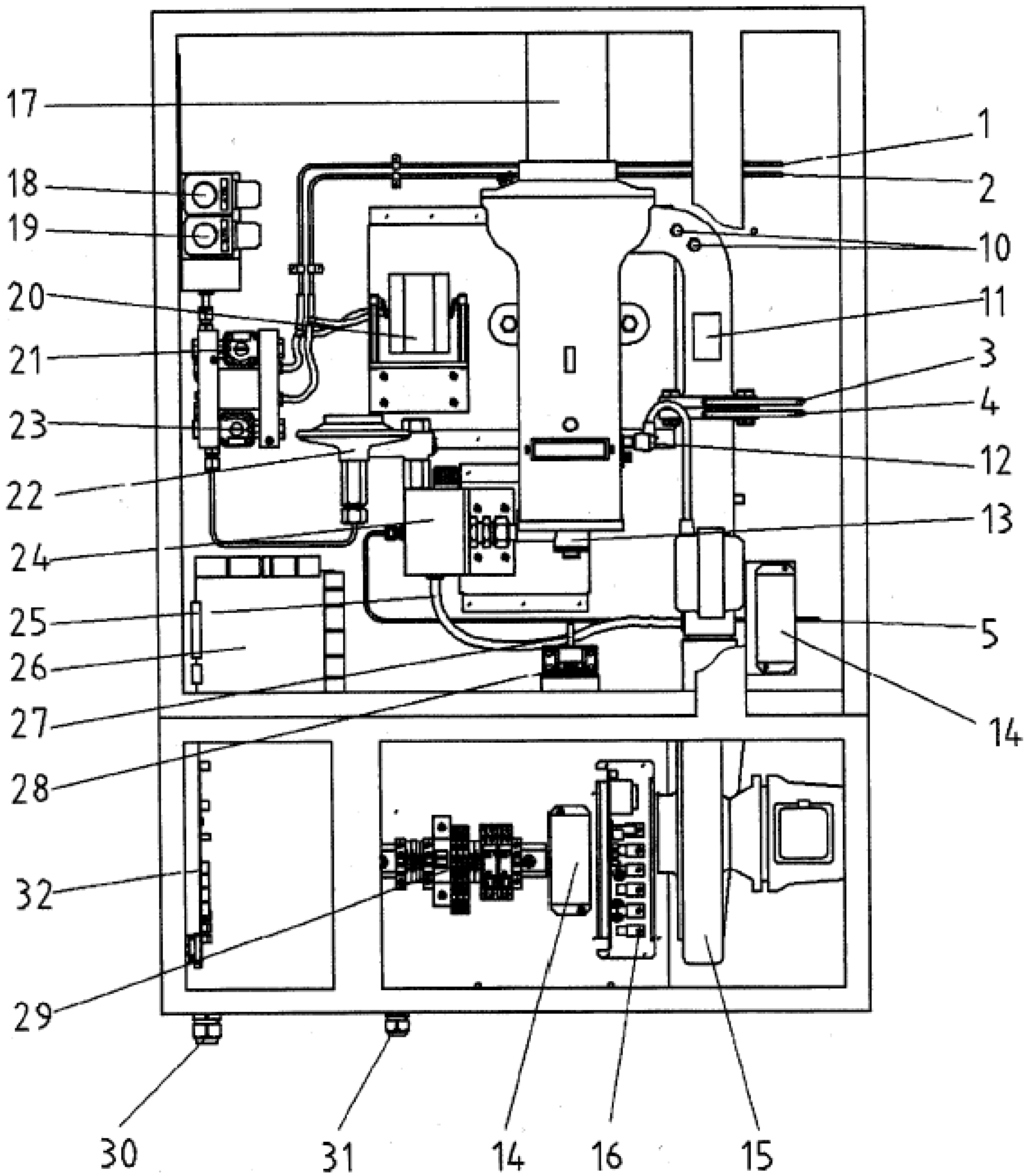


Figure 2: Inside View of CWD 2000 Combustion Calorimeter [1]

FireTOSS Calculations

The Combustion Calorimeter instrument in FireTOSS provides a data output of calorific value ($C.V._{dry}$) and specific gravity of natural gas (SG_{ng}) relative to air.

The density of the natural gas is calculated from the specific gravity of natural gas using the following equation:

$$\rho_{NG} = \rho_{Air} * SG_{NG} \tag{1.1}$$

where,

ρ_{NG} = density of natural gas (kg/m^3)
ρ_{Air} = density of ambient air (kg/m^3)
SG_{NG} = specific gravity of natural gas relative to air

For Equation 1.1, the density of ambient air is calculated using the FRL Laboratory Conditions measurements of ambient pressure and temperature [2].

In addition, the heat of combustion for the natural gas is calculated using the following equation:

$$\Delta H_{c,gross} = \frac{C.V._{dry}}{\rho_{NG}} \tag{1.2}$$

where

$\Delta H_{c,gross}$ = gross heat of combustion of the gas mixture in MJ/kg
$C.V._{dry}$ = calorific value (dry) of natural gas in MJ/m^3
ρ_{NG} = density of natural gas in kg/m^3

Equation 1.2 yields a value in terms of the dry calorific value, which does not account for water vapor. To account for water vapor, a correlation from Bossel [3] was used to convert to the net heat of combustion. This correlation was empirically developed and is specific for natural gas.

$$\Delta H_{c,net} = \Delta H_{c,gross} * 0.896 \tag{1.3}$$

Uncertainty

When operated within the guidelines specified in this document and within the User's Manual [1], the Combustion Calorimeter functions within the following limits:

Accuracy: +/- 1.0% for CV or Wobbe Index
+/- 0.8% for Specific Gravity
Linearity: +/- 0.2%
Repeatability: +/- 0.5%

In order to function within these limits, the Combustion Calorimeter must be kept in an ambient temperature of between 10°C and 38°C (50°F to 100°F) with a rate of change of no more than +/- 2°C (3.6°F) per hour. Further, the ambient temperature should be within +/-7°C (12.6°F) of the temperature at which calibration was performed. This data is tracked and recorded using a temperature sensor connected to data acquisition. The data recorded is analyzed and the operator is alerted if the temperature trend is outside of tolerance.

The Combustion Calorimeter is used to calculate the density and heat of combustion of the natural gas. A standard uncertainty for these two values can be determined by the accuracy given by the User's Manual and a set of data taken from the Combustion Calorimeter. The uncertainty of these measurements was calculated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [4], Special Publication 1007 [5] and the NIST Uncertainty Workshop [6], using the following equation:

$$u_C(\mathrm{y}) = \sqrt{\sum \mathrm{s}_\mathrm{i}^2 \mathrm{u}(\mathrm{x}_\mathrm{i})^2} \qquad (1.4)$$

where:

$u_C(\mathrm{y})$ = Combined standard uncertainty of the quantity being calculated
$\mathrm{u}(\mathrm{x}_\mathrm{i})$ = Standard uncertainty of each component that is used in the calculation of y
s_i = Sensitivity coefficient $\left({}^{\partial y}/_{\partial x_i}\right)$

DENSITY

The combustion calorimeter measures the specific gravity of the process gas (natural gas) relative to air at ambient conditions. The uncertainty in the specific gravity measurement can be calculated based on the specifications of the instrument and an analysis of scatter in the data. In order to evaluate the natural gas density, Equation 1.1 is used with ${}_{air}$ being calculated from the measured ambient conditions.

Applying Equation 1.4 to Equation 1.1 yields:

$$u_C(\rho_{\mathrm{NG}}) = \sqrt{(\mathrm{SG}_{\mathrm{NG}})^2\left(\mathrm{u}(\rho_{\mathrm{air}})\right)^2 + (\rho_{\mathrm{air}})^2\left(\mathrm{u}(\mathrm{SG}_{\mathrm{NG}})\right)^2} \qquad (1.5)$$

The uncertainty of the specific gravity has two parts: the uncertainty of the combustion calorimeter and the fluctuations over time. The uncertainty in the combustion calorimeter is a function of the accuracy, linearity, and repeatability of the instrument.

Union Instruments gives the accuracy of the combustion calorimeter specific gravity measurement as ± 0.8 % full scale [1], or 0.018 at the 0.2 -2.2 range setting. The linearity is listed as ± 0.2 % full scale and the repeatability is listed as ± 0.5 % full scale. It can be assumed that these errors have a rectangular probability distribution, in which case the standard

uncertainty is computed by dividing each component by $\sqrt{3}$ [4]. The standard uncertainties of these components are then, 0.01, 0.0025, and 0.0064, respectively.
The uncertainty over time can be calculated using a 30 day average standard deviation. NIST [4] states that for a sample of data, the uncertainty of the samples is:

$$U_s = {}^{\sigma}/_{\sqrt{n}} \tag{1.6}$$

where:

U_s = Standard uncertainty of the samples
σ = Standard deviation of the samples
n = Number of samples

Using this formula, the uncertainty of the specific gravity samples can be determined. Over a sample of 30 data points, the standard deviation was 0.002, which yields 0.0004 as the standard uncertainty.

The uncertainty components can be combined in quadrature to estimate the combined uncertainty of the specific gravity measurement. The result is $u(SG_{NG})$ =<u>0.012</u>.

Air can be treated as an ideal gas, in which case the density is expressed as:

$$\rho = \frac{P}{RT} \tag{1.7}$$

where:

ρ = gas density (kg/m^3)
P = gas pressure (kPa)
R = gas constant (0.287 kJ/kg/K for air)
T = gas temperature (K)

Uncertainty in the air density is a function of the Laboratory Conditions temperature and pressure measurements. Standard uncertainties for the temperature (0.14°C) and pressure (0.023 kPa) were computed based on an evaluation of the Lab Conditions measurements [2]. Uncertainty in the air density is calculated by applying Equation 1.4 to Equations 1.7.

$$u_C(\rho_{\mathrm{air}}) = \sqrt{\left(\frac{1}{\mathrm{RT}}\right)^2 (\mathrm{u(P)})^2 + \left(\frac{\mathrm{P}}{\mathrm{RT}^2}\right)^2 (\mathrm{u(T)})^2} \tag{1.8}$$

From Equation 1.8, the uncertainty in the density of air is 0.001 kg/m^3. Using Equation 1.5, the uncertainty in the natural gas density is then $u(\rho_{NG})$ = <u>0.014 kg/m^3</u>. This corresponds to a relative standard uncertainty of 2.5 % at the 30 day average specific gravity of 0.593.

HEAT OF COMBUSTION

Substituting Equations 1.1 and 1.2 into Equation 1.3 and applying Equation 1.4 yields:

$$u_C(\Delta \mathrm{H}_{c,net}) = \sqrt{\left(\frac{0.896}{\rho_{air}\mathrm{SG}_{NG}}\right)^2 (\mathrm{u(C.V.)})^2 + \left(\frac{-0.896\ \mathrm{C.V.}}{\rho_{air}\mathrm{SG}_{NG}^2}\right)^2 (\mathrm{u(SG_{NG})})^2 + \left(\frac{-0.896\ \mathrm{C.V.}}{\rho_{air}^2\mathrm{SG}_{NG}}\right)^2 (\mathrm{u}(\rho_{air}))^2} \quad (1.9)$$

The uncertainty of the heat of combustion is a function of the uncertainty of both the specific gravity and calorific value measurements from the combustion calorimeter. The specific gravity uncertainty was calculated above. The calorific value uncertainty is comprised of two parts: the uncertainty of the combustion calorimeter and the variance over time. The uncertainty in the combustion calorimeter is a function of the accuracy, linearity and repeatability of the instrument.

The combustion calorimeter manufacturer gives the accuracy of the combustion calorimeter heating value measurement as 1% of full scale [1]. The linearity is listed as ± 0.2 % and the repeatability is listed as ± 0.5 %. It can be assumed that these errors have a rectangular probability distribution, in which case the standard uncertainty is computed by dividing each component by $\sqrt{3}$ [4]. At the 35-45 MJ/m^3 range, the standard error associated with the accuracy is 0.26 MJ/m^3. The standard errors associated with the linearity and repeatability are calculated similarly to be 0.05 MJ/m^3 and 0.13 MJ/m^3, respectively.

The uncertainty over time can be calculated from Equation 1.4, using the 30 day average standard deviation. This yields a standard error of 0.028 for the variation of the measurement.

The uncertainty components can be combined in quadrature to estimate the combined uncertainty of the calorific value measurement. The result is $u(C.V.) =$ 0.295 MJ/m^3. This corresponds to a standard relative uncertainty in the calorific value of 0.8 % based on the 30 day average of 38.5 MJ/m^3. From Equation 1.9, the combined standard uncertainty in the natural gas heat of combustion is then $u_c(\Delta H_{c,net})$ = 1.05 MJ/kg.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The instrument shall be calibrated in accordance with FRL calibration procedures.
3. If data acquisition is used, the data acquisition equipment shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.

PROCEDURE

The following is the general procedure that shall be followed. The operator shall also be properly trained on all appropriate procedures.

1. Set up

1.1. The certification date on the calibration gas shall be checked to confirm that the gas certification has not expired.

1.1.1. If the instrument is being powered up, a calibration shall be performed.

1.2. The instrumentation shall be connected to the data acquisition hardware using the smallest voltage input range that will bound the output range of the instrument.

1.3. Ensure that adequate fuel pressure is available.

2. Pre-Test

2.1. The pilot flame shall be verified to be lit.

2.2. All valves leading to the instrument shall be verified as “OPEN”.

2.3. It shall be verified that a calibration has been performed and the environmental temperature requirements have been met.

3. Test

3.1. The display on the instrument shall show a stability reading (“STAB”) of less than 0.15 to signify a stable reading.

3.2. The data shall be monitored to verify continuity.

4. Post Test

4.1. No action shall be taken other than to verify that the instrument is still yielding stable readings.

4.2. The instrument shall be left in the “ON” position.

Combustion Calorimeter Documentation Requirements

The Combustion Calorimeter can be used as a stand-alone instrument in FireTOSS. The information that the user shall document about the FPC is shown in Table 1. The first column in Table 1 shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column in Table 1 shows whether the parameter is required in all cases, and the third column describes the method by which the field for each parameter is filled.

Table 1: Combustion Calorimeter Data Acquisition Input Parameters

Parameter	Required	Input Method
Calibration Status	True	Automatically updated
Description	False	User input
Bar Code	True	User input from list
Model Number	True	Automatically updated
Manufacturer	True	Automatically updated
Serial Number	True	Automatically updated
Time Out of Service	False	User input
Out of Service Reason	False	User input

Note that the Combustion Calorimeter is also included as part of the *Burner Gas Train* object in FireTOSS. However, all the information related to the instrument is added automatically.

References

1. "Users Manual – CWD 2000 Combustion Calorimeter – For high speed measurement of fuel gases" Union, 2007.
2. ATF FRL Instruction, "Laboratory Instruction LI017: Laboratory Conditions.
3. Bossel, U., "Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle," Oberrohrdorf, Switzerland, 2003. http://www.efcf.com/reports/E10.pdf
4. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD 1993.
5. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, Gaithersburg, MD 2003.
6. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.

Scope

This laboratory instruction covers the use, design and specifications of Weighing Devices used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Weighing devices are instruments primarily used to measure the instantaneous mass of an object or to observe changes in the mass over a period of time. Weighing devices can be classified as scales or balances. Scales measure the physical change in the shape and/or the position of the scale as a result of a weight being applied to the scale. Balances use a counteractive force, typically an electromagnetic force, to maintain the original shape and/or position of the balance when a weight is applied to the balance.

Weighing devices usually consist of three main components: the load cell(s), a weighing platform, and an indicator unit.

Load Cells

A load cell is a device that produces an electrical response proportional the force induced by a mass positioned on a weighing device. Many weighing devices use load cells that utilize either strain gauge or magnetic force restoration (MFR) methods.

Strain Gauge Load Cell

Strain gauge load cells use strain gauges that are positioned along a structural member of the load cell in a specific configuration for the application. Many scales contain strain gauge-based load cells. Most strain gauges are bonded to the load cell in the manner represented in Figure 1.

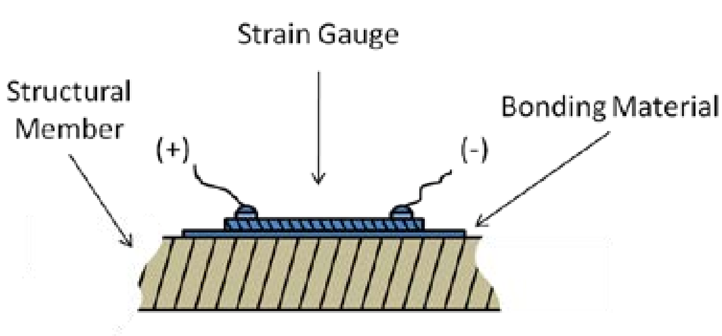


Figure 1. Stain gauge bonded to the structural member of a load cell

A common configuration is the use of a Wheatstone bridge containing four stain gauges, a full-bridge, to complete an electrical circuit as shown in Figure 2.

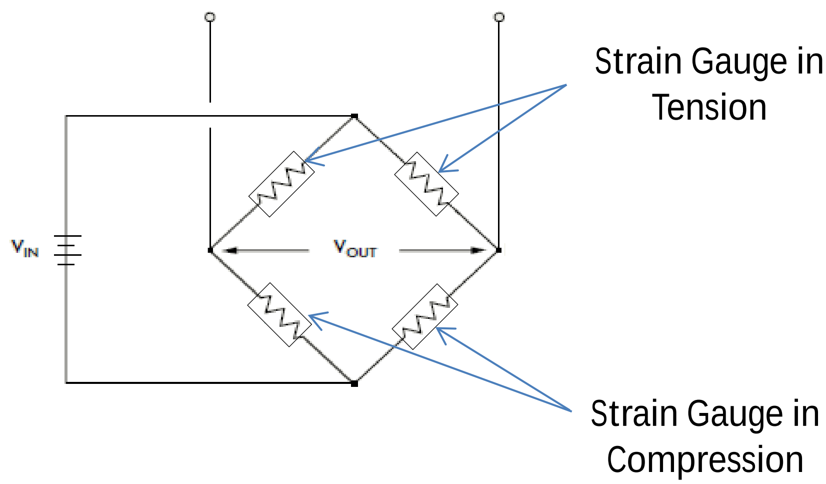


Figure 2. Wheatstone bridge circuit with a full-bridge configuration

A full-bridge configuration has many advantages including: a voltage output directly proportional to the applied load, a greater sensitivity than configurations with fewer strain gauges, and the ability to allow adverse temperature effects on the strain gauges to cancel out [1]. The strain gauges are positioned on the structural member allowing two gauges to each measure in tension and compression, shown in Figure 3.

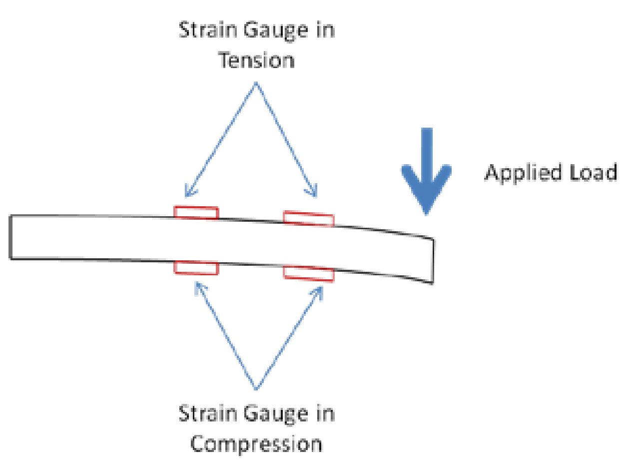


Figure 3. Position of strain gauges on a load cell in full-bridge configuration

Unstressed, the stain gauges are all of equal resistance and the output voltage of the circuit is zero. Tensing and compressing a strain gauge increases and decreases the electrical resistance, respectively, of the strain gauge. When a load is applied to the load cell, the structural member deforms and tenses two of the strain gauges while compressing the other two. This causes an imbalance in the electrical circuit and generates an output voltage directly proportional to the load applied to the load cell. Voltage measurements are generally less precise, but greater integrity in the structural member of the load cell allows for weighing objects with larger masses.

Magnetic Force Restoration Load Cell

MFR load cells use a force generated by an electromagnet to counteract the applied load. Many balances contain MFR-based load cells. When there is no applied load, the balance is in equilibrium and equal amounts of current pass through the negative and positive coils on the electromagnetic. The weighing platform sinks under an applied load and unbalances the system. This imbalance activates a sensor that increases and decreases the current passing through the positive and negative coils, respectively. This current imbalance generates a magnetic field, creating magnetic force that repels the magnetically reactive weighing platform until the balance returns to equilibrium, as shown in Figure 4.

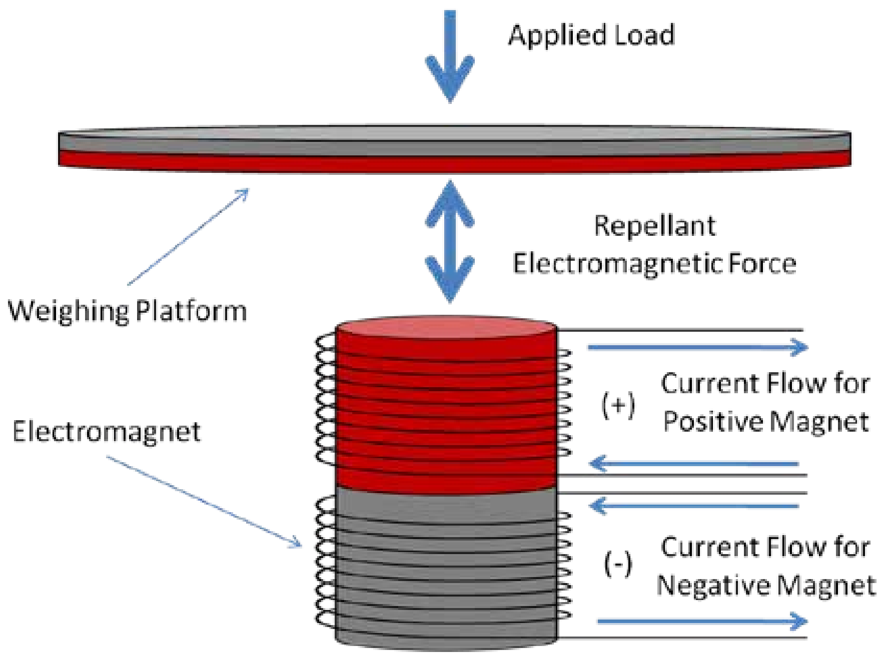


Figure 4. Schematic of electromagnet maintaining equilibrium in an MFR

The current differential between the two coils necessary for the electromagnet to maintain equilibrium is proportional to the applied load. Current measurements usually offer greater precision but limitations in the strength of the electromagnet confine MFR load cells to weighing objects with smaller masses.

Weighing Platforms

The weighing platform on a weighing device is used to support or contain an object during measurements and distribute the force caused by the objects mass to the load cell(s). Weighing platforms vary in size, shape, material, and load capabilities depending of the application of the weighing device. Some weighing platforms provide an additional apparatus to contain the object during mass measurements and reduce environmental interference. Objects are generally positioned on the weighing platform so that the center of mass of the object coincides with the center of the weighing platform.

Indicator

Indicators are devices that provide a readable display of the electronic output of the load cell readings. The analog signal from the load cell(s) is amplified and transmitted to an A/D converter where the signal is converted to a discrete digital number proportional to the magnitude of the analog signal. The digital signal is transmitted to a processor which computes and outputs the measurement value to the display and peripheral interfaces.

Prior to taking measurements, the weighing device must be zeroed with no load present to ensure accurate measurements. This action compensates for any existing environmental conditions that offset the measurement readings. Most indicators provide functions to zero, tare, and offset the measurement readings, as well as configuration options to adjust the preferred units of the measurements, such as conversions between weight and mass measurements.

Many weighing devices have indicators with adjustable measurement capabilities defined by the capacity of the weighing device and the number of available discrete values, or divisions, provided by the indicator. Typical indicators have between 256 and 10,000 divisions. Adjusting the capacity on the indicator redefines the readability, the capacity divided by the number of divisions, of a weighing device. Adjusting the indicator to lower capacity settings allows for more precise measurements.

Data Acquisition

Most indicators include output connections to connect peripheral devices such as the FRL Data Acquisition (DAQ) system. One connection type is an RS-232 communication interface which is used to transmit the weight and time to a recording device such as a computer or printer. RS-232 connections usually consist of DB9 serial (9-pin) or DB25 parallel (25-pin) communication ports. On some models, there is an option to install an analog output board, which converts the discrete digital number on the indicator display to an analog signal. Another option is an Ethernet output board. This allows direct connection to the FRL DAQ system through an Ethernet cable. This board’s output will match the output on the indicator. The timestamp for the data is derived from the FRL DAQ system’s time.

Uncertainty and Accuracy

In the United States, the field of weights and measures is generally governed by the National Institute of Standards and Technology (NIST) Handbook 44 document [2]. Handbook 44 divides weighing devices into accuracy classes I, II, III, III L, and IIII according to the number of scale divisions and the value of the verification scale divisions as shown in Figure 5. The verification scale division (e) should not be confused with the scale division (d). Although they are often times the same, a weighing device may have more scale divisions than the number of verification scale divisions. In Legal for Trade (LFT) applications, the accuracy or resolution of a weighing device must be set in accordance with the accuracy class for which it was certified. However, weighing devices often have flexible resolution modes to accommodate non-LFT or industrial applications. In standard or industrial mode, the resolution can be configured based on the sensitivity and measurement range of the load cell(s) and the quality of the indicator unit.

Table 3.
Parameters for Accuracy Classes

Class	*Value of the Verification Scale Division (d or e[1])*	*Number of Scale[4] Divisions (n)*	
		Minimum	*Maximum*
	SI Units		
I	*equal to or greater than 1 mg*	*50 000*	*--*
II	*1 to 50 mg, inclusive*	*100*	*100 000*
	equal to or greater than 100 mg	*5 000*	*100 000*
III[2,5]	*0.1 to 2 g, inclusive*	*100*	*10 000*
	equal to or greater than 5 g	*500*	*10 000*
III L[3]	*equal to or greater than 2 kg*	*2 000*	*10 000*
IIII	*equal to or greater than 5 g*	*100*	*1 200*
	Inch-Pound Units		
III[5]	*0.0002 lb to 0.005 lb, inclusive*	*100*	*10 000*
	0.005 oz to 0.125 oz, inclusive	*100*	*10 000*
	equal to or greater than 0.01 lb	*500*	*10 000*
	equal to or greater than 0.25 oz	*500*	*10 000*
III L[3]	*equal to or greater than 5 lb*	*2 000*	*10 000*
IIII	*greater than 0.01 lb*	*100*	*1 200*
	greater than 0.25 oz	*100*	*1 200*

[1] *For Class I and II devices equipped with auxiliary reading means (i.e., a rider, a vernier, or a least significant decimal differentiated by size, shape, or color), the value of the verification scale division "e" is the value of the scale division immediately preceding the auxiliary means.*

[2] *A scale marked "For prescription weighing only" may have a verification scale division (e) not less than 0.01 g.*
(Added 1986) (Amended 2003)

[3] *The value of a scale division for crane and hopper (other than grain hopper) scales shall be not less than 0.2 kg (0.5 lb). The minimum number of scale divisions shall be not less than 1000.*

[4] *On a multiple range or multi-interval scale, the number of divisions for each range independently shall not exceed the maximum specified for the accuracy class. The number of scale divisions, n, for each weighing range is determined by dividing the scale capacity for each range by the verification scale division, e, for each range. On a scale system with multiple load-receiving elements and multiple indications, each element considered shall not independently exceed the maximum specified for the accuracy class. If the system has a summing indicator, the n_{max} for the summed indication shall not exceed the maximum specified for the accuracy class.*
(Added 1997)

[5] *The minimum number of scale divisions for a Class III Hopper Scale used for weighing grain shall be 2000.*
(Added 2004)

Figure 5. Excerpt of NIST Handbook 44 summarizing the parameters for different accuracy classes

In more specific cases, some weighing devices adhere to custom specifications not presented by the general guidelines in NIST Handbook 44. These weighing devices adhere to the calibration procedures outlined in NIST Handbook 44 with adjusted accuracy standards according to the manufacturer's specifications. These specific accuracy standards are usually more stringent than the standards supplied in NIST

Handbook 44 and generally apply to weighing devices that perform very precise measurements.

The following components of measurement error, as determined by tolerances outlined in the manufacturer's specifications or NIST Handbook 44, are considered in the uncertainty analysis of a weighing device:

Tolerance
Readability
Linearity
Hysteresis
Repeatability
Creep
Sensitivity
Temperature effects on minimum dead load output
Temperature effects on sensitivity

The measurement uncertainty for a weighing device was determined using guidelines in the NIST Technical Note 1297 [3], Special Publication 1007 [4], and the NIST Uncertainty Workshop [5]. The uncertainty of mass measurements includes the allowable uncertainty, random uncertainty, and combined uncertainty.

ALLOWABLE UNCERTAINTY

The allowable uncertainty is determined from allowable tolerances provided in the manufacturer's specifications and NIST Handbook 44. The allowable tolerances defined by the manufacturer are:

Measurement tolerance
Linearity
Repeatability

Additional allowable tolerances mandated by NIST Handbook 44 are:

Zero balance
Sensitivity
Temperature effect on the minimum dead load output over a temperature change of 5°C

The error associated with each tolerance, *T*, assumes a rectangular probably distribution and can be calculated by dividing the tolerance by $\sqrt{3}$. The allowable uncertainty, U_A, can be calculated by combining the error components in quadrature using Equation 1.1.

$$U_A = \sqrt{\sum \left(\frac{T}{\sqrt{3}}\right)^2} \tag{1.1}$$

RANDOM UNCERTAINTY

The random uncertainty, U_R, is determined from random errors that occur naturally during operation. The errors are determined using sample measurements taken during typical test conditions. The random uncertainty is calculated by applying the standard deviation, *S*, and the number of measurements, *n*, in a sample to Equation 1.2.

$$U_R = \frac{S}{\sqrt{n}} \tag{1.2}$$

COMBINED UNCERTAINTY

The combined uncertainty, U_C, is determined from the combining the allowable uncertainty and random uncertainty in quadrature. The combined uncertainty is calculated using Equation 1.3.

$$U_C = \sqrt{\left({U_A}^2 + {U_R}^2\right)} \tag{1.3}$$

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The weighing device and data acquisition (if applicable) instrumentation shall be calibrated and marked with the calibration status in accordance with FRL calibration procedures.
3. The weighing device shall be installed in an area that minimizes excess air currents, vibration, and drastic temperature or humidity changes.
4. The weighing device shall be within manufacturer recommenced operating temperature range.
5. The weighing device shall be acclimated to the environment.

PROCEDURE

1. Pre-Test

1.1. Level the weighing device.

1.2. Connect power to the weighing device

1.2.1. Manufacturer may require the power to be connected for an extended period of time before measurements. Consult manufacturer documentation.

1.3. Run all data acquisition cords perpendicular to the power cord to minimize signal interference.

1.4. Zero the weighing device

1.4.1. If applicable, place weighting container onto the platform and tare the weighing device before applying load.

1.5. Center the object on the loading platform.

2. During the Test

2.1. The output of the weighing device shall be recorded for the duration of the experiment.

2.1.1. Exception – When the weighing device must be removed prior to the end of the experiment due to experiment design or damage. The elapsed time at which the instrument was removed and the reason for removal shall be recorded.

2.1.2. Exception- If the weighing device is used for a single point measurement, the display reading shall be documented in the datasheet or with a photo of the digital display.

2.1.2.1. In the case of single point measurements, wait for readings to stabilize before recording mass measurements.

3. Post Test

3.1. After the experiment, the weighing device shall be examined for visible damage.

3.1.1. If damage has occurred, the instrument shall be taken out of service at the time of the damage.

3.1.2. The laboratory engineer shall review the data to determine if there is a noticeable event that marked the damage to the instrument. If not, the instrument shall be taken out of service for the entire test.

3.2. Clean the platform of debris or residue.

Weighing Device Documentation Requirements

A weighing device shall be documented using the FireTOSS experiment design program. The required information that the user must document when using the weighing device in an experiment is shown in Table 1. The first column provides the input parameter, and the second column provides a brief description of that parameter. The third column lists whether the parameter is required in all cases. The fourth column lists how the parameter is entered into the FireTOSS design program.

Table 1. Data Acquisition Input Parameters

Parameter	Parameter Description	Required	Input Method
Calibration Status	Determines if the instrument was in calibration for the experiment.	TRUE	Automatic
Bar Code	FRL asset number for the load cell	TRUE	User Selectable from List
Description	Description of the load cell	FALSE	Automatic
Manufacturer	Manufacturer	TRUE	Automatic
Serial Number	The manufacturer provided serial number	TRUE	Automatic
Model Number	The manufacturer provided model number	TRUE	Automatic
Range	Peak value to which the load cell was calibrated	FALSE	Automatic
Mass offset	Subtract this offset from the mass data **Default value is 0**	FALSE	User
Smoothing Algorithm	Algorithm used to smooth the mass data. **Default Value is Running Average**	FALSE	User
Smoothing Algorithm Value	Parameter for the smoothing algorithm **Default value is 11**	FALSE	User
MLR Algorithm	Algorithm used to calculate the mass loss rate (MLR) **Default is Linear Regression**	FALSE	User
MLR Algorithm Value	Parameter for the MLR algorithm. **Default value is 31**	FALSE	User
Initial	Mass measured at the start of the experiment	FALSE	Automatic
Final Value	Mass measured at the end of the experiment	FALSE	Automatic
Mass Loss	Total mass loss during experiment.	FALSE	Automatic
Mass Data	Mass data measured by the load cell	FALSE	Automatic
Mass Loss Rate Data	Mass loss rate data calculated from the mass data	FALSE	Automatic

Parameter	Parameter Description	Required	Input Method
Average	Average mass loss rate for the entire experiment	FALSE	Automatic
Average 10-90	Average mass loss rate over the period where the 10 percent and 90 percent of the mass loss occurred	FALSE	Automatic
Corrected Mass Data	Mass data that has been corrected for the offset	FALSE	Automatic
Smoothed Mass Data	Mass data that has been corrected for the offset and smoothed	FALSE	Automatic
Time Out of Service	Indicates the elapsed test time that the instrument was removed from the test. All calculations for the data on the instrument cease at this time.	FALSE	User
Out of Service Reason	Specifies the reason that the instrument was removed from the experiment. Reasons typically include damage, impending damage, or test design	FALSE	User
Chart	Integer, Allows the user to group instrument data onto different charts. If this parameters is left empty all the charts will contain data for all instruments. A value of -1 indicates that the data will not be shown on a chart.	FALSE	User
Procedure for Out of Range Values Max	How to deal with data that went above the maximum allowable measurement reading.	FALSE	User
Procedure for Out of Range Values Min	How to deal with data that went below the minimum allowable measurement reading.	FALSE	User
Maximum Allowable measurement	The maximum measurement allowed to be used for the instrument	FALSE	Automatic
Minimum Allowable Measurement	The minimum measurement allowed to be used for the instrument	FALSE	Automatic
Readings Went out of Range	Indicates that the measurement went out of range.	FALSE	Automatic

Appendix A – Definitions of Common Errors in Weighting Device Measurements

Tolerance: The allowable difference between standard test loads and the measured load value calculated by the weighing device.

Readability: The readability of a weighing device is the smallest change in load which produces a signal that can be measured by the indicator. Readability is also referred to as the display resolution. Many error quantities are determined by the readability of the device.

Linearity: The deviation of the actual relationship between the load to signal output and a linear relationship throughout the entire capacity of the weighing device.

Hysteresis: The error associated with the direction and magnitude by which the load is applied. Hysteresis is calculated by applying loads ascending from zero to the rated output and then descending from the rated output to zero. The maximum difference obtained at each load step is considered the maximum hysteresis error.

Repeatability: The maximum difference between the load cell signal at repeated loads under identical loading and environmental conditions.

Creep: The change in signal output over time under constant load and environmental conditions.

Sensitivity: The sensitivity of the weighing device is equal to the smallest noticeable load applied to the device.

Temperature Effects: Errors associated with temperature change are more prevalent in weighing devices containing strain gauge load cells than MFR load cells due to their operating principles. Temperature can affect the material properties of the of the load cell, the electrical resistance of the strain gauge, and/or the bond of the strain gage to the beam.

References

1. Omega Engineering Inc. "Transactions in Measurement and Control: Force-Related Measurements (Vol. 3)." Stamford, CT, USA: Putman Publishing Company and Omega Press LLC, 1998.

2. NIST Weights and Measures Division. "Handbook 44: Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices." Gaithersburg, MD: National Institute of Standards and Technology, 2010.

3. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results." Gaithersburg, MD: National Institute of Standards and Technology, 1993.

4. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007." Gaithersburg, MD: National Institute of Standards and Technology, 2003.

5. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty." National Institute of Standards and Technology, Presentation given to CPSC, 2007.

1. **Title:** Procedure for Technical Research.

2. **Scope:**
   2.1. This Policy and Procedures Guideline establishes a system by which laboratory engineers perform technical research in an accredited manner. This guideline lays out minimum requirements for performing and documenting the technical research.
   2.2. The provisions of this procedure exclude data considered common knowledge.

3. **Description:**
   3.1. Technical research is performed to help answer questions through searching reference documents, product information or other sources of knowledge relevant to an engineering analysis.
   3.2. The source reference from which data is used in engineering analyses shall be documented in the "project file" or the report.
   3.3. Engineering judgment is to be used to assess the pertinence and accuracy of the data and the reference.

4. **Uncertainty**
   Where appropriate, multiple references will be compared to assess the uncertainty of the reference data.

5. **Procedure**
   5.1. Potential reference documents may come from any reputable source.
   5.2. The pertinence and accuracy of the reference and the data is assessed.
   5.3. The source is documented in accordance with Section 6 below.

6. **Documentation**
   Source documents shall be documented in a manner that allows it to be identified and located by other engineers with an equivalent level of training to that of the document author.

Scope

This Technical Reference covers the use, design and specifications of Pitot-Static Probes and Bi-directional Probes used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Pitot-static probes and bi-directional probes are used for point velocity calculations in a flow field based on measurements of the local differential pressure. They may be used for both internal and external flows. The probe designs are based on Bernoulli's principle which relates fluid velocity to the dynamic pressure. A typical configuration consists of the pressure probe inserted into a flow field with tubing connecting the probe to a differential pressure transducer. A thermocouple is placed near the probe location to monitor the local temperature. The thermocouple and pressure transducer are connected to the data acquisition system. All instrumentation must be calibrated according to the manufacturer and ATF specifications.

PITOT-STATIC PROBE

Figure 1 shows a schematic of a typical Pitot-static probe [1]. The probe is designed to measure dynamic pressure directly. It has two pressure sensors: one on the tip that senses total, or stagnation, pressure; and one or more along the side that sense the static pressure. The difference between these is the dynamic pressure, which is measured using a differential pressure transducer.

Pitot-static probes are generally used in clean environments because the pressure ports are typically small and susceptible to blockage. Pitot-static probes are relatively insensitive to misalignment over a range of ±15°, however can be used only for flow in one direction [1].

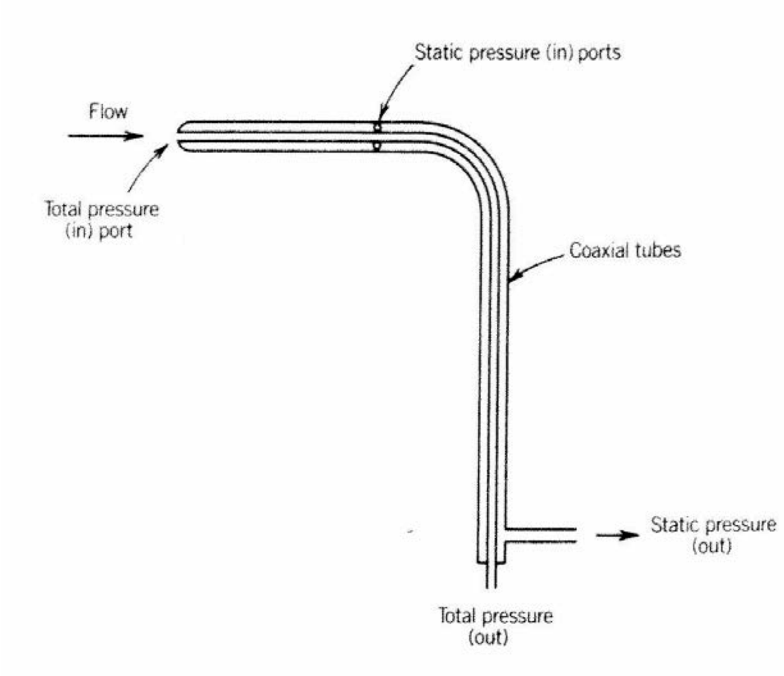


Figure 1: Schematic of a Pitot-static probe [1]

BI-DIRECTIONAL PROBE

A bi-directional probe is a device that contains two pressure ports facing opposite of each other to sense the static and total pressure of a point in the flow field. Figure 2 shows a schematic of a bi-directional probe. Bi-directional probes are frequently used in fire experiments because of their rugged design and their ability to sense pressure differentials in two directions. Additionally, bi-directional probes are relatively insensitive to alignment with the flow direction. Measured average velocities are accurate to within ± 10% with deviations as large as ± 50° between the probe axis and the flow direction [2].

While a Pitot-static probe measures dynamic pressure directly, a correction must be applied to bi-directional probe measurements in order to calculate velocity. This correction is discussed in the 'Calculations' section below.

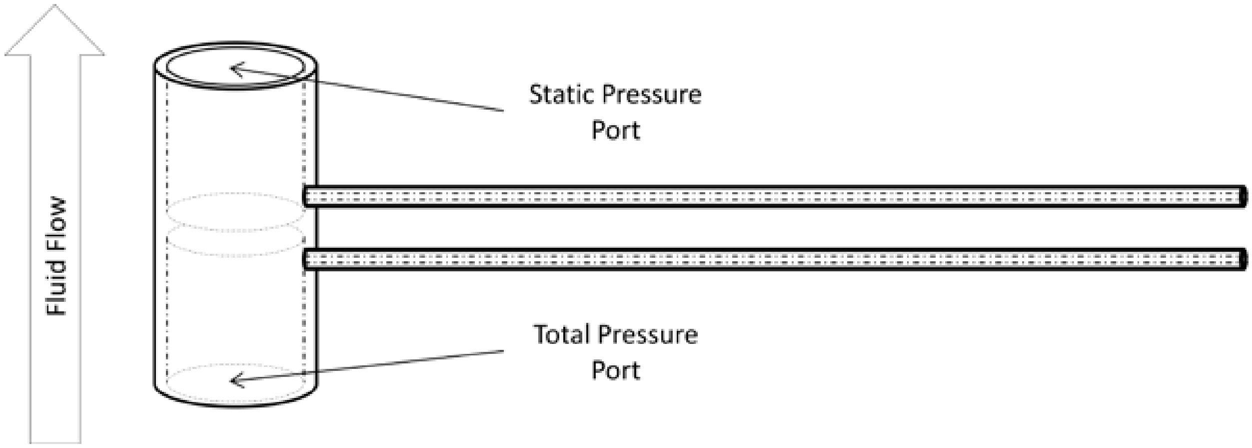


Figure 2: Schematic of a bi-directional probe

TEMPERATURE MEASUREMENT

In order to calculate velocity, temperature must be measured in addition to differential pressure. Typically this is accomplished by placing a thermocouple in the flow field, near the location of the probe. Figure 3 shows a photograph of a thermocouple mounted to a bi-directional probe. Further discussion on the use of thermocouples in the FRL can be found elsewhere [3].

Figure 3: Shielded thermocouple mounted to a bi-directional probe

PRESSURE TRANSDUCER

Pitot-static probes and bi-directional probes are connected to differential pressure transducers using plastic or metal tubing. Velocities encountered in typical fire experiments correlate to small differential pressures, on the order of 0.62 kPa (2.5 inches of water) or less. The range of a selected transducer must be selected accordingly.

MKS

The FRL uses MKS Type 220DD Baratron General Purpose Differential Pressure Manometers with a range of 0.13 kPa (0 – 1 Torr) [4]. Figure 4 shows a photograph of this instrument. The output of this device is 0 – 10 VDC.

Figure 4: MKS Type 220DD Differential Pressure Manometer

Setra

The FRL uses Setra model 267 pressure transducers [5]. These instruments are available with a wide range of input and output settings. Figure 5 shows a photograph of this instrument.

Figure 5: Setra Model 267 Differential Pressure Transducer

Calculations

VELOCITY CALCULATION

Pitot-Static Probe

The velocity is calculated according to the relation:

$$V = C\sqrt{\Delta P T} \qquad (1.1)$$

where ΔP is the measured differential pressure, T is the measured temperature at the velocity probe, and the flow factor C is calculated from $\sqrt{2/\rho_0 T_0}$ where T_0 is the reference temperature and ρ_0 is the fluid density at the reference temperature [2].

Bi-Directional Probe

Eqn. (1.1) also applies to bi-directional probes, however the pressure difference is slightly greater than the dynamic pressure given in (1.1) and a correction to C is required. This correction varies with flow conditions and is well represented by a function of the Reynolds number (Re) based on the probe diameter for 40 < Re < 3800 [2]:

$$\frac{\sqrt{\frac{2}{\rho_0 T_0}}\sqrt{\Delta P T}}{V} = 1.533 - 1.366\times10^{-3}\,\mathrm{Re} + 1.688\times10^{-6}\,\mathrm{Re}^2 - 9.706\times10^{-10}\,\mathrm{Re}^3 + 2.555\times10^{-13}\,\mathrm{Re}^4 - 2.484\times10^{-17}\,\mathrm{Re}^5 \qquad (1.2)$$

Values of C for Pitot static and bidirectional probes are listed in Table 1 for a reference condition of T_0 = 300K and 1 atm ($_0$ = 1.1774 kg/m^3) [6].

Table 1 Flow factor (C in Eqn 1.1) for Pitot and Bidirectional probes

Probe Type	Formula [2]	C Value at 300 K, 1 atm (m$^{3/2}$/kg$^{1/2}$ K$^{1/2}$) [6]
Pitot-static	$\sqrt{2/\quad {}_0 T_0}$	0.075248
Bi-directional	$\sqrt{2/\quad {}_0 T_0}$ / f(Re)	0.075248 / f(Re)

Figure 6 shows a chart of Eqn. (1.2) plotted as a function of Reynolds number. Most flow conditions of interest in Fire Product Collectors (FPC) are characterized by Reynolds numbers higher than the upper limit of 3800 prescribed to Eqn. (1.2) in [2]. The Reynolds number for typical flows in FRL FPC's can range as high as 18,000 – 20,000. However, Eqn. (1.2) cannot be realistically extrapolated to Reynolds numbers higher than 3800. Because of this, a value of 1.08 is commonly applied to bidirectional probe FPC velocity measurements in place of a value calculated from Eqn. (1.2) [7]. The RHS of Eqn. (1.2) has a value of 1.081 at Re = 2000. For this reason, the approach adopted by the FRL is to apply Eqn (1.2) for 40 < Re < 2000 and use the constant 1.08 value for Re > 2000.

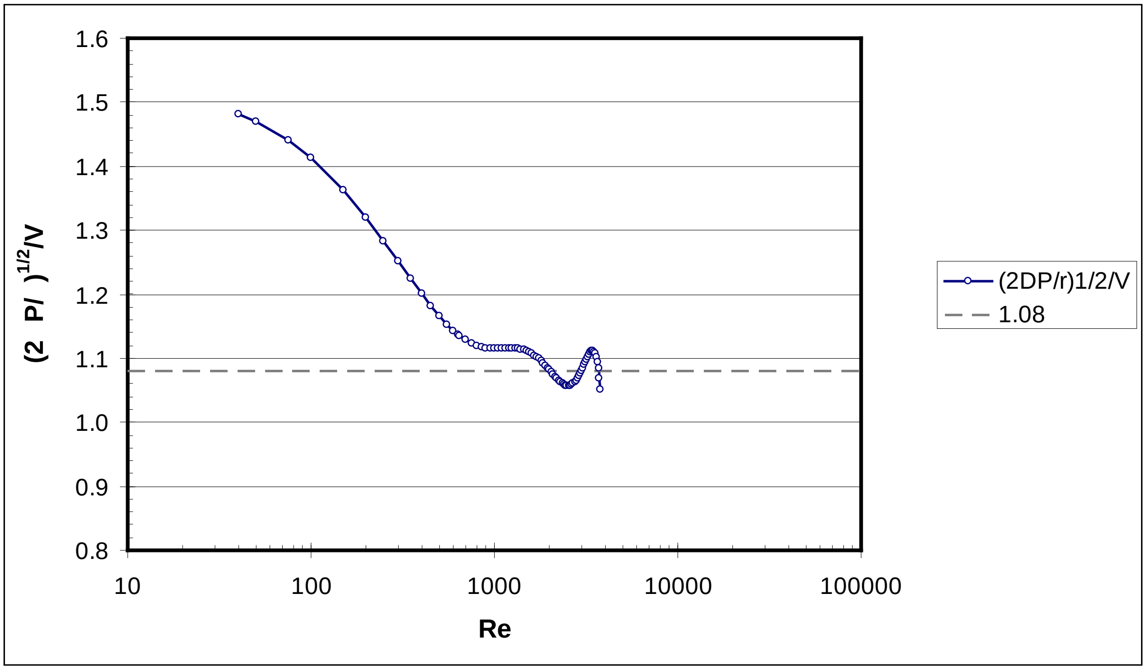


Figure 6: Plot of Equation (1.2) showing bi-directional velocity correction factor as a function of Reynolds number.

UNCERTAINTY CALCULATION

The uncertainty of the FPC exhaust duct velocity measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [7], Technical Note 1297 [8], and the NIST Uncertainty Workshop [9]. The combined standard uncertainty of the velocity is a combination of the uncertainty of its components given by the following equation:

$$u_c(\mathrm{V}) = \sqrt{\sum \mathrm{s}_\mathrm{i}^2 \mathrm{u}(\mathrm{x}_\mathrm{i})^2} \qquad (1.3)$$

where:

$u_c(\mathrm{V})$ = Combined standard uncertainty of the velocity
$\mathrm{u}(\mathrm{x}_\mathrm{i})$ = Standard uncertainty of each component
s_i = Sensitivity coefficient $(\partial \mathrm{V}/\partial \mathrm{x}_\mathrm{i})$

Using Eqn (1.1), the main sources of uncertainty are the differential pressure measurement, the temperature measurement, and the flow factor. Based on this, Eq. 1.3 can be applied to Eq. 1.1 to yield:

$$u_c(V) = \left[\left(\sqrt{\Delta PT}\right)^2 \left(\mathrm{u(C)}\right)^2 + \left(\frac{\mathrm{C}}{2}\sqrt{\frac{T}{\Delta P}}\right)^2 (\mathrm{u}(\Delta P))^2 + \left(\frac{\mathrm{C}}{2}\sqrt{\frac{\Delta P}{T}}\right)^2 \left(\mathrm{u(T)}\right)^2\right]^{1/2} \qquad (1.4)$$

where:

u(C) = Standard uncertainty of the flow factor C
$u(\Delta P)$ = Standard uncertainty of differential pressure measurement
u(T) = Standard uncertainty of the temperature measurement

Flow Factor

As shown in Table 1 the flow factor for a Pitot-static probe is a constant, based on the properties of air at the reference condition T = 300 K and P = 1 atm. The uncertainty of this value is taken as zero.

In the case of a bi-directional probe, the uncertainty stems from the error associated with the empirical fit of Eqn. (1.2). This error is taken as ± 5% [2].

Differential Pressure

MKS 220DD

The MKS 220DD pressure transducer has a range of 0 to 0.13 kPa (0 - 1 Torr). MKS lists the accuracy as ± 0.15% of the reading. It can be assumed that the accuracy from the MKS 220DD has a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing the accuracy by $\sqrt{3}$ [8]. At the maximum pressure of 0.13 kPa, the accuracy of the MKS 220DD is ± 0.2 Pa. The corresponding standard uncertainty is ± 0.12 Pa.

The uncertainty of the differential pressure measurement also includes a statistical component based on random fluctuations in the measurements. The standard uncertainty of the random fluctuations is calculated using Eqn. (1.5),

$$u = \frac{S}{\sqrt{n}} \qquad (1.5)$$

where:

S = Standard deviation of the measurements in a sample
n = Number of measurements in the sample

The standard uncertainty for the MKS 220DD, based on a sample containing 600 measurements, is ± 0.338 Pa.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the differential pressure readings. The result using the MKS 220DD is $u(\Delta P) = 0.359$ Pa. This translates to a relative combined standard uncertainty of 0.269 %.

Setra 267
Setra lists the accuracy for a model 267 transducer as ± 0.4% F.S., the linearity as ± 0.38% F.S., the hysteresis as 0.1% F.S., and the repeatability as 0.05 % F.S. [5]. It can be assumed that these each have a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing each component by $\sqrt{3}$ [8]. For a model with input range P = 0 – 0.62 kPa (0 – 2.5 inch H_2O) the standard uncertainty of the differential pressure readings is ± 2.04 Pa.

The statistical component of the standard uncertainty, based on a sample containing 600 measurements, is ± 0.453 Pa.

The uncertainties are combined in quadrature to calculate the standard uncertainty of the differential pressure readings. The result for the Setra 267 is $u(\Delta P) = 2.07$ Pa. This translates to a relative standard uncertainty of 0.33 %.

Temperature

The ATF FRL purchases Type-K thermocouples with a minimum accuracy of the greater of 1.1°C or 0.4% of the reading above 0°C. Temperature measurements in the FPC's are typically below 275°C, in which case the temperature accuracy is ± 1.1°C. It is assumed that the error from the thermocouple has a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing the accuracy by $\sqrt{3}$ [8]. The corresponding standard uncertainty for a temperature measurement is ± 0.64°C.

The standard uncertainty for the random fluctuations, based on a sample containing 600 measurements, is ±0.0021 °C.

The uncertainties are combined in quadrature to calculate the standard uncertainty of the temperature measurement. The result is $u(T) = 0.64$ °C. .

Summary

Table 2 summarizes the standard uncertainties of the velocity components as well as the combined standard uncertainty for velocity measurements for the conditions T = 275°C, P = 300 Pa. Under these conditions, the nominal velocity (as measured using a bi-directional probe) is V = 28.3 m/s.

Table 2 Summary of uncertainty values for point pressure measurement setups

Probe Type	Pressure Transducer	u(C)	$u(\Delta P)$ (Pa)	u(T) (°C)	u_c(V) (m/s)	Relative Combined Standard Uncertainty (%)
Pitot-Static	MKS 220DD	0	0.359	0.64	0.0254	0.08
Pitot-Static	Setra 267	0	2.07	0.64	0.107	0.35
Bi-directional	MKS 220DD	± 0.003	0.359	0.64	1.35	4.76
Bi-directional	Setra 267	± 0.003	2.07	0.64	1.35	4.77

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Scope

This Technical Reference covers the use, design and specifications of the Averaging Velocity Probes used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Calculations related to large scale Fire Product Collectors (FPC) rely on knowledge of the flow rate of air and products of combustion through the exhaust duct. Because velocity profiles in the ducts are generally non-uniform, there are two approaches to measuring the flow rate. The first is to rely on point velocity measurements and the application of a flow shape factor. The second approach is to measure the average velocity directly. Instrumentation used for point velocity measurements are covered in a separate document [1]. Averaging velocity probes are used to measure the average dynamic pressure across a section of pipe or duct, from which the velocity is calculated without requiring a flow shape factor. Components consist of the probe itself, plus a mounting bracket to attach the probe to the duct. A typical configuration consists of two or more probes mounted inside a section of FPC duct with tubing connecting the probes to a differential pressure transducer. A thermocouple is placed near the probe location to monitor the local temperature. The thermocouple and pressure transducer are connected to the data acquisition system. All instrumentation must be calibrated according to the manufacturer and ATF specifications.

Velocity Profiles

Flow in the FRL FPC exhaust ducts is turbulent, which generally causes velocity profiles to be flatter and more uniform. Additionally, each duct contains an orifice that is designed to enhance mixing. Despite this, velocity profiles in the FPC exhaust ducts are not uniform [2]. Figure 1 shows a chart of the velocity profile measured in the 14 MW FPC duct [2].

Figure 1: Velocity profile measured in the 14 MW FPC duct.

PROBE DESCRIPTION

Volu-Probe

The FRL uses externally mounted Volu-Probe Airflow Traverse Probes in the FPC exhaust ducts [3]. Figure 2 shows a schematic of the probe. The probe consists of two manifolds; one each for static and total pressure measurement. Each manifold has pressure ports spaced at equal area intervals as shown in Figure 3, producing a pressure representing the instantaneous average across the duct. Each manifold feeds to a 1.3 cm (0.5 inch) female NPT connection that is connected to a differential pressure transducer. The probes are mounted on one end with a 15.2 cm x 15.2 cm (6 inch x 6 inch) mounting plate, with the opposite end secured by a pin support. All components are constructed of stainless steel.

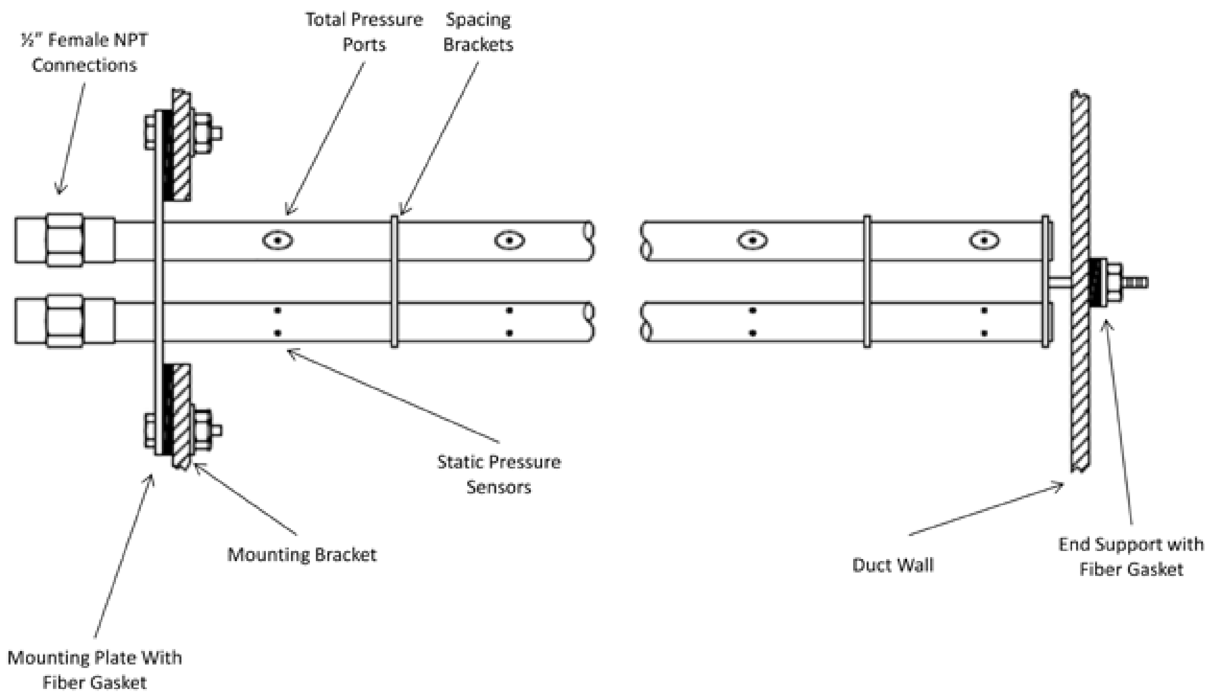

Figure 2: Schematic of the velocity traverse probes [2].

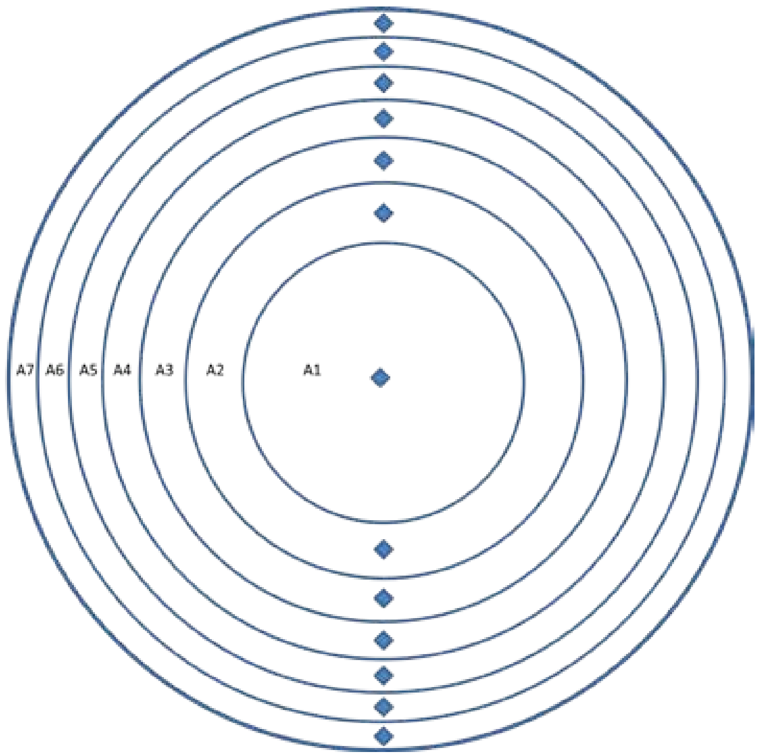

Figure 3: The surface area of the duct divided into sections of equal area.

Mounting Bracket

The probes are externally mounted to the duct using a 15.2 cm x 15.2 cm (6 inch x 6 inch) mounting bracket that is customized to fit the curvature of the exhaust duct (Figure 4). The mounting bracket is welded around a 10 cm (4 inch) hole in the exhaust duct. The probes are then inserted into the hole and the mounting plate is secured to the mounting bracket. High temperature fiber gasket is used to seal the space between the mounting plate and the mounting bracket as well as the duct wall at the end support.

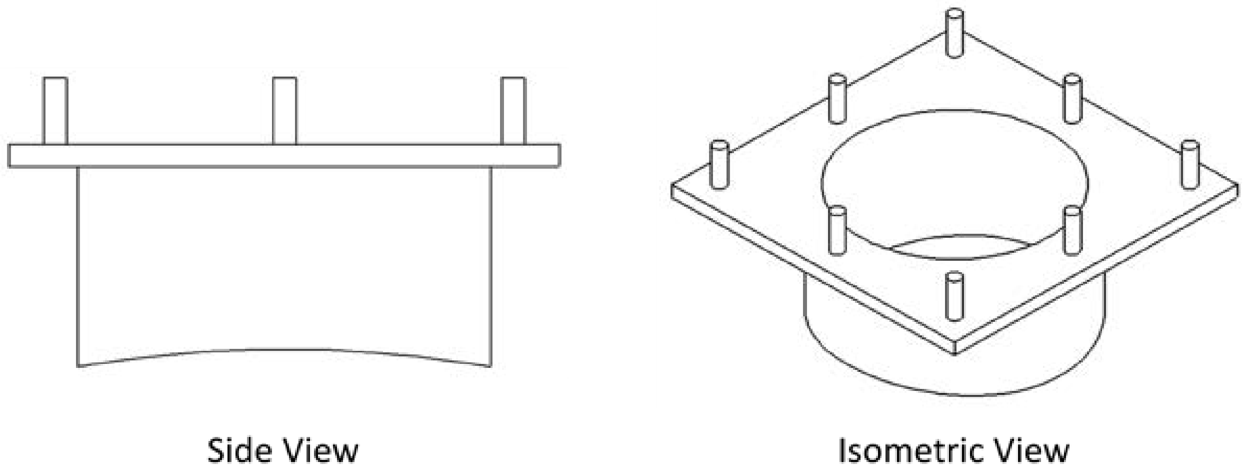

Figure 4: The mounting bracket used to mount the probes to the exhaust duct.

Probe Installation
The probes are installed in the exhaust duct based on manufacturer's specifications [3]. Specifications require that multiple probes are used to achieve the stated accuracy of ± 2 – 3 %, with the number of probes depending on duct diameter. The probes are installed at an angle from each other with an axial spacing of 3.8 cm (1.5 inch) between the centers of the manifolds on each probe (Figure 5). The static and total pressure manifolds from each probe are combined into a single static pressure line and a single total pressure line via 1.3 cm (0.5 inch) tubing and Swagelok tee unions. The tubing is connected to a single differential pressure transducer.

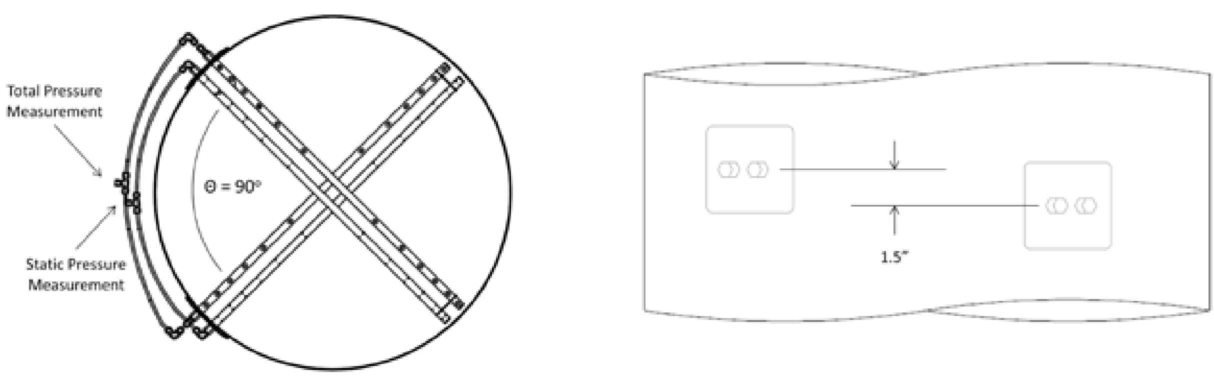

Figure 5: The layout of the velocity traverse probes in the exhaust hoods for two probes [3].

TEMPERATURE MEASUREMENT

In order to calculate velocity, temperature must be measured in addition to differential pressure. Typically this is accomplished by placing a thermocouple in the flow field, near the location of the probe. Further discussion on the use of thermocouples in the FRL can be found elsewhere [4].

PRESSURE TRANSDUCER

<u>Setra</u>

The FRL uses Setra model 267 pressure transducers for FPC measurements [5]. These instruments are available with a wide range of input and output settings. Generally, a transducer with a range of 0 – 622.7 Pa (0 – 2.5 inches of water) and an output of 4 – 20 mA works well in FPC applications. Figure 6 shows a photograph of this instrument.

Figure 6: Setra Model 267 Differential Pressure Transducer

Calculations

VELOCITY CALCULATION

The velocity is calculated according to the relation:

$$V = C\sqrt{\ PT} \qquad (1.1)$$

where P is the measured differential pressure, T is the measured temperature at the velocity probe, and the flow factor C is calculated from $\sqrt{2/\ {}_0 T_0}$ where T_0 is the reference temperature and $_0$ is the fluid density at the reference temperature [6].

UNCERTAINTY CALCULATION

The uncertainty of the FPC exhaust duct velocity measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [7], Technical Note 1297 [8], and the NIST Uncertainty Workshop [9]. The combined standard uncertainty of the velocity is a combination of the uncertainty of its components given by the following equation:

$$u_C(\mathrm{V}) = \sqrt{\sum \mathrm{s}_\mathrm{i}^2 \mathrm{u}(\mathrm{x}_\mathrm{i})^2} \qquad (1.2)$$

where:

$u_c(\mathrm{V})$ = Combined standard uncertainty of the velocity
$\mathrm{u}(\mathrm{x}_\mathrm{i})$ = Standard uncertainty of each component
s_i = Sensitivity coefficient $(\partial \mathrm{V}/\partial \mathrm{x}_\mathrm{i})$

Using Eq. (1.1), the main sources of uncertainty in the velocity are the differential pressure and temperature measurements. Based on this, Eq. 1.1 can be applied to Eq. 1.2 to yield:

$$u_c(V) = \left[\left(\sqrt{\Delta PT}\right)^2 (\mathrm{u}(\mathrm{C}))^2 + \left(\frac{\mathrm{C}}{2}\sqrt{\frac{T}{\Delta P}}\right)^2 (\mathrm{u}(\Delta P))^2 + \left(\frac{\mathrm{C}}{2}\sqrt{\frac{\Delta P}{T}}\right)^2 (\mathrm{u}(\mathrm{T}))^2\right]^{1/2} \qquad (1.3)$$

where:

u(C) = Standard uncertainty of the flow factor C
$\mathrm{u}(\Delta P)$ = Standard uncertainty of differential pressure measurement
u(T) = Standard uncertainty of the temperature measurement

Flow Factor

The flow factor is a constant, based on the properties of air at the reference condition T = 300 K and P = 1 atm. The uncertainty of this value ($u(C)$) is taken as zero.

Differential Pressure

The uncertainty of the differential pressure measurement is comprised of two components. The first component is associated with the probe, and the second is associated with the pressure transducer. Errors associated with the data acquisition system are negligible.

Probe Uncertainty

Volu-probe specifications indicate an accuracy of 2 – 3 %. For typical cold flow conditions in the 1 MW FPC (T = 300 K, V = 17.3 m/s, $\dot{m}$= 6.8 kg/s), the average differential pressure is P = 175.3 Pa.

The corresponding error in the pressure measurement, assuming 3% accuracy, is 10.52 Pa. Assuming a square distribution, the standard uncertainty is $u(\Delta P)_{probe}$ = 6.07 Pa [8].

Pressure Transducer

The Setra 267 pressure transducer has a range of 0 to 622.8 Pa (0 to 2.5 inches of water). Setra lists the accuracy as ± 0.4% F.S., the linearity as ± 0.38% F.S., the hysteresis as 0.1% F.S., and the repeatability as 0.05% F.S [4]. It can be assumed that the errors from the pressure transducer each have a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing each component by $\sqrt{3}$ [8]. Since these are all based on the full scale range of the transducer, they are independent of the measured value.

The uncertainty of the differential pressure measurement also includes variations arising from random fluctuations that occur naturally in the measurements. The standard uncertainty of the random fluctuations is calculated using equation 1.4,

$$u = \frac{S}{\sqrt{n}} \tag{1.4}$$

where:

S = Standard deviation of the measurements in a sample
n = Number of measurements in the sample

The standard uncertainty for the pressure readings, based on a sample containing 600 measurements, is ± 0.453 Pa.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the differential pressure readings. The result is $u(\Delta P)_{transducer}$ = 2.07 Pa.

The uncertainty associated with the probe and the pressure transducer are combined in quadrature to yield a combined standard uncertainty in the pressure measurement of $u(\Delta P)$ = 6.42 Pa.

Temperature

The temperature in the exhaust duct, T, is measured by a Type K thermocouple positioned at the center of the duct. The ATF FRL only purchases Type K thermocouples with a minimum accuracy of the greater of 1.1°C or 0.4% of the reading above 0°C. Assuming a reference temperature of 25°C, the error is ± 1.1°C. It is assumed that the error from the thermocouple has a rectangular probability distribution, in which case the standard uncertainty is calculated by dividing each component by $\sqrt{3}$ [8]. The standard uncertainty for a temperature measurement at 25°C is therefore ± 0.635°C.

The standard uncertainty for the random fluctuations, based on a sample containing 600 measurements, is ±0.0021 °C.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the temperature readings. The result is $u(T)$ = 0.635 °C. This translates to a relative combined standard uncertainty of 2.54 %.

Summary

Equation 1.2 is used to calculate the combined standard uncertainty in the velocity for the conditions P = 175.3 Pa, T = 300 K and V = 17.3 m/s. The resulting uncertainty is $u_c(V)$ = ± 0.31 m/s.

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Scope

This Technical Reference covers the use, design and specifications of sand burners and gas carts used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Sand burners are used in experiments to produce fires of known size and configurations. They are generally used for calibration of oxygen consumption calorimeters, but can be used whenever a known, fire size is needed. Sand burner and gas cart setups consist of a gaseous fuel supply, a gas cart consisting of fuel flow monitoring instrumentation and fuel flow control, and a square sand burner as shown in Figure 1. All instrumentation must be calibrated according to manufacturer and ATF specifications.

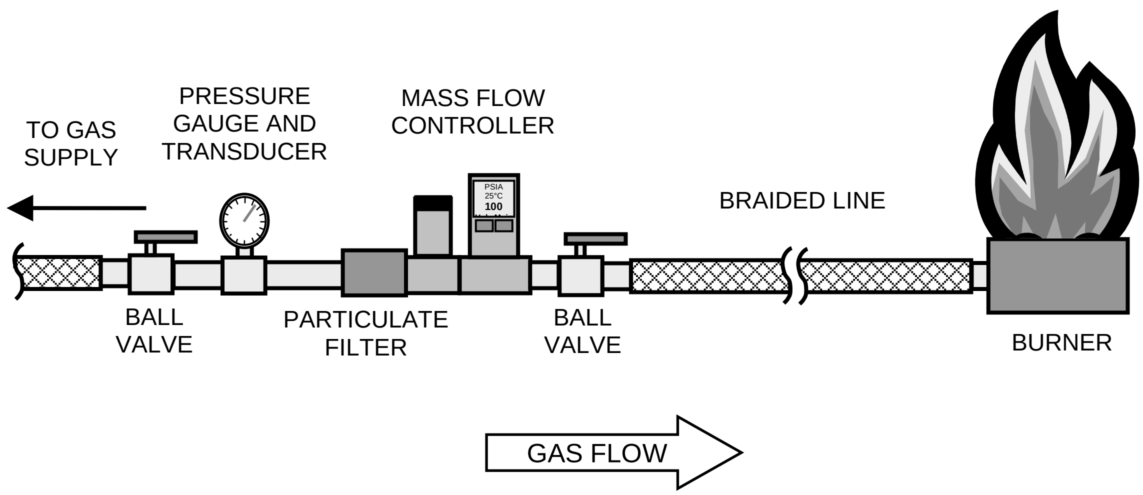

Figure 1. Sand burner and gas cart setup

GAS CART DESCRIPTION

The gas carts used by the FRL consist of fuel flow monitoring and control instrumentation mounted on a mobile cart. The cart also contains data acquisition hardware.

Gas Carts A, B, C & D are McMaster model 4731T72 instrument cart. The cart has two shelves. The bottom shelf is enclosed and has a lockable door. The flow control and monitoring instrumentation is mounted on the top shelf. A gas cart is shown in Figure 2.

Figure 2. Gas Cart A

Gas Cart E is a bi-level, mobile metal cart. The bottom shelf contains a sealable, waterproof box which houses the data acquisition components. The flow control and monitoring instrumentation is mounted on the top shelf. Gas Cart E is shown in Figure 3.

Figure 3. Gas Cart E

The flow control and monitoring instrumentation consists of components for pressure monitoring, flow control, and flow monitoring. Pressure monitoring is performed visually using a dial gauge and through data acquisition. A pressure gauge (0-206.8 kPa / 0-30 psig) is used to visually monitor the gas pressure in the train. A pressure transducer (Omegadyne PX209) transmits data to FireTOSS, but that data is only used for monitoring and is not used for calculations. For Gas Carts A, B, C, and D, flow control and monitoring is performed with an Alicat Scientific 16 Series Mass Flow Controller (MFC). For Gas Cart E, flow control and monitoring is performed with an Alicat Scientific MCR High-Flow Series MFC. A specified flow can be written to the MFC to control the fire size. The MFC also transmits an actual flow value to FireTOSS for monitoring and data acquisition purposes. A particulate filter (Arrow Pneumatics model 9076M for Carts A, B, C, and D; Parker Pneumatic model F602-10WJR/M4) is used in line upstream of the MFC. As shown in Table 1 FRL has five gas carts in operation: three with 1000 SLPM MFCs (Trains A, B, and D), one with a 100 SLPM MFC (Train C) and one with a 3000 SLPM MFC (Train E).

Gas Carts A, B, C, and D are connected to the natural gas main via 2.5 cm (1 inch) stainless steel braided hose (McMaster Carr Type 316), with 2.5 cm (1 inch) quick connect couplings to connect to the main and gas train. For the 1000 SLPM carts, the burner is connected to the cart using 2.5 cm (1 inch) stainless steel braided hose. For the 100 SLPM cart, the burner is connected to the cart using 0.64 cm (1/4 inch) stainless steel braided hose. Gas Cart E is connected to the gas main and to the burner via 5 cm (2 inch) stainless steel braided hose (McMaster Carr product number 5676T78).

Table 1. Gas Cart Properties

Gas Cart Type	Gas Train Name	HRR range (kW)
1000 SLPM Cart	A	0-575
1000 SLPM Cart	B	0-575
100 SLPM Cart	C	0-57.5
1000 SLPM Cart	D	0-575
3000 SLPM Cart	E	0-1320

SAND BURNER DESCRIPTION

The sand burners used in the ATF FRL are constructed in general accordance with the recommended ignition sources of ISO 9705 [1], ASTM E 1537 [2], and NFPA 286 [3]. Figure 3 shows a diagram of a typical sand burner. Natural gas is supplied to the sand burner via the gas inlet located at the base of the sand burner. As shown in Figure 3, the bottom of the sand burner contains a void space. A metal mesh is placed on a steel lip 7.5 cm (3 inch) from the bottom of the burner. The burner is then filled with a 2.5 cm (1 inch) layer of Fiberfrax, and 7.5 cm (3 inch) of small gravel. The Fiberfrax and gravel are used to diffuse the natural gas evenly across the entire opening of the burner.

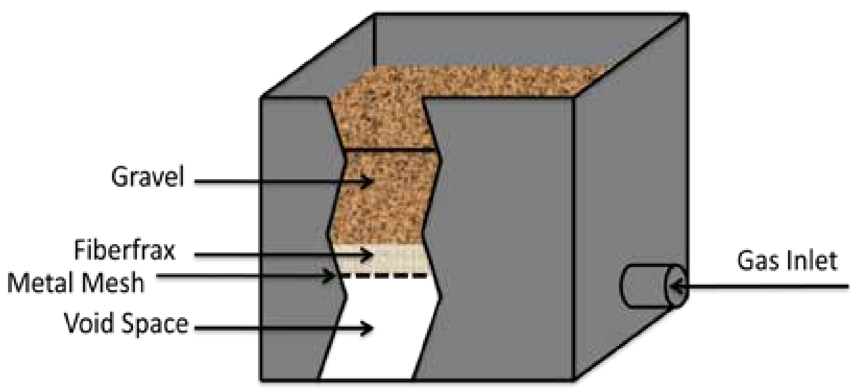

Figure 4 – Diagram of a Typical Sand Burner

There are three sizes of sand burners available for use in the FRL. The length and width of the burners are shown in Table 2. All sand burners available for use have the same height of 0.20 m.

Table 2. Sand Burner Sizes

Quantity Available	Sand Burner Size (m)
3	0.41 x 0.41
1	0.71 x 0.71
1	0.30 x 0.30
1	0.20 x 0.20

FUEL

The primary type of fuel used in sand burners is natural gas, however other gaseous fuels may be used. Natural Gas is composed primarily of methane. See Appendix A for more information on the properties of natural gas.

DATA ACQUISITION

The instrumentation used on the gas carts is wired into an Allen Bradley Micrologix 1400 Programmable Logic Controller (PLC). Only the Analog I/O channels are used for data acquisition for the gas train. As seen in Figure 4, the PLC is located in an electrical box mounted inside of the enclosed lower shelf of the cart. A full list of channels assigned to instrumentation can be found in Appendix B. The PLC is an Ethernet based control module.

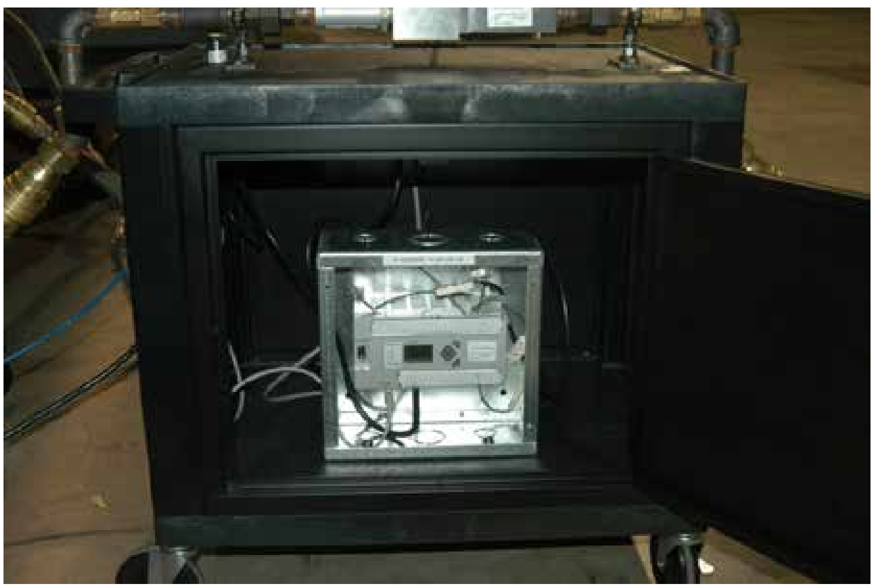

Figure 5. Allen Bradley MicroLogix 1400 PLC inside Gas Cart

IGNITION SOURCE

Ignition of the sand burners is achieved using a 6 mm (1/4 inch) diameter stainless steel "wand" fueled by a propane tank with a needle control valve, as seen in Figure 5.

Figure 6. Propane "Wand" Ignition Source

FireTOSS Calculations

HEAT RELEASE RATE CALCULATION

The heat release rate (HRR) of the fire is calculated using the flow rate of the fuel and the combustion properties of the fuel. Equation (1.1) expresses the HRR in terms of the mass flow rate of the fuel.

$$\dot{Q} = \times \dot{m} \times H_{C,net} \qquad (0.1)$$

Equation (1.2) expresses the HRR in terms of the volumetric flow rate of the fuel.

$$\dot{Q} = \times \times \dot{V} \times H_{C,net} \qquad (0.2)$$

where

$\dot{Q}$ = heat release rate of the burner (kW)
= combustion efficiency of the fuel (assumed to be 1 for gaseous fuels).

$\dot{m}$ = mass flow rate of the fuel (kg/s)
$H_{C,net}$ = net heat of combustion of the fuel (kJ/kg)
= density of the fuel (kg/m³)
$\dot{V}$ = volumetric flow rate of the fuel (m³/s)

An example of heat release rate for natural gas calculated for a variety of flow rates is shown in Table 3.

Table 3 - Heat Release Rate vs. Natural Gas Flow Rate

HRR (kW)	Natural Gas Flow Rate (SLPM)
10	17.4
50	87.0
100	173.9
500	869.6
1000	1739.3
1500	2609
2000	3478.6
2500	4348.3
2800	4870

Uncertainty and Accuracy

The uncertainty of the burners was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [4], Special Publication 1007 [5] and the NIST Uncertainty Workshop [6]. The combined standard uncertainty of the heat release rate is a combination of the uncertainty of its components, including flow, density and heat of combustion, among other factors, and is given by the following equation:

$$u_c(\dot{Q}) = \sqrt{\sum s_i^2 u(x_i)^2} \quad (0.3)$$

where:

$u_c(\dot{Q})$ = Combined standard uncertainty of the burner heat release rate
$u(x_i)$ = Standard uncertainty of each heat release rate component
s_i = Sensitivity coefficient $(\partial y/\partial x_i)$

Using the volumetric formulation (Eq. 1.2), the main sources of uncertainty in the sand burner heat release rate are the volumetric flow rate (given by the mass flow controller), the density, and the heat of combustion, (both extracted from the combustion calorimeter, see Appendix A and [7]). Based on this, Eq. 1.3 can be applied to Eq. 1.2 to yield:

$$u_c(\dot{Q}) = \left[\begin{matrix} \left(\rho_{NG}\Delta H_{c,net}\right)^2 \left(u(\dot{V}_{NG})\right)^2 + \left(\dot{V}\Delta H_{c,net}\right)^2 \left(u(\rho_{NG})\right)^2 \\ +\left(\rho_{NG}\dot{V}\right)^2 \left(u(\Delta H_{c,net})\right)^2 \end{matrix} \right]^{1/2} \qquad (0.4)$$

where:

$u(\dot{V}_{NG})$ = Standard uncertainty of Natural Gas Volumetric Flow Rate
$u(\rho_{NG})$ = Standard uncertainty of Natural Gas Density
$u(\Delta H_{c,net})$= Standard uncertainty of Natural Gas Heat of Combustion

Standard uncertainties for the natural gas density (0.015 kg/m^3) and heat of combustion (1.05 MJ/kg) were computed based on an evaluation of the combustion calorimeter [7].

The uncertainty of the volumetric flow rate is evaluated by considering the operation of the MFC and the makeup of natural gas. The MFC reading is based on the pressure drop of a gas as it passes through a laminar flow element. The flow rate is based on the viscosity of the flowing gas. If the gas being used is not what has been selected on the controller a conversion factor must be used. The conversion has the form [8]:

$$\dot{V}_2 = \dot{V}_1 \left(\frac{\eta_1}{\eta_2}\right) \qquad (0.5)$$

where:

$\dot{V}_2$ = Volumetric flow rate of gas in use (SLPM)
$\dot{V}_1$ = Flow reading produced by the MFC (SLPM)
η_2 = Viscosity of gas in use
η_1 = Viscosity of gas for which MFC is set

Since natural gas is a blend of species with methane having the largest concentration, the MFC is set up using the properties of methane (η_1). The flow rate of natural gas ($\dot{V}_2$) is proportional to the flow reported by the mass flow controller ($\dot{V}_1$) based on Eq. 1.5:

$$\dot{V}_{NG} = \dot{V}_{CH_4} \left({}_{CH_4} / {}_{NG} \right)$$

where

$\dot{V}_{NG}$ = Flow rate of natural gas (SLPM)

$\dot{V}_{CH_4}$ = Flow rate of methane as measured by the MFC (SLPM)

$_{CH_4}$ = Viscosity of methane at 25°C; $_{CH_4}$ = 111.296 Poise [8]

$_{NG}$ = Viscosity of natural gas at 25°C in Poise

The uncertainty in the natural gas flow rate ($\dot{V}_{NG}$) can be calculated by applying Eq. 1.3 to the expression above. Treating the viscosity ratio as a single term yields:

$$u(\dot{V}_{NG}) = \sqrt{\left(\frac{\eta_{CH_4}}{\eta_{NG}}\right)^2 \left(u(\dot{V}_{CH_4})\right)^2 + \left(\dot{V}_{CH_4}\right)^2 \left(u\left(\frac{\eta_{CH_4}}{\eta_{NG}}\right)\right)^2} \qquad (0.6)$$

The uncertainty in the methane flow rate ($\dot{V}_{CH_4}$) can be divided into two components. The first component is the accuracy and repeatability of the MFC. The second component is the random fluctuations that occur in the flow measurement.

Alicat Scientific lists the MFC accuracy as ± (0.8% of full scale + 0.2% of the reading) and the repeatability as ± 0.2 % of full scale [8]. It can be assumed that these errors have a rectangular probability distribution, in which case the standard uncertainty is computed by dividing each component by $\sqrt{3}$ [4]. The error associated with accuracy in the mass flow controller increases as the flow increases; therefore, a high flow will yield the highest (absolute) uncertainty. The accuracy is calculated at 100 % capacity (1000 SLPM) as:

(0.008 x 1000 SLPM) + (0.002 x 1000 SLPM) = ±10 SLPM

The corresponding standard uncertainty is 5.8 SLPM. Similarly, the repeatability is calculated as:

(0.002 x 1000 SLPM) = ±2 SLPM

The corresponding standard uncertainty is 1.2 SLPM.

The contribution to the uncertainty based on random fluctuations in the measurement is evaluated using a statistical analysis. The standard uncertainty is calculated as:

$$u = \frac{S}{\sqrt{n}} \qquad (0.7)$$

where:

S = Sample standard deviation

n = Number of measurements used in the evaluation of S

The standard uncertainty at maximum flow, based on a sample of 236 data points, is 0.22 SLPM.

The standard uncertainties are combined in quadrature to calculate the combined standard uncertainty of the methane flow rate. The result is $(\dot{V}_{CH_4})$ = 5.9 SLPM.

In order to calculate the uncertainty in the natural gas flow rate, the uncertainty associated with the natural gas viscosity must be estimated. However, it is difficult to obtain an accurate viscosity of a gas mixture with over 10 components such as natural gas. The NIST predictive model SUPERTRAPP [9] was used to determine the viscosity of natural gas based on average gas concentrations provided by Washington Gas (see Table 4). According to the SUPERTRAPP developer, Marcia Huber of NIST, the accuracy of the model for natural gas is about 2% [10]. The SUPERTRAPP model provides a natural gas viscosity prediction of 113.25 Poise at 25°C and 14.695 psia, which is only 1.8% different from the viscosity of pure methane. However the SUPERTRAPP model predicts the viscosity of pure methane to be 113.42 Poise, which is 1.9% different from the actual viscosity of pure methane, but only 0.2 % different from the natural gas viscosity prediction. This indicates that the viscosity of natural gas is very close to that of pure methane.

Based on work performed by Neil Hartman of Alicat Scientific, the viscosity of natural gas was calculated using the semi-empirical formula of Wilke [11]. Hartman, found that the actual difference between the viscosity of natural gas as compared to pure methane is less than 0.6% [12].

Based on this, the combined standard uncertainty in the natural gas flow rate is calculated to be $u(\dot{V}_{NG})$ = 8.4 SLPM.

Table 4 - Average Natural Gas Concentrations (Dry) – Determined from data provided by Washington Gas for 88 days from December 15, 2004 – March 30, 2005.

	Average Concentration (%)	**Standard Deviation** (%)	**± Error**	**Percent Error**
Methane	94.116	0.363	0.73	0.77
Ethane	3.386	0.343	0.69	20.25
Propane	0.650	0.063	0.13	19.50
i-Butane	0.092	0.007	0.01	16.28
n-Butane	0.127	0.013	0.03	20.90
Neopentane	0.001	0.0003	0.001	57.74
i-Pentane	0.042	0.004	0.01	17.04
n-Pentane	0.031	0.003	0.01	17.18
Nitrogen	0.632	0.089	0.18	28.31
CO_2	0.848	0.049	0.10	11.49
C6+ 47/35/17	0.074	0.006	0.01	15.47
Water	0.000	N/A	N/A	N/A

Using the standard uncertainties of the natural gas flow rate, density and heat of combustion, the combined standard uncertainty in the heat release rate of the burner can be determined by Equation (1.4) (repeated below for convenience):

$$u_c(\dot{Q}) = \underline{17.8\ \text{kW}}$$

This translates to a relative combined standard uncertainty of 3.1 % at a flow of 1000 SLPM.

Appendix A – Calculation of Natural Gas Properties

In order to calculate the heat release rate of the burner using Equation (1.1), the properties of the gas are needed. The most typical fuel gas that will be used by the FRL to fuel the burners is natural gas. Natural gas is a mixture of gases whose major components are methane, propane, i-butane, n-butane, neopentane, i-pentane, n-pentane, nitrogen, carbon dioxide, ethane and heavier hydrocarbons with six or more carbon atoms (referred to by Washington Gas as "C6+ 47/35/17"). These component concentrations vary over time, thus varying the properties of the natural gas. Therefore, the properties of natural gas supplied to the FRL were calculated using a combustion calorimeter which measured the calorific value and specific gravity of the natural gas [7].

Combustion Calorimeter

A Union CWD 2000 Combustion Calorimeter was used to determine the calorific value and specific gravity of the natural gas supply [13]. The caloric value was measured over a range of 35000-45000 kJ/m^3 and the specific gravity was measured over a range of 0.2-2.2, with respect to air. Both of these values are output as a 4-20 mA current. The calorimeter is automatically calibrated every weekday.

Density

The density ( ) of natural gas is calculated based on the specific gravity of the gas and the relationship of natural gas density to air density:

$$\rho_{NG} = \rho_{Air} * SG_{NG} \qquad (0.8)$$

where

ρ_{NG} = density of natural gas in kg/m^3
ρ_{Air} = density of air in kg/m^3
SG_{NG} = specific gravity of natural gas in relation to air

Substituting Equation 1.8 into the ideal gas law yields:

$$\rho_{NG} = \frac{SG_{NG} * P}{R * T} \qquad (0.9)$$

where

P = Pressure (Pa)
R = Gas Constant for Air, 287 J/kg•K
T = Temperature (K)

The density of the natural gas is calculated as a static value for sand burners. The specific gravity is the average of a two minute baseline reading taken prior to the start of the test. The values used for pressure and temperature are at STP to coincide with the output of the mass flow controller.

Net heat of combustion

The calorific (heating) value of natural gas is determined by the combustion calorimeter and output in kJ/m^3. However, the gas property necessary for the burner calculations in Equation (1.1) is the net heat of combustion ($H_{C,\,net}$) in units of kJ/kg. The gross heat of combustion of natural gas was calculated based on the heating value and the density of natural gas:

$$\Delta H_{c,gross} = \frac{C.V.}{\rho_{NG}} \tag{0.10}$$

where

$\Delta H_{c,gross}$= gross heat of combustion of the gas mixture in kJ/kg
$C.V.$ = calorific value of natural gas in kJ/m^3
ρ_{NG} = density of natural gas in kg/m^3

This calculation yields a value in terms of the higher heating value, which does not account for water vapor. To account for water vapor, a correlation from Bossel [14] was used to convert to the lower heating value.

$$\Delta H_{c,net} = \Delta H_{c,gross} * 0.896 \tag{0.11}$$

The heat of combustion of the natural gas is calculated as a static value for sand burners. The calorific value is the average of a two minute baseline reading taken prior to the start of the test. The natural gas density is the average density calculated during the same two minute baseline.

Appendix B – Data Acquisition Channel Assignments

Train A

Channel	FireTOSS Channel Name	Instrument
Analog Input 1	ML135_AI_01	MFC Read Value
Analog Input 2	ML135_AI_02	Pressure Transducer
Analog Input 3	ML135_AI_03	Unassigned
Analog Input 4	ML135_AI_04	Unassigned
Analog Output 1	ML135_AO_01	MFC Write Value
Analog Output 2	ML135_AO_02	Unassigned

Train B

Channel	FireTOSS Channel Name	Instrument
Analog Input 1	ML136_AI_01	MFC Read Value
Analog Input 2	ML136_AI_02	Pressure Transducer
Analog Input 3	ML136_AI_03	Unassigned
Analog Input 4	ML136_AI_04	Unassigned
Analog Output 1	ML136_AO_01	MFC Write Value
Analog Output 2	ML136_AO_02	Unassigned

Train C

Channel	FireTOSS Channel Name	Instrument
Analog Input 1	ML133_AI_01	MFC Read Value
Analog Input 2	ML133_AI_02	Pressure Transducer
Analog Input 3	ML133_AI_03	Unassigned
Analog Input 4	ML133_AI_04	Unassigned
Analog Output 1	ML133_AO_01	MFC Write Value
Analog Output 2	ML133_AO_02	Unassigned

Train D

Channel	FireTOSS Channel Name	Instrument
Analog Input 1	ML178_AI_01	MFC Read Value
Analog Input 2	ML178_AI_02	Pressure Transducer
Analog Input 3	ML178_AI_03	Unassigned
Analog Input 4	ML178_AI_04	Unassigned
Analog Output 1	ML178_AO_01	MFC Write Value
Analog Output 2	ML178_AO_02	Unassigned

Train E

Channel	FireTOSS Channel Name	Instrument
Analog Input 1	ML134_AI00_00	MFC Read Value
Analog Input 2	ML134_AI00_01	Pressure Transducer
Analog Input 3	ML134_AI00_02	Unassigned
Analog Input 4	ML134_AI00_03	Unassigned
Analog Output 1	ML134_AO00_00	MFC Write Value
Analog Output 2	ML134_AO_01	Unassigned

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Scope

This Technical Reference covers the use, design and specifications of the tube burner used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

The tube burner is used in experiments to produce fires of known size and configurations. It is generally used for calibration of oxygen consumption calorimeters, but can be used whenever a known fire size is needed. The tube burner setup consists of a natural gas fuel supply, a gas train consisting of fuel flow monitoring instrumentation and fuel flow control, and the tube burner itself. All instrumentation must be calibrated according to manufacturer and ATF specifications.

GAS TRAIN AND FLOW CONTROL/MONITORING DESCRIPTION

The tube burner uses a gas train which is located in the Mezzanine of the FRL. This gas train contains the primary fuel supply valve, the flow control and flow monitoring devices, and the emergency shut off valve for the tube burner. All control and monitoring is achieved within this gas train. The actual burner only has on/off style valves and is not equipped for control/monitoring. The overall gas train is shown in Figure 1.

Figure 1 - Gas train in Mezzanine

Shutoff Valve

This is a mechanical gate valve placed at the inlet of the gas train. This valve is purely mechanical and must be operated manually by rotating the handle. Rotating the handle clockwise opens the valve and rotating the handle counterclockwise closes the valve. This valve is kept closed at all times prior to and after testing to prevent leakage of gas into the laboratory or plenum space. The valve is shown in Figure 1.

Figure 2 –Manual shutoff for Mezzanine gas train

Type 99 Pressure Reducing Regulator

The natural gas supply pressure is regulated through this device, shown in Figure 2, to approximately 200 kPa (29 psia). Fluctuations in the inlet pressure are reduced through this regulator and a steady pressure is maintained downstream. This device utilizes a yoked double-diaphragm pilot to mechanically control the output pressure. It does not contain any electrical parts and does not communicate with the DAQ.

Figure 3 – Type 99 Pressure Reducing Regulator

Maxon Valve Emergency Shutoff

The Maxon valve, shown in Figure 3, is a normally closed valve placed in the main flow line. The valve is connected to four separate shutoff switches located in each burn room in the laboratory (Two each in the MBR and LBR). If any of the four switches are pressed this valve is closed, stopping the flow of gas through the train. There is, however, a significant amount of pipe between the burner and the shutoff valve, and thus additional safety measures have been implemented to prevent a release of gas.

Figure 4 – Maxon Emergency Shutoff Valve

<u>Instromet IRM-A Rotary Gas Meter</u>

This device, shown in Figure 4, is a rotary meter designed to measure the volume of gas flow in the line. Measurements are made through the use of counter rotating figure-eight rotors in a chamber of constant volume. Each revolution displaces a fixed volume of gas in four strokes. Each revolution is timed, producing a frequency output that is directly proportional to the volume flow rate. The volume flow rate is independent of any properties of the gas, including pressure, density, and viscosity.

Figure 5 – Instromet IRM-A Rotary Gas Meter with mounted pressure transducer and thermocouple

Gas pressure and temperature are monitored inside the flow meter through the use of a pressure transducer and thermocouple, respectively. The output signal from the flow meter is converted from frequency to amperage using a frequency converter. These instruments are described below.

OmegaDyne Pressure Transducer

The pressure of the gas flowing through the rotary gas meter is measured using an OmegaDyne very high accuracy millivolt output pressure transducer (PX01K1-050AV). This device is powered by a 10 VDC power supply mounted in the gas train electrical box and produces an output of 3 mV/V of supply. This device has a range of 0 - 344.7 kPa (0-50 psia) and outputs a signal from 0-30 mV. The output is read by the FieldPoint module and converted to pressure and used for calculations of mass flow rate.

Type-K Thermocouple

An inconel sheathed, Type-K thermocouple is used to measure the gas temperature at the rotary gas meter. The temperature is read using a calibrated thermocouple FieldPoint unit with a range of -270 °C through 1770 °C using cold junction compensation. This data is used for calculations of the mass flow rate of the gas.

Pepperl+Fuchs KFD2-UFC-Ex1.D Universal Frequency Converter

The Universal Frequency Converter is used to transform the frequency output of the rotary gas meter into a current signal that can be read by the FieldPoint module connected to the DAQ system. This device is not involved in the flow of gas; it is an electrical component that allows the frequency signal from the rotary gas meter to be measured by the existing DAQ. This device is mounted in the electrical box near the natural gas train in the plenum and is shown below on the right side of Figure 5.

Figure 6 – Pepperl+Fuchs KFD-UFC-1.D Universal Frequency Converter and SOLA 24 VDC power supply

Masoneilan Flow Control Valve

This is a pneumatically actuated valve that is used to restrict the amount of flow allowed to discharge from the burner. This device is driven by compressed air supplied through a 0.64 cm (1/4 inch) tube and controlled by an analog voltage input. The compressed air is stored in a large tank at the south end of the mezzanine. The measured flow rate from the IRM-A rotary gas meter is used in a PID feedback control loop in order to adjust this valve to produce the desired flow rate. The control loop is designed to operate using the heat release rate parameter, and determination of this value as a function of the volume flow rate requires the use of continuous measurements of the heat content, specific gravity, temperature, and pressure of the gas. Measurements of all of these parameters must be made in order to accurately control the heat release rate by means of this valve. The device is shown below in Figure 6. The compressed air tube is attached to the regulator on the bottom left of the device. The pressure gauges indicate the inlet air pressure, and a ball indicator on the front panel displays the position of the valve. The valve is shown “closed” in this image.

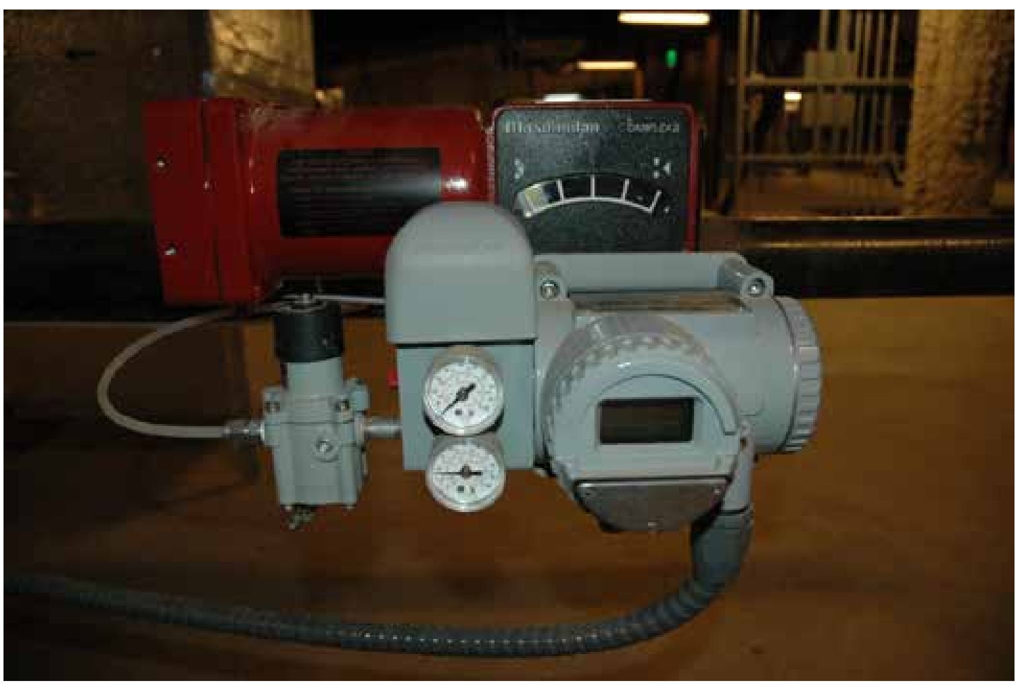

Figure 7 – Masoneilan flow control valve

BURNER DESCRIPTION

The tube burner is capable of producing fires as large as 6 MW. It has a height of 95 cm above the floor and plan dimensions of 162 cm x 122 cm. The burner consists of eleven parallel tubes which have 3.8 mm holes drilled along the top side with a spacing of 2.54 cm. These tubes are the release point for the natural gas. The tubes are divided in half with the ends at the center of the burner capped. The opposite ends are connected to manifolds at each side of the burner that distribute natural gas. The tubes are grouped into "banks" (numbered 1-4). The banks are opened and closed independently using solenoid valves. Banks are opened successively to increase the fire size. There are also two tubes which run perpendicular to and beneath the main tube banks which serve as pilot ignition tubes. The pilot tubes have 1.85 mm holes drilled along the top with a spacing of 1.3 cm. The fuel banks and pilot banks are fed by a 7.6 cm (3 inch) distribution pipe which is connected to the natural gas train by 7.6 cm (3 inch) stainless steel braided hose. Figure 7 shows the tube burner with the pilot banks ignited. A 10,000 V spark igniter is used to ignite the fuel passing through the pilot tubes. An electronic photoelectric sensor (Fireye) is used to monitor the presence of a flame at the pilot tubes.

Figure 8. Tube Burner (shown with pilot bank ignited)

Burner Solenoid Valves

There five separate solenoid valves used to control the output of the tube burner. They are normally closed valves each intended to activate at various heat release rates, allowing additional banks to open as fire sizes increase up to 6 MW. The standard activation heat release settings for the valves are shown below in Table 1. The solenoid valve used to control tube bank 4 is shown below in Figure 8.

Table 1 - Solenoid valve activation heat release rates

Solenoid Valve	Activation HRR (kW)
Pilot	0
Tube Bank "1"	4500
Tube Bank "2"	3000
Tube Bank "3"	1500
Tube Bank "4"	400

Figure 9 – Solenoid valve connected to tube bank "4"

Regulator for Burner Pilot Tubes
This is a pressure regulator placed in line with the pilot solenoid valve used to limit the amount of flow exiting the solenoid valve. Figure 9 shows a photograph of the regulator. The use of this regulator makes setting the heat release rate of the burner accurately below 400 kW impossible. Instead the flow rate is generally maintained by the set pressure of the regulator at a steady 250 kW. As a result, the tube burner should not be used to provide calibrated heat release rates below 1 MW.

Figure 10 – Pressure regulator (center) and solenoid valve (left) for gas burner pilot tube

Fireye Flame Safeguard Controller
This device is connected to the burner solenoid valves as a safeguard against releasing natural gas into the laboratory. It is mounted to the base of the tube burner and contains a UV flame detector that prevents the solenoid valves to the primary tube banks from opening if the pilot flame is not lit. The device provides an alarm signal and shuts off the flow of gas if no pilot flame is detected for 10 seconds.

The Fireye provides activation power to the burner solenoid valves. When the pilot flame is lit and detected, the Fireye provides input power to a set of relays. The relays are powered by the Fireye controller and controlled by the FieldPoint module. The input power from the Fireye is used to switch on the burner solenoid valves when the relay is activated. The relays can be seen in Figure 10 along the right side of the circuit box below the electrical conduit ports.

The Fireye is also used to control three LED lights on the front of the gas burner electrical circuit box. The green light on the left indicates that the Fireye unit has 120 VAC power supplied. The green light in the middle indicates that the solenoid valve for the pilot tubes is in the open position. The red light on the right indicates that the Fireye flame detector has indicated an unsafe condition and disabled all solenoid valves to prevent the release of gas. The LED lights on the box are shown in Figure 11. The Fireye device can be seen in the lower left corner of Figure 10.

Figure 11 – Gas burner electrical circuit box containing Fireye (bottom left corner), FieldPoint Module (top) and solid state relays (right)

Figure 12 - Gas burner electrical circuit box with LED indicator lights

FUEL DESCRIPTION

The primary type of fuel used in the tube burner is natural gas, which is composed primarily of methane. See Appendix A for more information on the fuel used in the tube burner.

DATA ACQUISITION

Data acquisition for the tube burner is achieved using National Instrument (NI) FieldPoint modules. There are two sets of FieldPoint modules that are used to control and monitor the tube burner. The FieldPoint modules and the instrumentation attached to them are listed in Table 2. The FieldPoint modules are ethernet based control modules.

Table 2. FieldPoint Setup and Locations

FieldPoint Name (COMM Resource)	Physical Location	Devices Attached	Quantities Measured/Controlled	FieldPoint Module Address	Channel	Wiring Terminals
Gas Train (10.243.235.36)	Electrical Box Adjacent to Gas Train	P&F KFD2 Universal Frequency Converter	Volumetric Flow Rate	FP-AI-110 @ 3	0	(2,18)
		Masoneilan Flow Control Valve	Valve Position	FP-A0-200 @ 1	0	(1,2)
		Inconel Type-K Thermocouple	Gas Temperature	FP-TC-120 @2	0	(1,2)
		OmegaDyne Pressure Transducer	Gas Pressure	FP-TC-120 @2	1	(3,20)
Gas Burner (10.243.235.35)	Electrical Box Underneath Tube Burner	Green Power LED Relay	Open/Closed	FP-DO-410 @ 1	0	(1,2)
		Tube Bank 4 Solenoid Valve	Open/Closed	FP-DO-410 @ 1	1	(3,4)
		Tube Bank 3 Solenoid Valve	Open/Closed	FP-DO-410 @ 1	2	(5,6)
		Tube Bank 2 Solenoid Valve	Open/Closed	FP-DO-410 @ 1	3	(7,8)
		Tube Bank 1 Solenoid Valve	Open/Closed	FP-DO-410 @ 1	4	(9,10)
		FireEye Reset Warning Alarm Relay	Open/Closed	FP-DO-410 @ 1	5	(11,12)
		FireEye Warning Alarm	Flame Present?	FP-DO-301 @ 2	0	(1,17)

FireTOSS Calculations

HEAT RELEASE RATE CALCULATION

The heat release rate (HRR) of the fire is calculated using the flow rate of the fuel and the combustion properties of the fuel. Equation (1.1) expresses the HRR in terms of the mass flow rate of the fuel.

$$\dot{Q} = \times \dot{m} \times H_{C,net} \qquad (0.1)$$

Equation (1.2) expresses the HRR in terms of the volumetric flow rate of the fuel.

$$\dot{Q} = \times \times \dot{V} \times H_{C,net} \qquad (0.2)$$

where

$\dot{Q}$ = heat release rate of the burner (kW)
= combustion efficiency of the fuel (assumed to be 1 for gaseous fuels).
$\dot{m}$ = mass flow rate of the fuel (kg/s)
$H_{C,net}$ = net heat of combustion of the fuel (kJ/kg)
= density of the fuel (kg/m³)
$\dot{V}$ = volumetric flow rate of the fuel (m³/s)

The density term in Eqn. 1.2 refers to the density of the natural gas at the point where the flow rate $(\dot{V})$ is measured. The natural gas density is measured by the combustion calorimeter which operates at ambient conditions [1]. Therefore, the measured density must be corrected to correlate with the conditions in the gas train. Using the ideal gas law, the density in the gas train can be expressed as:

$$\rho_2 = \frac{SG(NG)}{R_{air}} \frac{P_2}{T_2} \qquad (0.3)$$

where

$SG(NG)$ = specific gravity of the natural gas measured at the combustion calorimeter
R_{air} = gas constant for air (0.287 kJ/kg/K)
ρ_2, P_2, T_2 = gas properties in the natural gas train at the location of the flow meter

An example of heat release for natural gas calculated for a variety of flow rates is shown in Table 3.

Table 3 - Heat Release Rate vs. Natural Gas Flow Rate

HRR (kW)	Natural Gas Flow Rate (SLPM)
500	869.6
1000	1739.3
2000	3478.5
3000	5217.8
4000	6957.0

Uncertainty and Accuracy

The uncertainty of the burners was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [1], Special Publication 1007 [2] and the NIST Uncertainty Workshop [3]. The combined standard uncertainty of the heat release rate is a combination of the uncertainty of its components, including flow, density and heat of combustion, among other factors, and is given by the following equation:

$$u_c(\dot{Q}) = \sqrt{\sum s_i^2 u(x_i)^2} \qquad (0.4)$$

where:

$u_c(\dot{Q})$ = Combined standard uncertainty of the burner heat release rate
$u(x_i)$ = Standard uncertainty of each heat release rate component
s_i = Sensitivity coefficient $(\partial y/\partial x_i)$

Using the volumetric formulation (Eqs. 1.2 and 1.3), the sources of uncertainty that are considered in the tube burner heat release rate are the volumetric flow rate, the natural gas density and heat of combustion, (both extracted from the combustion calorimeter, see Appendix A and [4]), and the pressure and temperature measurements. Based on this, Eq. 1.4 can be applied to Eq. 1.2 and 1.3 to yield:

$$u_c(\dot{Q}) = \left[\begin{array}{c} \left(\frac{\partial \dot{Q}}{\partial SG}\right)^2 (u(SG))^2 + \left(\frac{\partial \dot{Q}}{\partial P_2}\right)^2 (u(P_2))^2 + \left(\frac{\partial \dot{Q}}{\partial T_2}\right)^2 (u(T_2))^2 \\ + \left(\frac{\partial \dot{Q}}{\partial \dot{V}_{NG}}\right)^2 \left(u(\dot{V}_{NG})\right)^2 + \left(\frac{\partial \dot{Q}}{\partial \Delta H_{c,net}}\right)^2 \left(u(\Delta H_{c,net})\right)^2 \end{array} \right]^{1/2} \quad (0.5)$$

where:

$u(SG)$ = Standard uncertainty of natural gas specific gravity measurement at the combustion calorimeter
$u(P_2)$ = Standard uncertainty of pressure measurement in the natural gas train
$u(T_2)$ = Standard uncertainty of temperature measurement in the natural gas train
$u(\dot{V}_{NG})$ = Standard uncertainty of natural gas volumetric flow
$u(\Delta H_{c,net})$ = Standard uncertainty of natural gas heat of combustion

Standard uncertainties for the natural gas specific gravity (0.012) and heat of combustion (1.05 MJ/kg) were computed based on an evaluation of the combustion calorimeter [4].

The uncertainty of the volumetric flow rate is a factor of the accuracy and repeatability of the IRM-A Rotary Meter. An analysis was performed to evaluate contributions from the data acquisition system, including the frequency converter, and random fluctuations in the data to the combined uncertainty of the gas flow rate. It was found that these sources were negligible in comparison to the contribution from the flow meter accuracy. These were therefore not considered in the analysis that follows.

Instromet lists the accuracy of the IRM-A rotary meter as ±1% of the reading, and the repeatability as less than 0.05 % of the reading [5]. The nominal peak flow rate through the flow meter (for a 6 MW fire) is 0.087 m^3/s (11000 CFH). The combined standard uncertainty at this flow rate is $u(\dot{V}_{NG})$ = 5.0 x 10^{-4} m^3/s (63.6 CFH).

The temperature of the natural gas in the flow meter is monitored by a K-type thermocouple with error limits of ± 1.1 °C. The corresponding standard uncertainty, assuming a rectangular distribution, is $u(T_2)$ = 0.64 °C. The OmegaDyne pressure transducer has an accuracy of ± 0.25 %. At a nominal operating pressure of 200 kPa the standard uncertainty is $u(P_2)$ = 0.31 kPa.

Using the standard uncertainties listed above, the combined standard uncertainty of the tube burner heat release rate is calculated (using Eq. 1.4) as = 179.9 kW. This equates to a relative combined standard uncertainty of 3.1 % at a nominal heat release rate of 5890 kW.

Appendix A – Calculation of Natural Gas Properties

In order to calculate the heat release rate of the burner using Equation (1.1), the properties of the gas are needed. The most typical fuel gas that will be used by the FRL to fuel the burners is natural gas. Natural gas is a mixture of gases whose major components are methane, propane, i-butane, n-butane, neopentane, i-pentane, n-pentane, nitrogen, carbon dioxide, ethane and heavier hydrocarbons with six or more carbon atoms (referred to by Washington Gas as "C6+ 47/35/17"). These component concentrations vary over time, thus varying the properties of the natural gas. Therefore, the properties of natural gas supplied to the FRL were calculated using a combustion calorimeter which measured the calorific value and specific gravity of the natural gas [4].

Combustion Calorimeter

A Union CWD 2000 Combustion Calorimeter was used to determine the calorific value and specific gravity of the natural gas supply [6]. The caloric value was measured over a range of 35000-45000 kJ/m^3 and the specific gravity was measured over a range of 0.2-2.2, with respect to air. Both of these values are output as a 4-20 mA current. The calorimeter is automatically calibrated every weekday.

Density

The density ( ) of natural gas is calculated in real-time throughout the test based on the specific gravity of the gas and the relationship of specific gravity to density:

$$\rho_{NG} = \frac{SG_{NG} * P}{R * T} \quad (0.6)$$

where

ρ_{NG} = density of natural gas, kg/m^3
SG_{NG} = specific gravity of natural gas in relation to air
P = pressure of gas in the gas train, Pa
R = gas constant for air, 287 J/kg•K
T = temperature of gas in gas train, K

The specific gravity is the average of a two minute baseline reading taken prior to the start of the test.

Net heat of combustion

The calorific (heating) value of natural gas is determined by the combustion calorimeter used and output in kJ/m^3. However, the gas property necessary for the burner calculations in Equation (1.1) is the net heat of combustion ($H_{C,\,net}$) in units of kJ/kg. The net heat of combustion of natural gas was calculated based on the heating value and the density of natural gas:

$$\Delta H_{c,gross} = \frac{C.V.}{\rho_{NG}} \tag{0.7}$$

where

$\Delta H_{c,gross}$= gross heat of combustion of the gas mixture in kJ/kg
$C.V.$ = calorific value of natural gas in kJ/m^3
ρ_{NG} = density of natural gas in kg/m^3

This calculation yields a value in terms of the higher heating value, which does not account for water vapor. To account for water vapor, a correlation from Bossel [7] was used to convert to the lower heating value.

$$\Delta H_{c,net} = \Delta H_{c,gross} * 0.896 \tag{0.8}$$

The heat of combustion of the natural gas is calculated as a static value for tube burners. The calorific value is the average of a two minute baseline reading taken prior to the start of the test. The natural gas density is the average density calculated during the same two minute baseline.

Appendix B – Tube Burner Flow Chart and Wiring Diagram

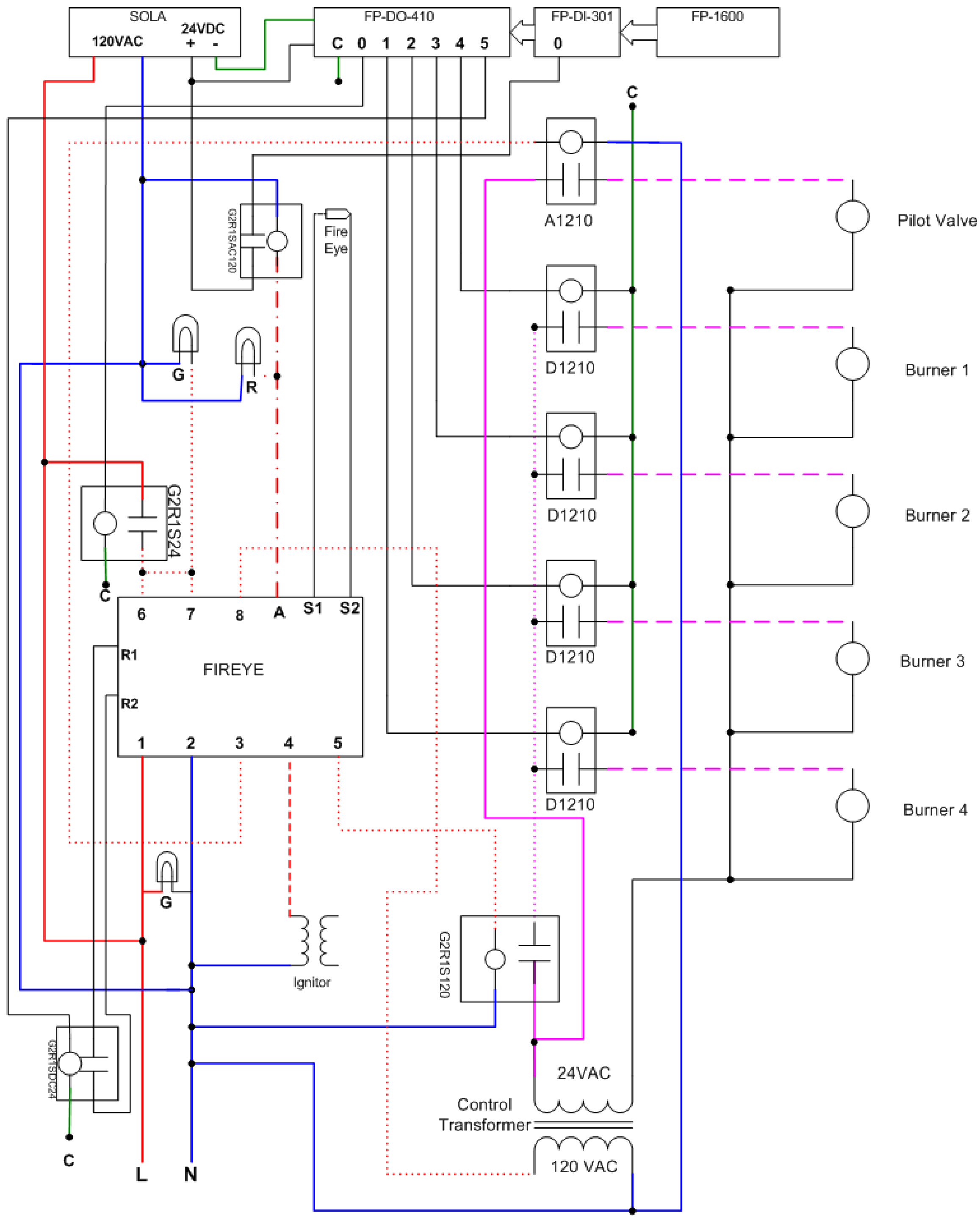

Figure 13. Wiring Diagram for Tube Burner Electrical Box

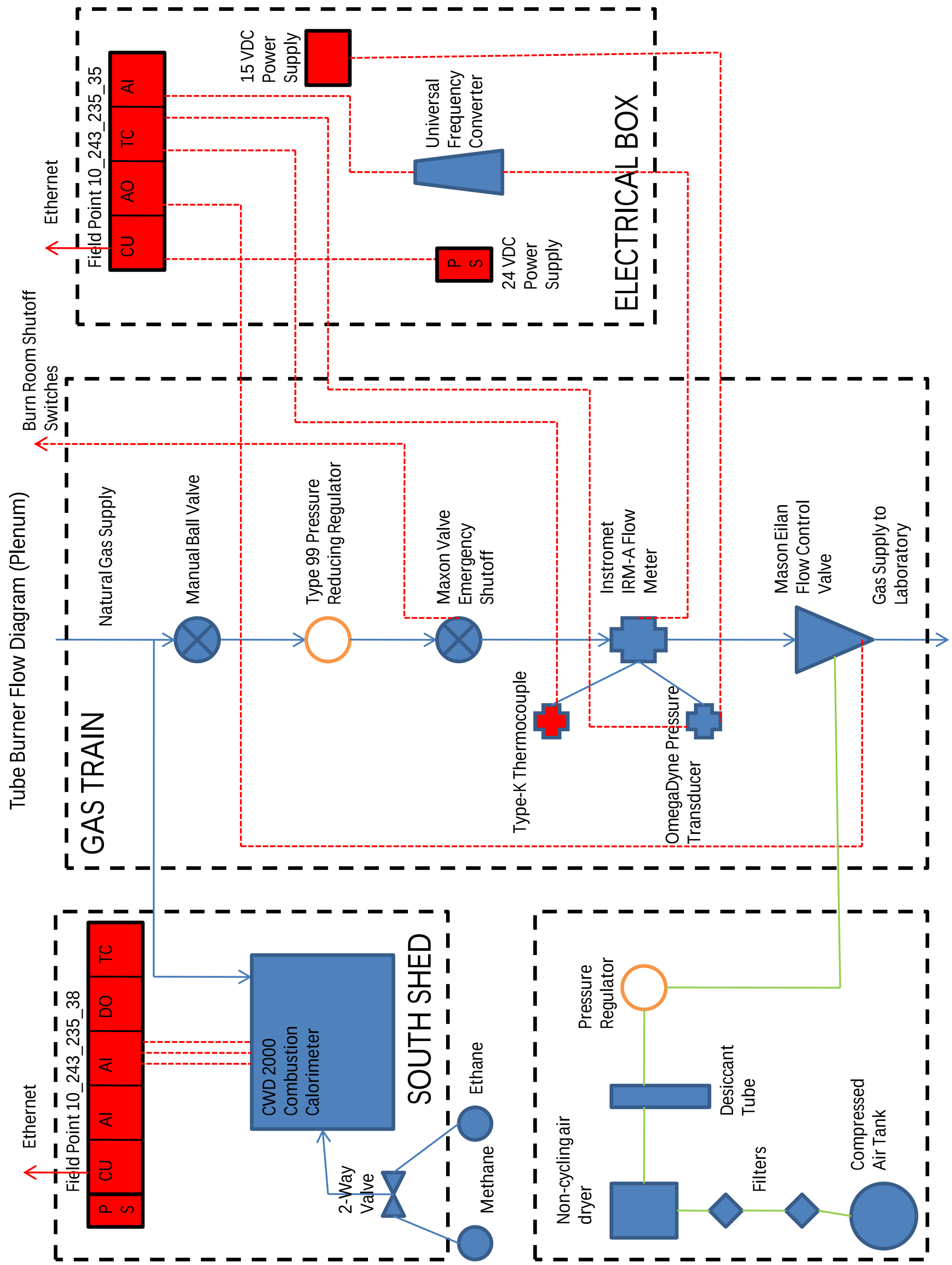

Figure 14. System Flow Chart for Components Located in Mezzanine

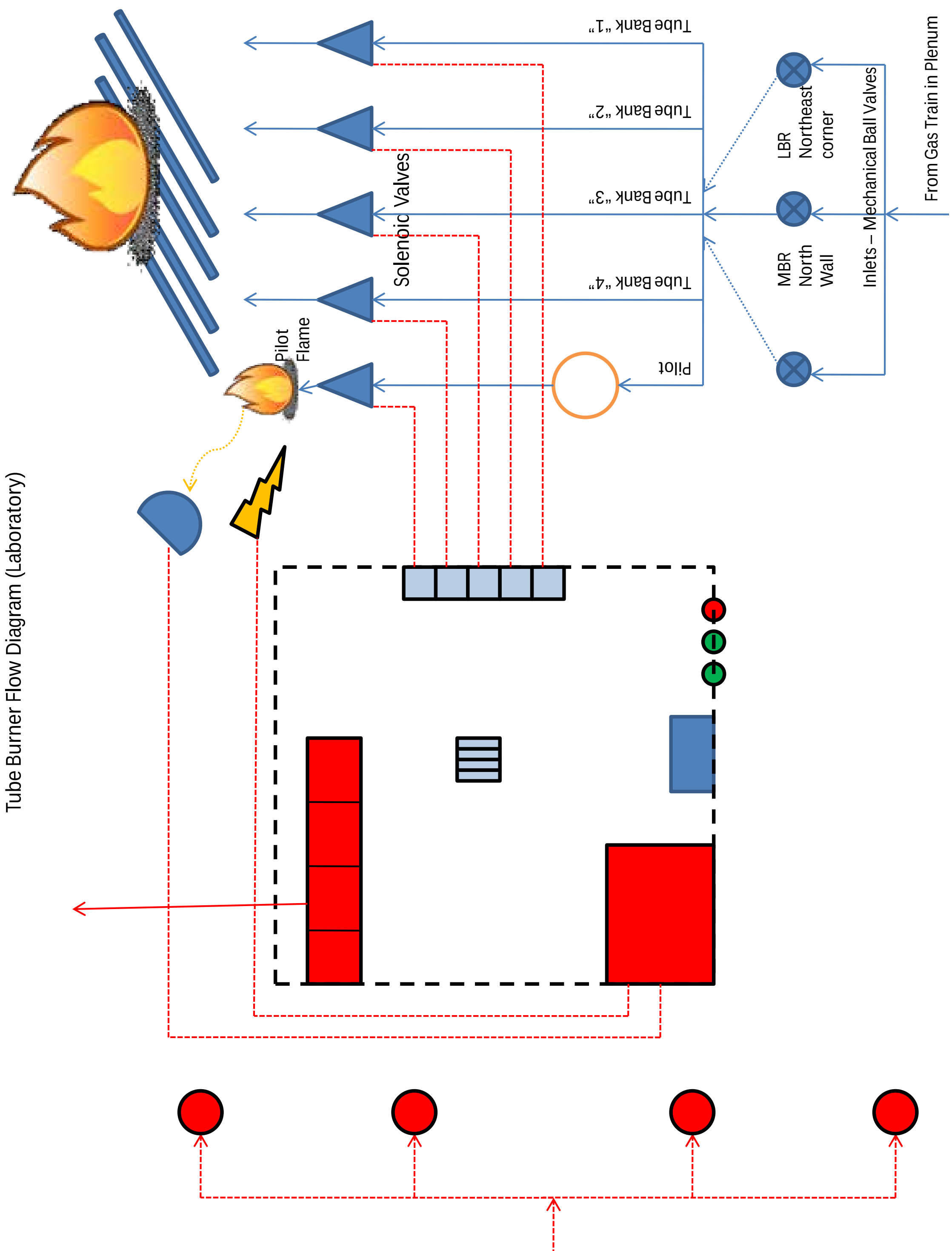

Figure 15. System Flow Chart for Tube Burner and Tube Burner Electrical Box

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7. Bossel, U., "Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle," Oberrohrdorf, Switzerland, 2003. http://www.efcf.com/reports/E10.pdf

Scope

This Technical Reference covers the use, design and specifications of the 1 MW Square Fire Products Collector (FPC) in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

General

The 1 MW Square FPC collects smoke and other products of combustion generated during fire experiments. A FPC consists of a collection hood connected to an exhaust duct, with air drawn through the duct by one or more variable speed fans. A FPC serves two purposes:

1) To remove combustion products from a laboratory space, and
2) To optimize the flow field for measurement and quantitative analyses of the combustion products.

A FPC provides four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production [1]. When used in conjunction with a weighing device, such as a load cell, the mass loss rate (MLR) of the burning object can be calculated. Gas species yields, smoke yield, and the effective heat of combustion of a burning item can then be calculated based on the MLR.

The 1 MW Square FPC is located in the southeast corner of the FRL's Medium Burn Room (MBR). Figure 1 shows a photograph of the collection hood and exhaust duct for the 1 MW square FPC.

Figure 1. 1 MW Square FPC

Hood and Collection System

Physical Dimensions

Figure 2 shows a plan view schematic of the 1 MW Square FPC collection hood in the MBR. The square 3.0 m collection hood transitions to a circular exhaust duct with an internal diameter of 0.65 m. A 0.39 m diameter orifice plate is located near the entrance of the exhaust duct, approximately 4.8 m above the floor. The orifice enhances mixing of the fire products prior to reaching the instrumentation locations. The exhaust duct has a vertical run of approximately 12 m before transitioning to a horizontal run above the MBR ceiling. The base of the collection hood is 2.9 m above the MBR floor; however skirts can be added to reduce the height to 2.1 m.

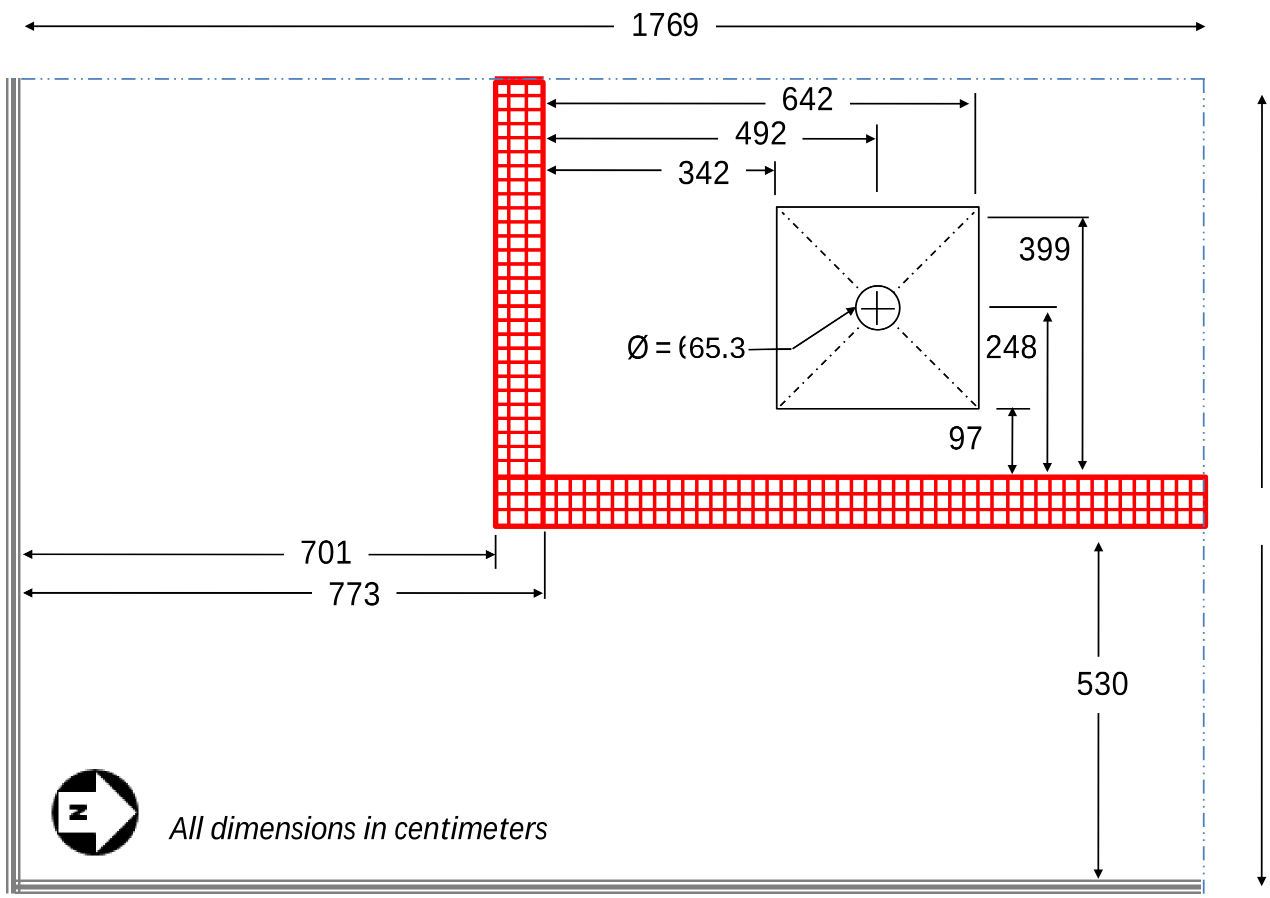

Figure 2: Plan view of 1 MW Square FPC in the MBR.

Instrument Locations

Instruments are located at two levels in the FPC exhaust duct, as shown in Figure 3. The first instrument station is located approximately 3.8 m downstream of the inlet orifice. This station is located below the MBR ceiling and is accessible via a fixed platform. The first instrument station is used for flow measurement and gas sampling. The second instrument station is located approximately 6 m downstream of the first station, at the mezzanine level directly above the MBR. This station houses the laser and white light smoke measurement instruments.

Flow Control

Flow in the FPC is controlled by a system of variable speed fans and actuated dampers that are programmed to maintain a fixed mass flow rate. The system is operated by a PC in the FRL Control Room. The FRL FPC's were designed to flow 6.8 kg/s (12,000 SCFM) per 1 MW heat release rate; this flow rate represents the approximate maximum capacity of the 1 MW square FPC.

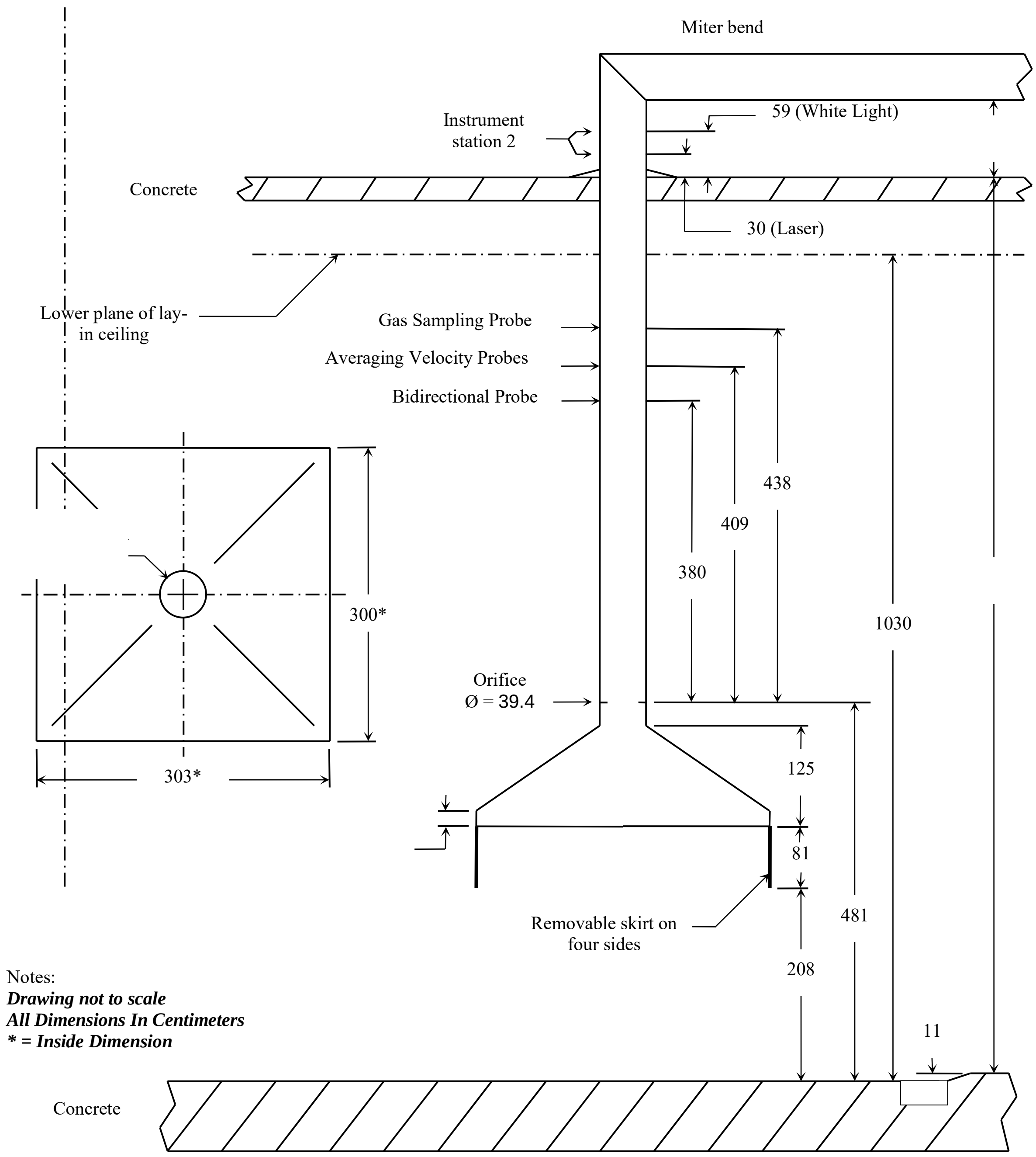

Figure 3: Elevation view of 1 MW Square FPC in the MBR.

Instrumentation

The 1 MW Square FPC is equipped with instrumentation to measure gas species concentrations, temperature, velocity, and smoke concentration.

Gas Species Measurement

The system of instrumentation used to measure gas species concentrations consists of a gas sampling probe located in the duct, tubing to transport the sample, a pump, sample conditioning equipment, and a gas analyzer.

Figure 4 shows a schematic of the gas sampling probe used in the 1 MW Square FPC. The gas sampling probe is a stainless steel tube with an outside diameter of 19.1 mm (0.75 inch) containing 30 sampling holes positioned at even intervals across the length of the probe. The sampling holes have diameters of either 3mm or 4 mm, and are spaced at 20 mm intervals. Figure 5 shows a detailed schematic of the gas sampling probe.

The gas sampling probe is installed across the center of the exhaust duct with the sampling holes facing downstream. The probe is located 4.4 m downstream of the inlet orifice. The sample is drawn from both ends of the sampling probe and transported to the gas analysis rack through a single 9.5 mm (3/8 inch) diameter Teflon gas sampling line.

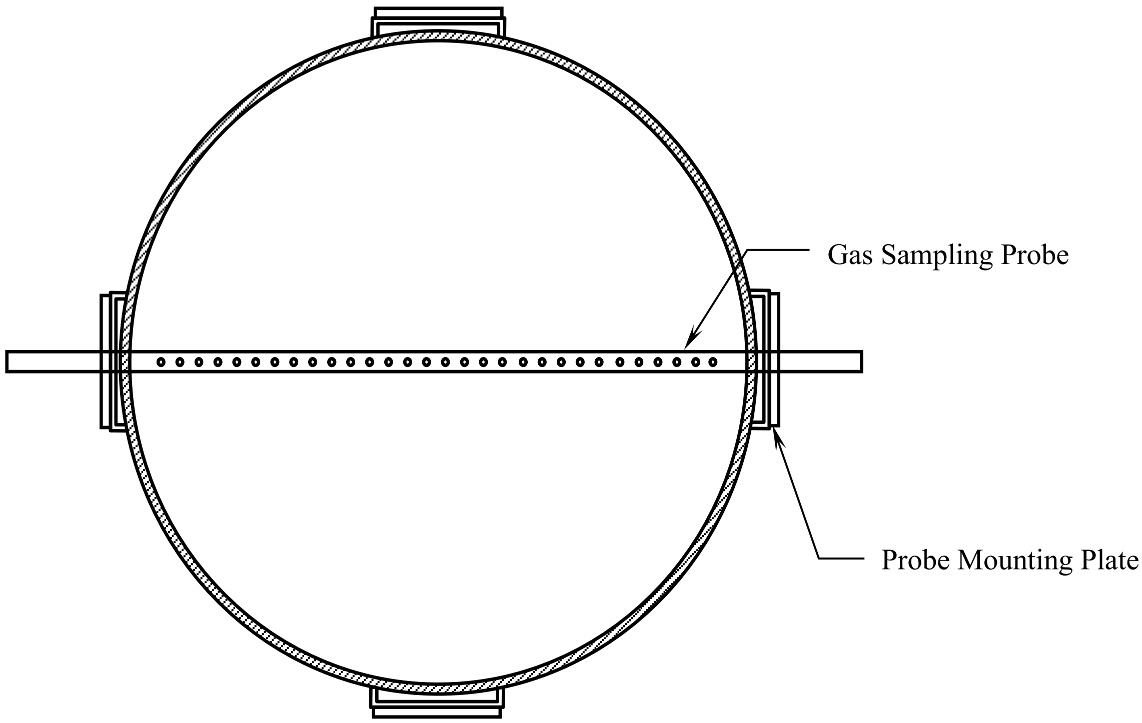

Figure 4. Schematic of the gas sampling probe mounted in the duct

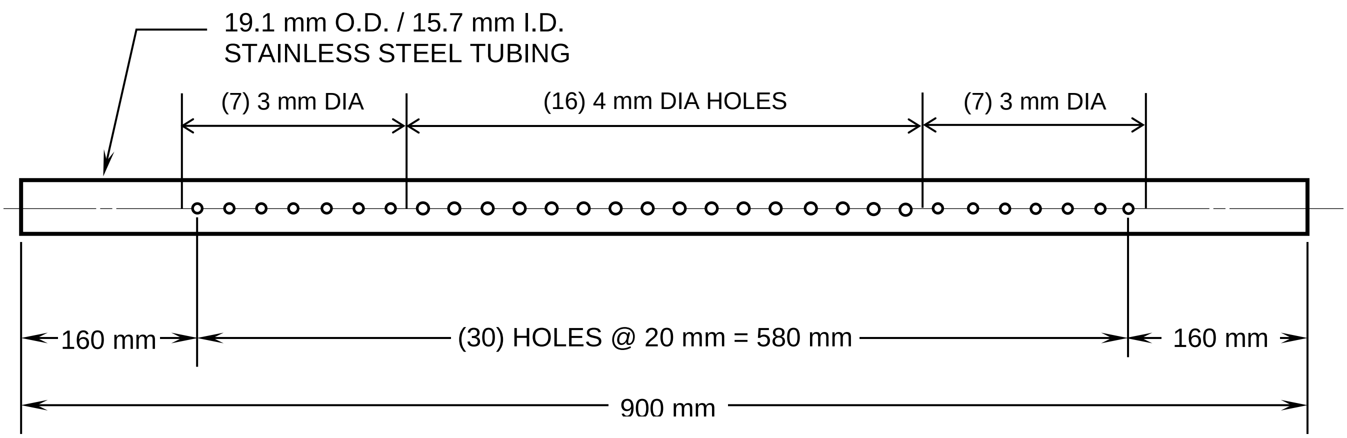

Figure 5. Detailed schematic of the gas sampling probe showing hole locations

Tubing from the gas sampling probe is connected to a gas analysis rack constructed by Fire Testing Technology Limited (FTT), shown in Figure 6. This rack, located in a conditioned space on the mezzanine level above the MBR, includes a Servomex 4100C Xentra gas analyzer, gas train, pressure and flow control, filtering, and moisture removal.

Figure 6: Photo of the 1 MW Square FPC gas analysis rack

The gas analyzer is configured to measure oxygen, carbon monoxide and carbon dioxide. Table 1 lists the output range for these three gas species measured for the 1 MW FPC. Additional details on the gas analyzer rack are provided elsewhere [2 - 4].

A delay exists between the time that the gas sample is extracted from the duct and the time it reaches the analyzer. This delay time is determined by introducing a step-change in gas composition flowing past the gas sampling probe and monitoring the output of the analyzer for change in measured gas concentration. The delay time used in each experiment is documented in the FireTOSS datasheet. The gas analyzer was modified by Servomex to permit higher sample flow rates in order to reduce the sample delay times [4, 5].

Table 1. Servomex 4100C gas species measurement ranges.

Gas Species	Range
Oxygen (O_2)	0 – 25 %
Carbon Dioxide (CO_2)	0 – 10 %
Carbon Monoxide (CO)	0 – 1 %

Flow Measurement

The flow of gases in the duct is measured using a pressure transducer, velocity probe, and thermocouple.
Details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6].

Pressure Transducer
A Setra model 267 pressure transducer with a range of 0 – 620 Pa (0 – 2.5 inches of water) and an output of 4 – 20 mA is used for differential pressure measurement in the 1 MW Square FPC [7]. The transducer is connected to the differential pressure probes through a solenoid valve that can be closed to facilitate baseline readings and probe purging.

Velocity Probe
Velocity measurements in the 1 MW Square FPC are performed using a bi-directional probe [8]. Figure 7 shows a schematic of the probe. The probe consists of two ports; one facing upstream and the other downstream. The differential pressure measured between the two ports is used to calculate the velocity at the probe location. A flow shape factor is applied to calculate the average duct velocity. The probes are mounted to the exterior of the duct via a 19 cm diameter mounting plate. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [9].

The 1 MW Square FPC duct is equipped with additional velocity probes. A pair of VOLU-probe/1SS Stainless Steel Pitot Airflow Traverse Probes [10] is mounted approximately 30 cm downstream of the bi-directional probes, as shown in Figure 3. Figure 8 shows a schematic of the probe. The probe consists of two manifolds; one each for static and total pressure measurement. Each manifold has pressure ports spaced at equal area intervals, producing a pressure representing the instantaneous average across the duct. The probes are mounted to the exterior of the duct via a 15 cm x 15 cm mounting plate on one end, with the opposite end secured by a pin support. Two probes are mounted at a 90° angle, per manufacturer specifications [11]. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [12].

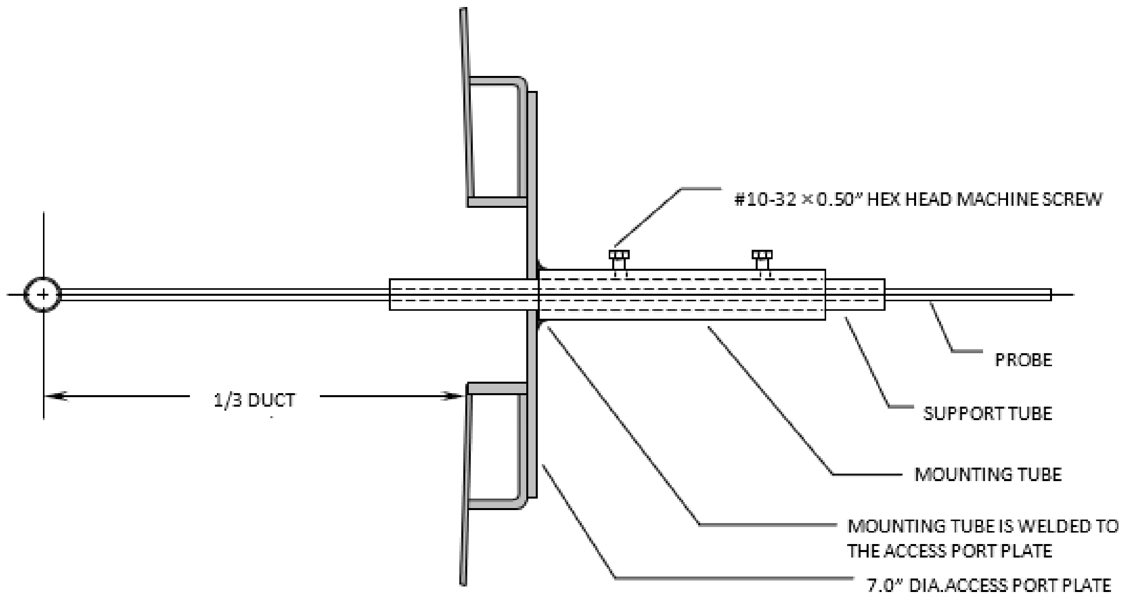

Figure 7: Schematic of the bi-directional probes.

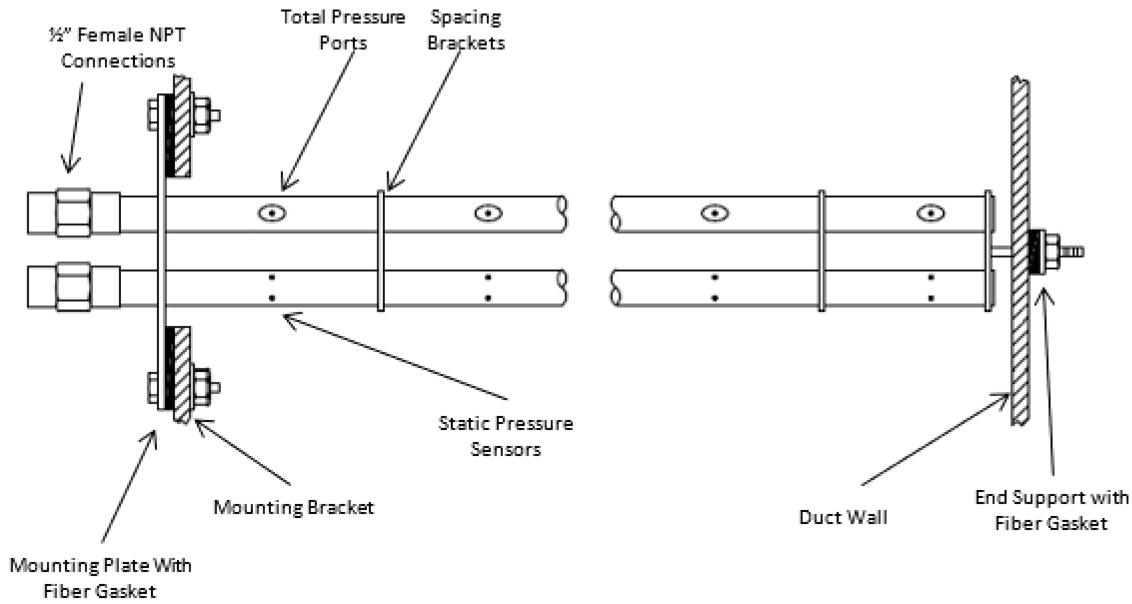

Figure 8: Schematic of the velocity traverse probes [10].

Thermocouple
Two 1.5 mm (0.062 inch) Inconel-sheathed Type K special limits of error (SLE) thermocouples are used to monitor the gas temperature in the 1 MW FPC duct. Type K thermocouples have a peak temperature range of approximately 1250 ºC (2282 ºF). Type-K SLE thermocouple wire has a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. Additional information on thermocouples can be found in the Laboratory Instruction [13].

Smoke Measurement

Smoke is measured in the 1 MW Square FPC using optical density meters (ODMs) [14, 15]. Both laser and white-light ODMs are used in the 1 MW Square FPC. The ODM access ports are located approximately 6 m downstream of the velocity and gas sampling probes.

The laser ODM uses a low-power (0.5 mW) Helium-Neon (HeNe) laser that emits continuous light at 632 nm. The laser ODM uses two photodiode detectors; the main detector is used to measure the beam intensity as it is attenuated by the smoke and fire gases in the FPC. A compensating detector located near the laser head is used to account for changes in the laser output during a test so that these are not erroneously attributed to smoke attenuation by the main detector.

The white-light ODM, which is manufactured by Fire Testing Technology (FTT), uses a broad-band visible (white) light source. The light source consists of a halogen lamp and a series of lenses and apertures that combine to create a nearly collimated beam with a 25 mm diameter at the source. The light receiver uses a silicon photoelectric cell in front of which is a spectral filter to accommodate the human eye. The source and receiver are mounted to a rigid frame on opposite sides of the duct.

Data Acquisition

Data acquisition for the 1 MW Square FPC is achieved using an Allen Bradley (AB) SLC 500 series Programmable Logic Controller (PLC). The system is equipped with a SLC 5/05 processor which has an IP address of 10.243.235.183. The FPC instrumentation and the corresponding FireTOSS tag are listed in Table 2. The PLC is located inside a cabinet on the east wall of a climate controlled instrument shed located on the mezzanine level, above the MBR. This shed houses the data acquisition and gas analysis instrumentation for all of the MBR FPCs.

Table 2. Data Acquisition Setup

Devices Attached	Quantity Measured	FireTOSS Tag
Laser ODM – Main	Light transmission	AB183_AI01_08
Laser ODM – Compensating	Light transmission	AB183_AI01_09
White Light ODM	Light transmission	AB183_AI01_10
Gas Analyzer – O_2	Gas Concentration	AB183_AI04_04
Gas Analyzer – CO_2	Gas Concentration	AB183_AI04_03_F
Gas Analyzer – CO	Gas Concentration	AB183_AI04_05
Pressure Transducer	Pressure	AB183_AI04_01_F
Thermocouple 1	Temperature	AB183_TC11_01
Thermocouple 2	Temperature	AB183_TC11_02

Measurement Range

The practical HRR measurement range for the 1 MW Square FPC is from 10 kW to 1700 kW. This represents a range of HRR values over which the 1 MW FPC has a linear response. The minimum change in HRR that can be resolved with the 1 MW Square FPC is approximately 5 kW. Data from calibration experiments performed over the full measurement range of the FPC are shown in Appendix A.

Calibration

A calibration burner [16] is used to determine the calibration factor, or C Factor, for a FPC. The type of calibration burner is selected based on the desired maximum HRR needed for the calibration. For the 1 MW Square FPC, sand burners [17] are used to determine the C Factor.

Calculations

The calculations used to determine the HRR, and other output quantities, from the FPC are defined in the FPC Laboratory Instruction [1].

Uncertainty and Accuracy

Fire Products Collectors are designed to provide four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production. The uncertainty associated with each of these quantities, calculated from measurements in the 1 MW Square FPC, was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [18], Technical Note 1297 [19], and the NIST Uncertainty Workshop [20]. The analysis outlined below is based primarily on data collected from natural gas fires generated using sand burners; the burner output was fixed for a period of five minutes at progressively increasing HRR levels [1, 17]. Uncertainty was calculated for nominal fire sizes of 50 kW, 500 kW and 1100 kW, representing low, middle and high ends of the operating range.

The combined standard uncertainty for a calculated output y, based on a number (i) of uncorrelated input quantities x_i, is a combination of the uncertainty of each component. It is expressed mathematically by the following equation:

$$u_c(y) = k\sqrt{\sum s_i^2 u(x_i)^2} \quad (1)$$

where:

$u_c(y)$ = Combined standard uncertainty in the output y
$u(x_i)$ = Standard uncertainty of each component x_i
s_i = Sensitivity coefficient associated with each component $(\partial/\partial x_i)$
k = Coverage factor

The expression used to calculate the oxygen consumption HRR is a complex function of multiple variables and physical constants [1, 21]. The formulations used to calculate CHRR, gas species production and smoke production are considerably simpler and use many of the same measured input variables [1]. The approach taken in this analysis was to calculate the uncertainty in the HRR first. This necessitates calculating the standard uncertainty for most of the variables and parameters used in the other output quantities. A spreadsheet formulation was used to apply Equation (1) to perform the uncertainty calculations [22].

Table 3 summarizes the combined standard uncertainty for each output quantity of the 1 MW Square FPC. The HRR, CHRR and CO_2 production rate values are based on data collected from the natural gas calibration burner experiments. Because the natural gas fires produce relatively little smoke, data for the rate of smoke release (RSR) are from separate experiments. The RSR data is from a corrugated cardboard fire with a peak HRR of approximately 300 kW. Details on how these uncertainty values were determined are provided in the sections that follow.

Table 3. Uncertainty Summary

Quantity	Calculated Value	Combined Standard Uncertainty	Relative Uncertainty
Heat Release Rate (HRR)	520 kW	34	6.4 %
Convective Heat Release Rate	385 kW	24	6.3 %
Mass Production Rate – CO_2	26 g/s	1.6	6.3 %
Mass Production Rate – CO	0.07 g/s	0.01	13.9 %
Rate of Smoke Release – Laser	2.7 m^2/s	0.14	5.5 %

Heat Release Rate

The oxygen consumption heat release rate is calculated according to [1]:

$$HRR = C\left[E\phi - \left(E_{CO} - E\right)\frac{1-\phi}{2}\frac{X_{CO}}{X_{O_2}}\right]\left(\frac{\dot{m}}{1+\phi(\alpha-1)}\right)\left(\frac{MW_{O_2}}{MW_{air}}\right)\left(1-X_{H_2O}^{0}\right)X_{O2}^{0} \qquad (2)$$

The oxygen depletion factor, , in Equation 2 is a function of two co-dependent pairs: the concentrations of oxygen and carbon dioxide in the incoming air and in the product stream $(X_{O_2}, X_{O_2}^0)$ $(X_{CO_2}, X_{CO_2}^0)$. It has been shown that, under these circumstances, the approach to properly account for the uncertainty is to re-write Equation 2 in terms of the raw inputs [18]. Based on this, Equation (2) was broken down into thirty three components and a standard uncertainty was determined for each. Table 4 shows a list of the components along with a brief description.

Table 4: Components used in the oxygen consumption HRR calculation

Component	Description (Units in parentheses)
A_{O_2}	Current output from oxygen analyzer (A)
$A_{O_2,zero}$	Current output from oxygen analyzer flowing zero gas (A)
$A_{O_2,span}$	Current output from oxygen analyzer flowing span gas (A)
$A_{O_2,base}$	Current output from oxygen analyzer during pre-test baseline (A)
$X_{O_2,zero}$	Mole fraction of oxygen in zero gas (A)
$X_{O_2,span}$	Mole fraction of oxygen in span gas (A)
A_{CO_2}	Current output from carbon dioxide analyzer (A)
$A_{CO_2,zero}$	Current output from carbon dioxide analyzer flowing zero gas (A)
$A_{CO_2,span}$	Current output from carbon dioxide analyzer flowing span gas (A)
$A_{CO_2,base}$	Current output from carbon dioxide analyzer during pre-test baseline (A)
$X_{CO_2,zero}$	Mole fraction of carbon dioxide in zero gas (A)
$X_{CO_2,span}$	Mole fraction of carbon dioxide in span gas (A)
A_{CO}	Current output from carbon monoxide analyzer (A)
$A_{CO,zero}$	Current output from carbon monoxide analyzer flowing zero gas (A)
$A_{CO,span}$	Current output from carbon monoxide analyzer flowing span gas (A)
$X_{CO,zero}$	Mole fraction of carbon monoxide in zero gas (A)
$X_{CO,span}$	Mole fraction of carbon monoxide in span gas (A)
$M_{air,dry}$	Molecular weight of dry air (g/mol)
M_{H_2O}	Molecular weight of water (g/mol)
M_{O_2}	Molecular weight of oxygen (g/mol)
E	Net heat release of natural gas per kg of oxygen consumed (kJ/kg)

Component	Description (Units in parentheses)
E_{CO}	Net heat release of carbon monoxide per kg of oxygen consumed (kJ/kg)
α	Volumetric expansion factor (--)
RH	Relative humidity of incoming air (%)
P_{amb}	Ambient pressure (Pa)
T_{amb}	Ambient temperature (K)
C_{bdp}	Bi-directional probe constant (--)
f	Velocity flow shape factor (--)
D	Duct diameter (m)
T_1	Duct temperature at the sampling location (K)
T_2	Duct temperature at the sampling location (K)
$A_{dp,meas}$	Current output from the pressure transducer (A)
$A_{dp,zero}$	Current output from the pressure transducer during pre-test baseline (A)

Variables and constants are grouped in Table 4 according to four primary categories: gas species concentrations, physical constants, ambient conditions and mass flow rate. A discussion of the uncertainty analysis for each category is given below.

Gas Species Concentration

ASTM E 2536 identifies three sources of error that should be considered in the estimation of uncertainty for oxygen measurements in a cone calorimeter: the data acquisition system, random (Type A) scatter in the data signal, and calibration [23]. Instrumentation used in the cone calorimeter is similar to what is used in large scale calorimeter hoods such as the 1 MW FPC. Based on this, these three sources of error were considered for the gas species uncertainty evaluation (O_2, CO_2 and CO) performed here. A fourth source, calibration gas error, was added based on discussions with the instrument retailer [24].

Table 4 lists two components that contribute to gas species measurements: the unscaled analyzer signal (A_i) and the mole fractions in the calibration gases (X_i). The following sections provide details related to the uncertainty estimate for each component.

Analyzer Signal Uncertainty

The uncertainty estimate in the recorded analyzer signal included contributions from the data acquisition hardware and fluctuations in the data. The contribution from data acquisition hardware came from manufacturer's specifications. The uncertainty contribution associated with data fluctuations came from a statistical analysis of the raw signal collected in a calibration burner experiment.

The Servomex gas analyzer used in the 1 MW Square FPC sends an analog 4 – 20 mA signal to an Allen Bradley (AB) SLC 500 series programmable logic controller (PLC) through a 1746 NI16I 16 bit I/O module. Specifications for the AB hardware include a digital resolution of 640 nA and a calibrated accuracy of better than 0.15 % of range [25].

The standard uncertainty associated with fluctuations in the analyzer signal was estimated using the sample standard deviation. Calculations were performed using data recorded when the analyzer output was steady. Analyzer signals listed in Table 4 are divided into two categories: calibration ($A_{i,zero}$, $A_{i,span}$) and experiment (A_i, $A_{i,base}$). For the calibration signal uncertainty, the sample standard deviation was calculated over one minute periods during an 'AUTOCAL' cycle. For the experiment signal uncertainty the sample standard deviation was calculated during a calibration burner experiment. Statistics were performed for data spanning several minutes.

The combined uncertainty was calculated by combining the data acquisition and statistical components.

Calibration Gas Uncertainty
The 1 MW Square FPC is equipped with a modified Servomex Xentra 4100 gas analyzer that contains individual cells to measure each of the three species concentrations. Oxygen concentration is measured in a paramagnetic cell with 0 – 25 % range; CO_2 and CO are measured in non-dispersive infrared (NDIR) cells with peak concentration ranges of 10 % and 1 %, respectively. Each cell is calibrated using zero and span gases. The zero gas and CO / CO_2 span gas come with certifications from the supplier. The oxygen analyzer is spanned with ambient air; the uncertainty estimate for ambient O_2 concentration was taken from the literature [18].

The zero gas is "Zero" grade (99.99 %) nitrogen. Assuming a rectangular distribution, the standard uncertainty is +/- 5.8 x 10^{-5}. The CO/CO_2 span gas is a Primary Standard grade mixture with certified accuracy of 1% for CO and 0.02 % for CO_2. The concentrations of CO and CO_2 in the span gas are nominally 0.8 % and 8 %, respectively, with the balance comprised of N_2. Assuming a rectangular distribution, the standard uncertainties of CO_2 and CO in the span gas are estimated to be 1.2 x 10^{-4} and 4.6 x 10^{-5}, respectively. Laboratory air is used to span the oxygen analyzer; the concentration is taken as 20.95 %. The estimated uncertainty associated with the oxygen span concentration is estimated to be 0.05 % [18]. This estimate was verified through a comparison with a high purity certified O_2/N_2 mixture.

Physical Constants
Physical constants include the molecular weights of oxygen (M_{O_2}), dry air ($M_{air,dry}$) and water (M_{H_2O}), in addition to the volumetric expansion factor (α) and the net heat release per unit mass of oxygen consumed for natural gas (E) and carbon monoxide (E_{CO}). The standard uncertainty of the molecular weights was taken as zero. The standard uncertainties of the remaining constants were based on previous work and summarized in Table 5 [18].

Table 5: Summary of uncertainty in physical constants

Parameter	Value	Standard Uncertainty
α (--)	1.104	0.048
E (kJ/kg O_2)	12550	19.95
E_{CO} (kJ/kg O_2)	17690	10

Ambient Conditions

Ambient conditions are measured using a wall mounted weather station that is permanently housed in the MBR. The weather station measures relative humidity, temperature and absolute pressure. Additional information, including the uncertainty analysis for each of the measured quantities, can be found in the laboratory instruction [28]. Table 6 shows a summary of the standard uncertainty for the ambient temperature, pressure and relative humidity.

Table 6: Ambient conditions uncertainty summary

Quantity	Standard Uncertainty
T_a (°C)	0.6
P_a (Pa)	115.5
RH (%)	2.2

Mass Flow Rate

The mass flow rate is expressed as:

$$\dot{m} = \rho \, \dot{V} \quad (3)$$

where ρ is the gas density (kg/m^3) and $\dot{V}$ is the volumetric flow rate (m^3/s). The density was expressed in terms of temperature using the ideal gas law:

$$\rho = \rho_{std} \frac{T_{std}}{T} \quad (4)$$

where the standard condition is taken as 300 K and 1 atm. The volumetric flow rate was calculated using:

$$\dot{V} = f \, A \, V \quad (5)$$

where f is the flow shape factor, A is the duct area (m^2) and V is the velocity (m/s). The flow shape factor was calculated using data from flow traverse measurements conducted previously [29]. The duct area is a function of the diameter, D (0.65 m). The velocity was calculated according to [6]:

$$V = \sqrt{\frac{2\,\Delta P\, T}{\rho_{std} T_{std}}} \Big/ C_{bdp} \tag{6}$$

where P is the differential pressure measured by the velocity probe (Pa) and T (K) is the temperature inside the duct. C_{bdp} is the bi-directional probe factor that has been shown to be a constant (1.08 ± 5 %) over the range of Reynolds numbers encountered in the duct flow [8]. Combining the above equations and substituting ($T_{std} = 300\ K$, $\rho_{std} = 1.18\ kg/m^3$) yields:

$$\dot{m} = \frac{20.875\, D^2 f}{C_{bdp}} \sqrt{\frac{\Delta P}{T}} \tag{7}$$

The temperature was taken as the average of two independent measurements at each time step and the differential pressure was expressed as:

$$\Delta P = \Delta P_{meas} - \Delta P_{baseline} = \left(m_{dp} A_{dp} + b_{dp}\right)_{meas} - \left(m_{dp} A_{dp} + b_{dp}\right)_{baseline} \tag{8}$$

where m_{dp} and b_{dp} are the calibration factors for the differential pressure transducer. The differential pressure is corrected by subtracting a baseline value, which is measured in a separate experiment with the transducer cross-ported. Consolidating terms, the differential pressure can be expressed as:

$$\Delta P = m_{dp}\left(A_{dp,meas} - A_{dp,baseline}\right) \tag{9}$$

The calibration constant, m_{dp}, for the pressure transducer was 38920.1 Pa/A. This yields the expression for mass flow rate:

$$\dot{m} = \frac{4118.26\, D^2 f}{C_{bdp}} \sqrt{\frac{A_{dp,meas} - A_{dp,baseline}}{T}} \tag{10}$$

The standard uncertainty in the diameter measurement was calculated from the standard deviation of five independent measurements. The result was D = 0.653 ± 0.001 m. To account for the duct not being perfectly circular this uncertainty was increased to ± 0.005 m. The standard uncertainty in the flow shape factor (*f*) was estimated based on the standard error in the least squares regression from the traverse data [29]. The standard uncertainty in the temperature (± 1.6 K) was taken from the literature [18].

The combined standard uncertainty in the pressure transducer data was calculated based on manufacturer's specifications for the data acquisition hardware and pressure transducer, in addition to a statistical analysis of the signal. The data acquisition hardware is the same as what is used for the gas analyzers; the standard uncertainty is 7.1 x 10^{-8} A. The standard uncertainty for a Setra model 267 pressure transducer is a function of the input range for the instrument; for a device with input range P = 0 – 0.62 kPa (0 – 2.5 inch H_2O) the standard uncertainty is 5.2 x 10^{-5} A [9]. The uncertainty associated with data fluctuation in the transducer output was calculated from the sample standard deviation collected during a calibration burner experiment. Table 7 shows a summary of the combined standard uncertainty for the pressure measurement for three fire sizes and a baseline.

Table 7: Combined standard uncertainty in the differential pressure measurement.

Fire Size	Combined Standard Uncertainty (A)
Baseline	5.2 x 10^{-5}
50 KW	1.2 x 10^{-4}
520 kW	1.6 x 10^{-4}
1055 kW	1.8 x 10^{-4}

Summary

Table 8 shows a summary of the uncertainty in the oxygen consumption heat release rate performed for three fire sizes. The first column lists the 33 components (with units in parentheses) that comprise the oxygen consumption HRR calculation, as described in Table 4. For each component, the nominal value obtained for a 520 kW fire is listed in column 2. Column 3 lists the standard uncertainty for each component that was discussed in the preceding sections. Columns 4 – 6 list the sensitivity coefficients calculated for fire sizes of 50 kW, 520 kW and 1055 kW.

Table 8: Summary of HRR uncertainty calculations

Variable / Parameter x_i	Nominal Value	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient $\lvert s_i \rvert$		
			50 kW	520 kW	1055 kW
A_{O_2}	0.01681	8.2 x 10^{-6}	1.1 x 10^{6}	9.8 x 10^{5}	1.1 x 10^{6}
$A_{O_2,zero}$	0.00400	6.2 x 10^{-7}	4.3 x 10^{3}	4.3 x 10^{4}	8.6 x 10^{4}
$A_{O_2,span}$	0.01741	1.8 x 10^{-6}	4.9 x 10^{3}	4.9 x 10^{4}	9.8 x 10^{4}
$A_{O_2,base}$	0.01739	1.3 x 10^{-6}	1.1 x 10^{6}	9.9 x 10^{5}	1.1 x 10^{6}
$X_{O_2,zero}$	0.00000	5.8 x 10^{-5}	2.7 x 10^{2}	2.7 x 10^{3}	5.5 x 10^{3}
$X_{O_2,span}$	0.20950	5.0 x 10^{-4}	3.2 x 10^{2}	3.1 x 10^{3}	6.2 x 10^{3}
A_{CO_2}	0.00479	1.0 x 10^{-5}	9.3 x 10^{4}	7.9 x 10^{4}	8.3 x 10^{4}
$A_{CO_2,zero}$	0.00400	2.3 x 10^{-7}	4.6 x 10^{2}	5.0 x 10^{3}	9.9 x 10^{3}
$A_{CO_2,span}$	0.01680	1.3 x 10^{-6}	4.1 x 10^{2}	4.5 x 10^{3}	9.1 x 10^{3}
$A_{CO_2,base}$	0.00406	9.7 x 10^{-7}	9.3 x 10^{4}	8.0 x 10^{4}	8.4 x 10^{4}
$X_{CO_2,zero}$	0.00000	5.8 x 10^{-5}	7.4 x 10^{1}	8.0 x 10^{2}	1.6 x 10^{3}
$X_{CO_2,span}$	0.08000	1.2 x 10^{-4}	6.5 x 10^{1}	7.2 x 10^{2}	1.5 x 10^{3}
A_{CO}	0.00403	2.9 x 10^{-6}	1.7 x 10^{4}	1.4 x 10^{4}	1.5 x 10^{4}
$A_{CO,zero}$	0,00400	1.4 x 10^{-6}	1.7 x 10^{4}	1.4 x 10^{4}	1.5 x 10^{4}
$A_{CO,span}$	0.01680	1.6 x 10^{-5}	4.8 x 10^{0}	3.6 x 10^{1}	6.8 x 10^{1}
$X_{CO,zero}$	0.00000	5.8 x 10^{-5}	2.6 x 10^{4}	2.3 x 10^{4}	2.5 x 10^{4}
$X_{CO,span}$	0.00800	4.6 x 10^{-5}	7.6 x 10^{0}	5.7 x 10^{1}	1.1 x 10^{2}
$M_{air,dry}$ (g/mol)	28.97	0	0	0	0
M_{H_2O} (g/mol)	18	0	0	0	0
M_{O_2}(g/mol)	32	0	0	0	0
E (kJ/kg)	12550	19.95	4.2 x 10^{-3}	4.2 x 10^{-2}	8.4 x 10^{-2}
E_{CO} (kJ/kg)	17690	10	5.2 x 10^{-6}	4.0 x 10^{-5}	7.8 x 10^{-5}
α (--)	1.104	0.048	2.3 x 10^{-1}	2.5 x 10^{1}	9.3 x 10^{1}
RH (%)	51.69	2.16	9.2 x 10^{-3}	1.1 x 10^{-1}	2.2 x 10^{-1}
P_{amb} (Pa)	101107	115.5	1.3 x 10^{-6}	5.6 x 10^{-5}	1.1 x 10^{-4}
T_{amb} (K)	298.95	0.59	7.9 x 10^{-3}	3.4 x 10^{-1}	6.9 x 10^{-1}
C_{bdp}	1.08	0.054	4.6 x 10^{1}	4.6 x 10^{2}	9.3 x 10^{2}
f (--)		7.6 x 10^{-3}	4.8 x 10^{1}	4.8 x 10^{2}	9.7 x 10^{2}
D (m)	0.653	0.005	1.6 x 10^{2}	1.6 x 10^{3}	3.2 x 10^{3}
T_1 (K)	401.88	1.6	4.3 x 10^{-2}	3.2 x 10^{-1}	5.4 x 10^{-1}
T_2 (K)	401.30	1.6	4.3 x 10^{-2}	3.2 x 10^{-1}	5.4 x 10^{-1}
$A_{dp,meas}$ (A)	0.00648	1.6 x 10^{-4}	1.1 x 10^{4}	1.0 x 10^{5}	1.4 x 10^{5}
$A_{dp,zero}$ (A)	0.00400	5.2 x 10^{-5}	1.2 x 10^{4}	1.1 x 10^{5}	1.4 x 105

The combined standard uncertainty for each fire size was calculated by combining terms in Table 8 according to Equation 1. The results are summarized in Table 9; the values represent a coverage factor of k = 1. In the case of a normal distribution, this translates to a confidence level of approximately 68%. To obtain a higher confidence level a higher coverage factor can be applied. A coverage factor of k = 2 in a normally distributed population provides a confidence level of approximately 95 %.

Table 9: Combined standard uncertainty in the heat release rate

Fire Size (kW)	Combined Standard Uncertainty (kW)	Relative Uncertainty (%)
50	4	7.6
520	33	6.3
1055	67	6.4

Table 10 shows a list of the variables that contribute most significantly to the combined uncertainty. The HRR is highly sensitive to the oxygen concentration measurements (A_{O_2}, $A_{O_2,base}$) as demonstrated by the large sensitivity factor shown for these variables in Table 8. At the fire size increases, the terms associated with the mass flow become more significant (C_{bdp}, D, $A_{dp,meas}$). These terms account for more than 75 % of the combined uncertainty at 1055 kW, with the differential pressure probe factor (C_{bdp}) being dominant.

Table 10: Contribution to the combined uncertainty

Variable / Parameter x_i	Fire Size 50 kW	520 kW	1055 kW
A_{O_2} (A)	14.0	9.1	20.8
$A_{O_2,base}$ (A)	12.0	0.2	0.0
$X_{CO,Zero}$ (--)	14.9	0.2	0.0
C_{bdp} (--)	39.4	55.0	55.5
D (m)	4.1	5.7	5.8
$A_{dp,meas}$ (A)	12.0	25.5	14.3

Convective Heat Release Rate

The convective heat release rate (CHRR) is expressed as:

$$\dot{Q}_c = \dot{m}\,(h_2 - h_1) \tag{11}$$

where $\dot{Q}_c$ is the convective heat release rate (kW), $\dot{m}$ is the mass flow rate (kg/s) and h_1 and h_2 are the enthalpies of the incoming air and product stream, respectively (kJ/kg). The mass flow rate is evaluated in the same manner as in the HRR calculation (Equation 11) and is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The standard uncertainty in each of these is the same as in the HRR analysis.

The enthalpy difference is calculated according to a polynomial fit evaluated over the temperature range:

$$h_2 - h_1 = \left(\alpha T + \beta \frac{T^2}{2} + \gamma \frac{T^3}{3} + \delta \frac{T^4}{4} + \varepsilon \frac{T^5}{5} \right) \Bigg|_{T_1}^{T_2} \qquad (12)$$

where , , , , are fit parameters. Data used to fit the coefficients was taken from two sources [30, 31]. The error associated with the fit parameters is negligible; the uncertainty in enthalpy was assumed to be solely due to error in the temperature measurement[1]. The standard uncertainty in temperature is the same as in the HRR analysis. Table 11 shows a summary of the CHRR and the combined standard uncertainty in the CHRR for each corresponding HRR step; the values represent a coverage factor of k = 1.

Table 11: Convective heat release rate uncertainty summary

HRR (kW)	CHRR (kW)	Combined Uncertainty (kW)	Relative Uncertainty (%)
50	32	6	19
520	386	24	6.3
1055	791	45	5.7

Gas Species Production

The gas species mass production rate is expressed as:

$$\dot{m}_x = \dot{m} \left(X_x - X_{x,base} \right) \frac{M_x}{M_a} \qquad (13)$$

Where $\dot{m}_x$ is the production rate of species x (kg/s), $\dot{m}$ is the mass flow rate in the exhaust duct (kg/s), X_x and $X_{x,base}$ are the mole fractions of species x in the product stream and the incoming air, respectively (mol/mol), M_x is the molecular weight of species x (g/mol) and M_a is the molecular weight of air (g/mol).

[1] The polynomial fit parameters used for the enthalpy calculation were those for air.

All variables in Equation (13) are evaluated in the same manner as in the HRR calculation (Equation 1). The mass flow rate is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The mole fractions are calculated from the analyzer current and calibration concentrations. The standard uncertainty in each of these is the same as in the HRR analysis.

Table 12 and Table 13 show summaries of the combined uncertainty in the CO_2 and CO production rates, respectively, for three fire sizes. The values represent a coverage factor of k = 1. Relative uncertainty levels in the CO production rate are high at low HRR mainly because of the low CO levels generated by natural gas fires.

Table 12: Combined uncertainty in the CO_2 production rate

HRR (kW)	$\dot{m}_{CO_2}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
50	2.2	0.1	6.6
520	26	1.6	6.3
1055	55	3.7	6.7

Table 13: Combined uncertainty in the CO production rate

HRR (kW)	$\dot{m}_{CO}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
50	0.01	0.01	94.3
520	0.07	0.01	13.9
1055	0.1	0.01	9.2

Smoke Production

The rate of smoke release (RSR) is expressed as:

$$RSR = k\dot{V} \quad (14)$$

where k (m^{-1}) is the optical extinction coefficient measured by the ODM and $\dot{V}$ (m^3/s) is the volumetric flow rate in the exhaust duct.

The standard uncertainty for the extinction coefficient is described in the ODM Technical Reference [15]. For the laser system the relative standard uncertainty is less than 1 % for k > 0.1 m^{-1}; for k > 0.2 m^{-1} the relative uncertainty is less than 0.5 %.

Uncertainty in the volumetric flow rate was calculated in a manner similar to the procedure used for the mass flow rate in the HRR analysis. The volumetric flow rate is a function of the same six quantities as the mass flow rate ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f).

Smoke data was collected from an experiment in which corrugated cardboard was the primary fuel. The peak HRR in this experiment was approximately 300 kW; at this fire size the extinction coefficient measured by the laser ODM was 0.63 m^{-1}, yielding a smoke release rate of 2.7 m^2/s. The combined standard uncertainty in the RSR under these conditions was 0.14 m^2/s or 5.5 %.

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Appendix A – Experimental Data

Figure 9 shows heat release rate data from a calibration burner experiment conducted under the 1 MW Square FPC using gas train "C" and a 20 cm square burner [17]. Gas train "C" has a maximum flow rate of 100 SLPM, which for natural gas translates to a peak fire size of approximately 57 kW. The calibration burner was run through a series of 5-minute duration steps with outputs of 0, 2, 5, 10, 15, 25 and 50 kW. Data from the burner is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burner and FPC during each of the seven steps; the average values are plotted together in Figure 10. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 9. The slope of a linear fit through this data is the C-Factor [1].

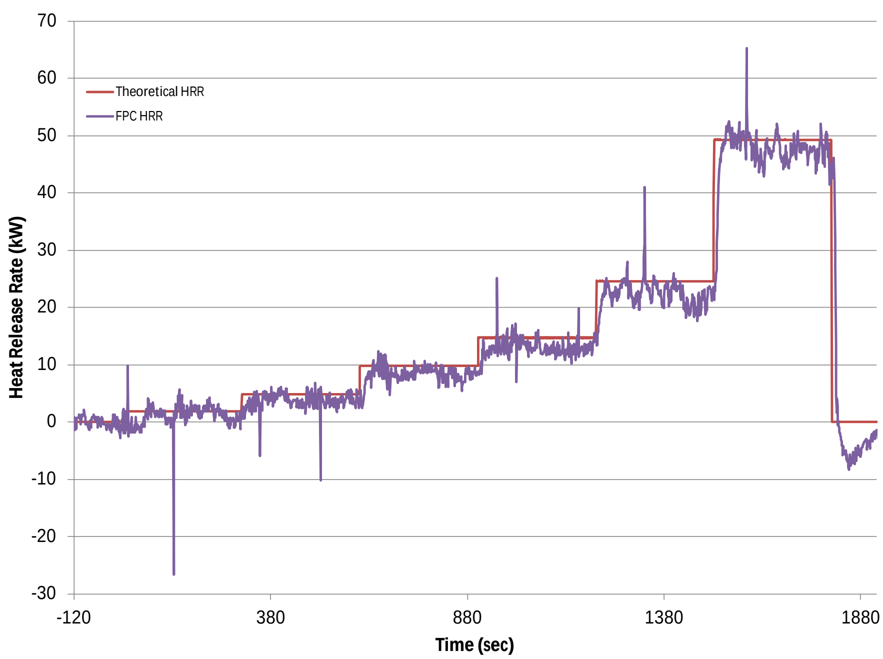

Figure 9: Heat release rate data from a calibration burner experiment under the 1 MW Square FPC.

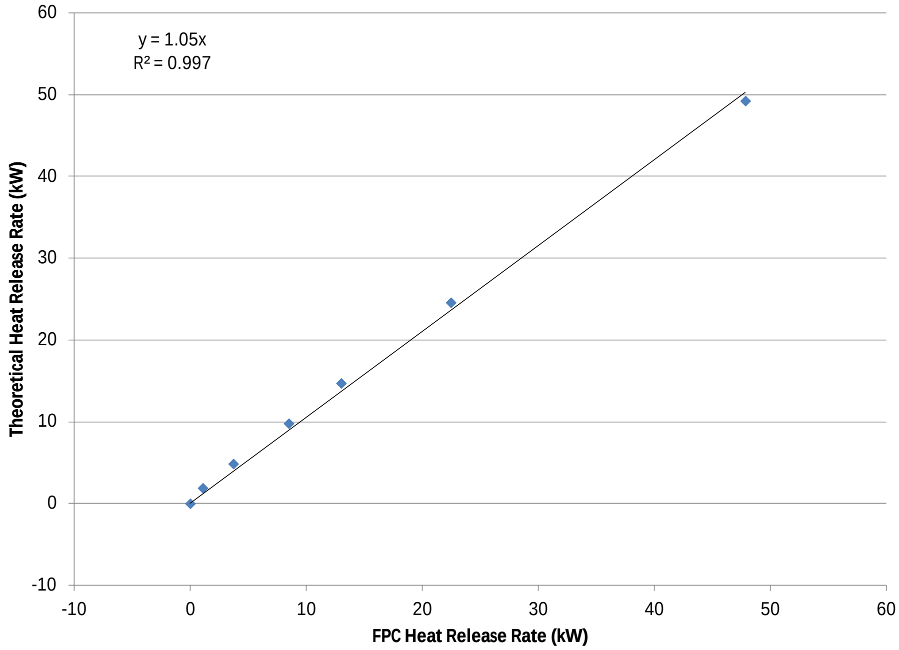

Figure 10: Average theoretical HRR plotted against average FPC HRR for an experiment using gas train "C" and a 20 cm square calibration burner.

Figure 11 shows heat release rate data from a calibration burner experiment conducted under the 1 MW Square FPC using gas trains "A" and "B" and a pair of 41 cm square burners [17]. Gas trains "A" and "B" each have a maximum flow rate of 1000 SLPM, which for natural gas translates to a peak fire size of approximately 570 kW. When run simultaneously they can produce a peak fire size of approximately 1100 kW. The calibration burners were run through a series of 5-minute duration steps with combined outputs of 0, 25, 50, 100, 300, 500, 700, 900 and 1100 kW. Data from the burners is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burners and FPC during each of the nine steps; the average values are plotted together in Figure 12. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 11. The slope of a linear fit through this data is the C-Factor [1].

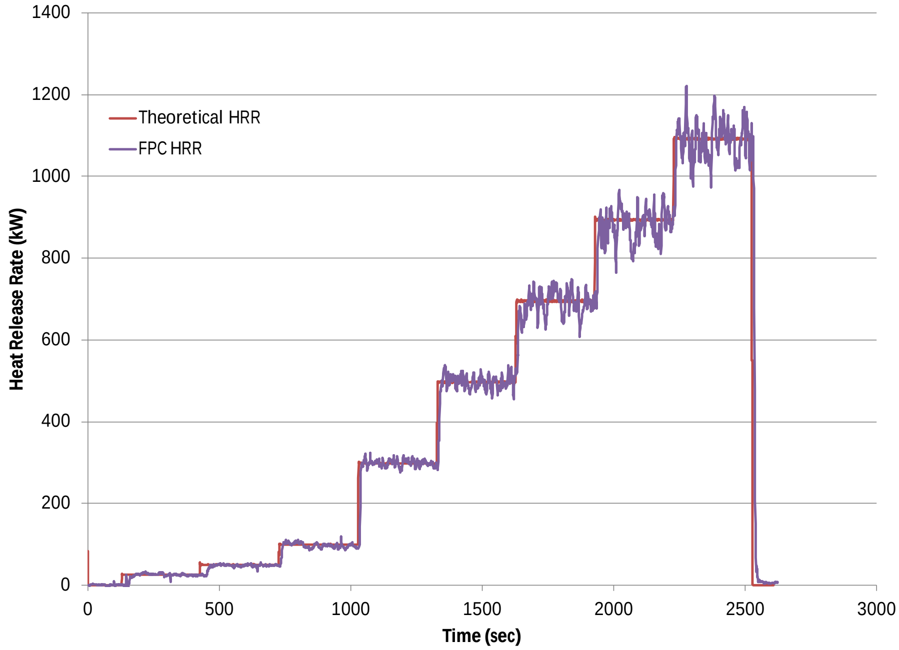

Figure 11: Heat release rate data from a calibration burner experiment under the 1 MW Square FPC.

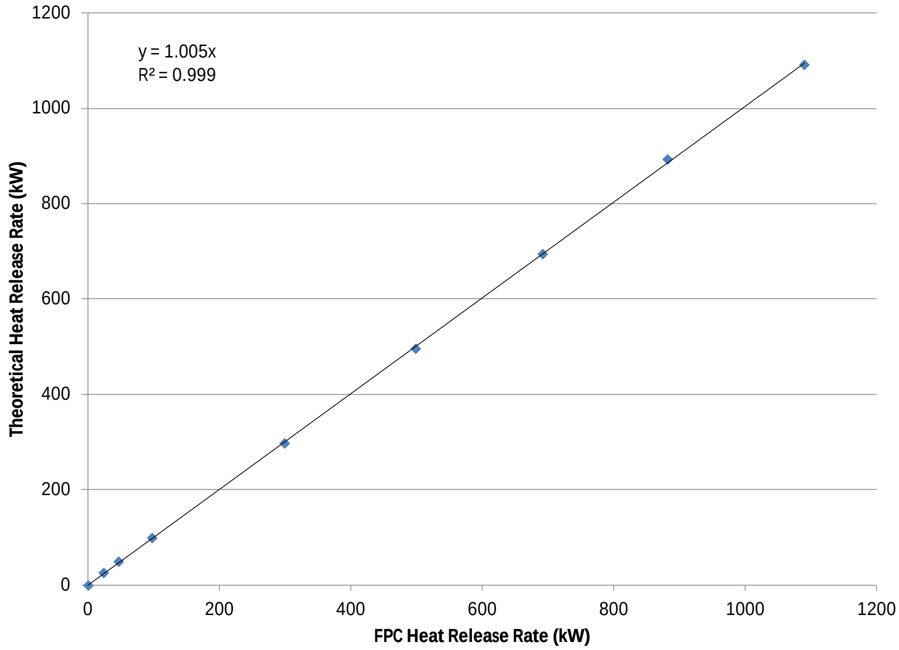

Figure 12: Average theoretical HRR plotted against average FPC HRR for an experiment using gas trains "A" and "B" and a pair of 41 cm square calibration burners.

Scope

This Technical Reference covers the use, design and specifications of the 1 MW Round Fire Products Collector (FPC) in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

General

The 1 MW Round FPC collects smoke and other products of combustion generated during fire experiments. A FPC consists of a collection hood connected to an exhaust duct, with air drawn through the duct by one or more variable speed fans. A FPC serves two purposes:

1) To remove combustion products from a laboratory space, and
2) To optimize the flow field for measurement and quantitative analyses of the combustion products.

A FPC provides four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production [1]. When used in conjunction with a weighing device, such as a load cell, the mass loss rate (MLR) of the burning object can be calculated. Gas species yields, smoke yield, and the effective heat of combustion of a burning item can then be calculated based on the MLR.

The 1 MW Round FPC is located in the southeast corner of the FRL's Medium Burn Room (MBR). Figure 1 shows a photograph of the collection hood and exhaust duct for the 1 MW Round FPC.

Figure 1: 1 MW Round FPC

Hood and Collection System

Physical Dimensions

Figure 2 shows a plan view schematic of the 1 MW Round FPC collection hood in the MBR. The 3.3 m diameter collection hood and transitions to a circular exhaust duct with an internal diameter of 0.66 m. A 0.39 m diameter orifice plate is located near the entrance of the exhaust duct, approximately 6.0 m above the floor. The orifice enhances mixing of the fire products prior to reaching the instrumentation locations. The exhaust duct has a vertical run of approximately 10.9 m before transitioning to a horizontal run above the MBR ceiling. The base of the collection hood is 3.8 m above the MBR floor; however, skirts can be added to reduce the height to 2.8 m.

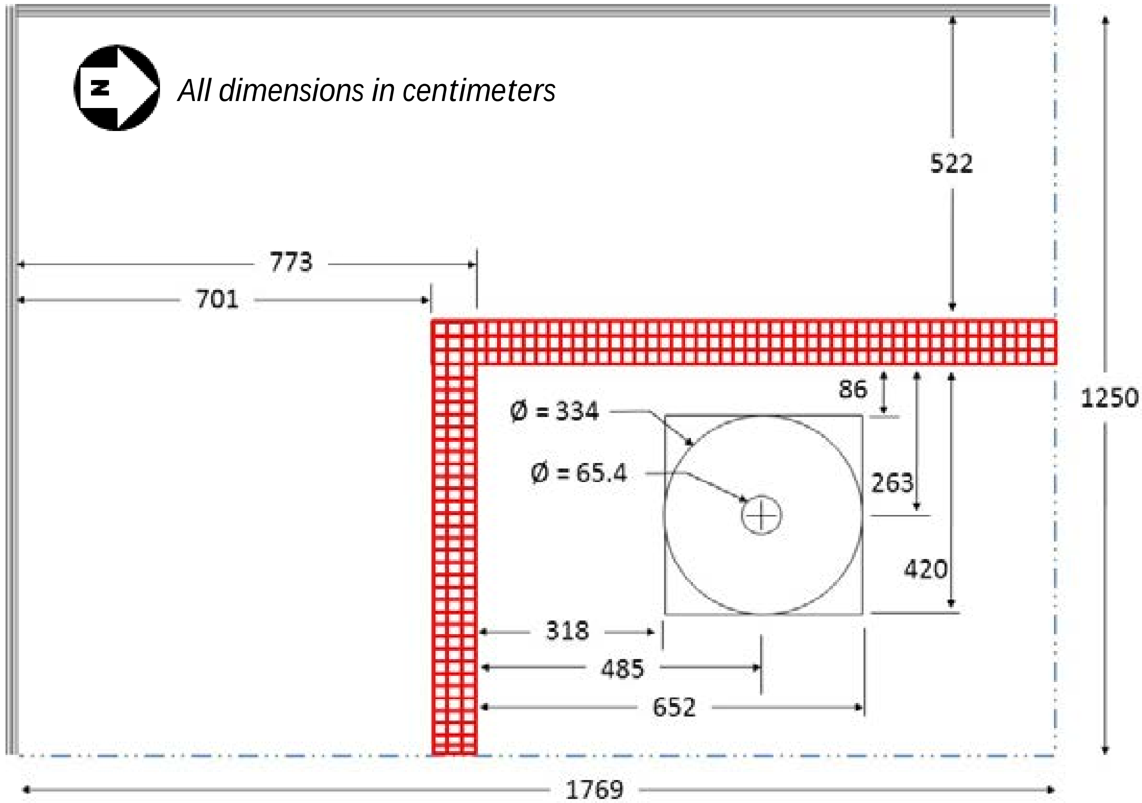

Figure 2: Plan view of 1 MW Round FPC in the MBR.

Instrument Locations

Instruments are located at two levels in the FPC exhaust duct, as shown in Figure 3. The first instrument station is located approximately 3.5 m downstream of the inlet orifice. This station is located below the MBR ceiling and is accessible via a fixed platform. The first instrument station is used for flow measurement and gas sampling. The second instrument station is located approximately 5 m downstream of the first station, at the mezzanine level directly above the MBR. This station houses the laser and white light smoke measurement instruments.

Flow Control

Flow in the FPC is controlled by a system of variable speed fans and actuated dampers that are programmed to maintain a fixed mass flow rate. The system is operated by a PC in the FRL Control Room. The FRL FPC's were designed to flow 6.8 kg/s (12,000 SCFM) per 1 MW heat release rate; this flow rate represents the approximate maximum capacity of the 1 MW Round FPC.

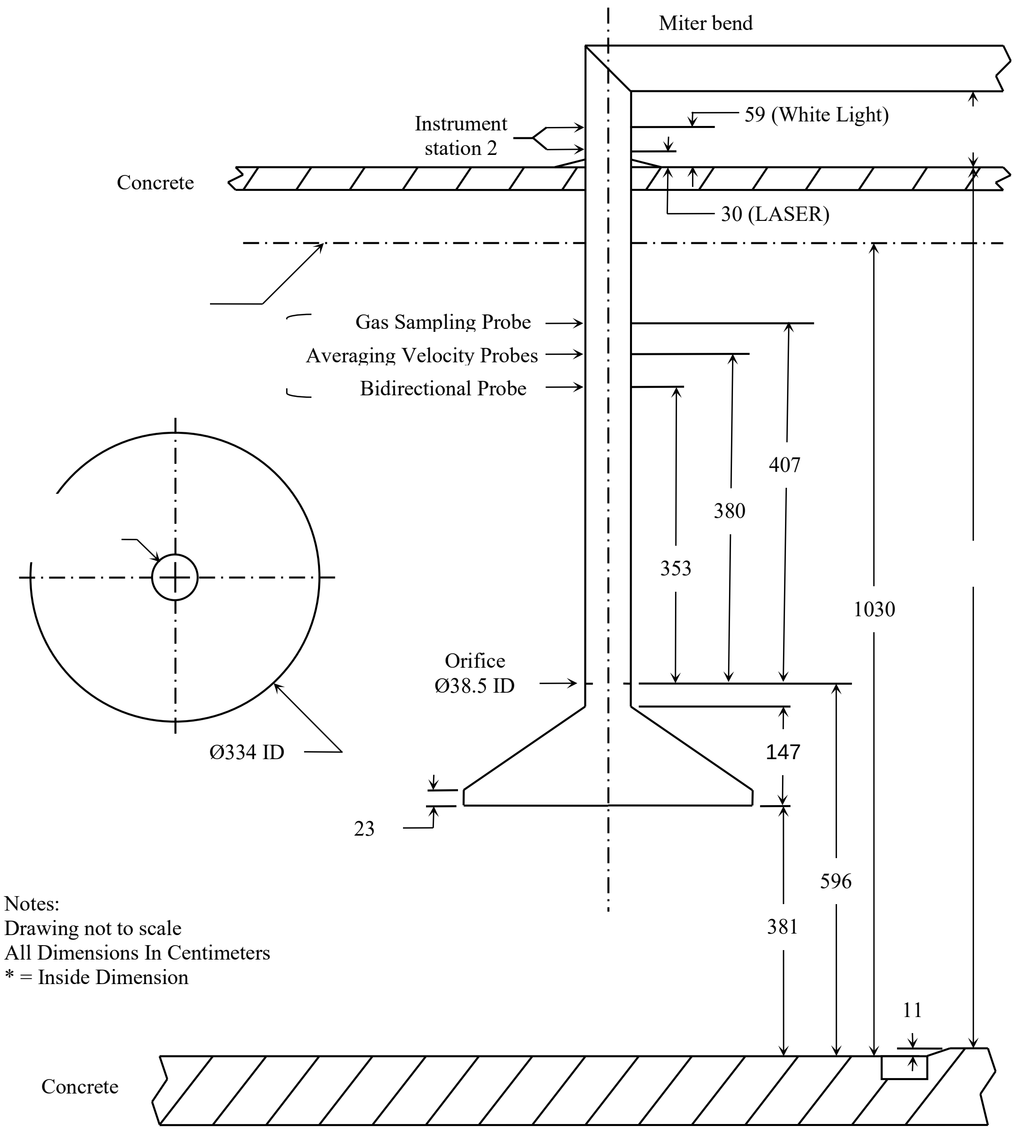

Figure 3: Elevation view of 1 MW Round FPC in the MBR.

Instrumentation

The 1 MW Round FPC is equipped with instrumentation to measure gas species concentrations, temperature, velocity, and smoke concentration.

Gas Species Measurement

The system of instrumentation used to measure gas species concentrations consists of a gas sampling probe located in the duct, tubing to transport the sample, a pump, sample conditioning equipment, and a gas analyzer.

Figure 4 shows a schematic of the gas sampling probe used in the 1 MW Round FPC. The gas sampling probe is a stainless steel tube with an outside diameter of 19.1 mm (0.75 inch) containing 30 sampling holes positioned at even intervals across the length of the probe. The sampling holes have diameters of either 3 mm or 4 mm and are spaced at 20 mm intervals. Figure 5 shows a detailed schematic of the gas sampling probe.

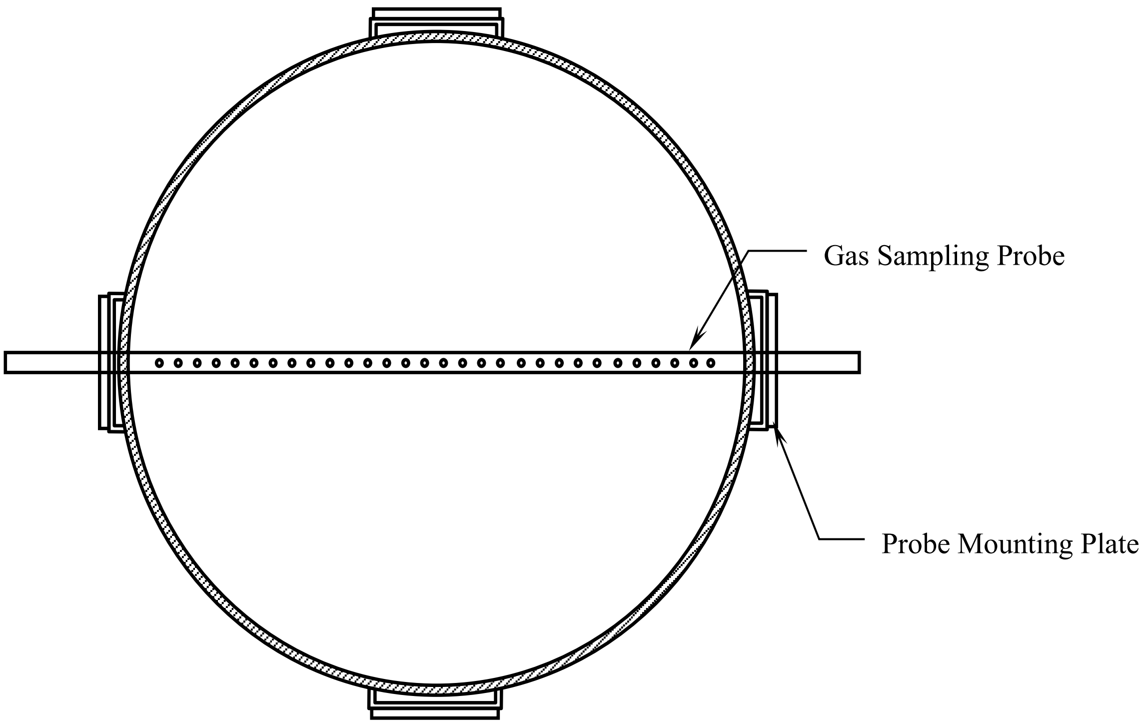

Figure 4. Schematic of the gas sampling probe mounted in the duct

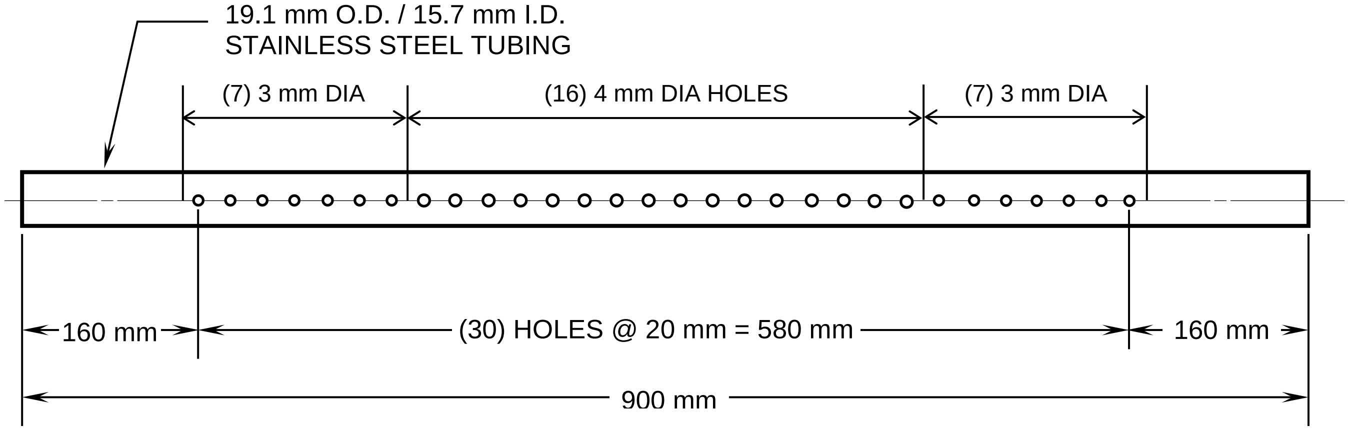

Figure 5. Detailed schematic of the gas sampling probe showing hole locations

The gas sampling probe is installed across the center of the exhaust duct with the sampling holes facing downstream. The probe is located 4.1 m downstream of the inlet orifice. The sample is drawn from both ends of the sampling probe and transported to the gas analysis rack through a single 9.5 mm (3/8 inch) diameter Teflon gas sampling line.

Tubing from the gas sampling probe is connected to a gas analysis rack constructed by Fire Testing Technology Limited (FTT), shown in Figure 6. This rack, located in a conditioned space on the mezzanine level above the MBR, includes a Servomex 4100 gas analyzer, gas train, pressure and flow control, filtering, and moisture removal.

Figure 6: Photo of the 1 MW Round FPC gas analysis rack

The gas analyzer is configured to measure oxygen, carbon monoxide and carbon dioxide. Table 1 lists the output range for these three gas species measured for the 1 MW FPC. Additional details on the gas analyzer rack are provided elsewhere [2 - 4].

A delay exists between the time that the gas sample is extracted from the duct and the time it reaches the analyzer. This delay time is determined by introducing a step-change in gas composition flowing past the gas sampling probe and monitoring the output of the analyzer for change in measured gas concentration. The delay time used in each experiment is documented in the FireTOSS datasheet. The gas analyzer was modified by Servomex to permit higher sample flow rates in order to reduce the sample delay times [4, 5].

Table 1. Servomex 4100 gas species measurement ranges.

Gas Species	Range
Oxygen (O_2)	0 – 25 %
Carbon Dioxide (CO_2)	0 – 10 %
Carbon Monoxide (CO)	0 – 1 %

Flow Measurement

The flow of gases in the duct is measured using a pressure transducer, velocity probe, and thermocouple. Details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6].

Pressure Transducer

A Setra model 267 pressure transducer with a range of 0 – 620 Pa (0 – 2.5 inches of water) and an output of 4 – 20 mA is used for differential pressure measurement in the 1 MW Round FPC [7]. The transducer is connected to the differential pressure probes through a valve that can be closed to facilitate baseline readings and probe purging.

Velocity Probe

Velocity measurements in the 1 MW Round FPC are performed using a bi-directional probe [8]. Figure 7 shows a schematic of the probe. The probe consists of two ports: one facing upstream and the other downstream. The differential pressure measured between the two ports is used to calculate the velocity at the probe location. A flow shape factor is applied to calculate the average duct velocity. The probes are mounted to the exterior of the duct via a 19 cm diameter mounting plate. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [9].

The 1 MW Round FPC duct is equipped with additional velocity probes. A pair of VOLU-probe/1SS Stainless Steel Pitot Airflow Traverse Probes [10] is mounted approximately 30 cm downstream of the bi-directional probes, as shown in Figure 3. Figure 8 shows a schematic of the probe. The probe consists of two manifolds: one each for static and total pressure measurement. Each manifold has pressure ports spaced at equal area intervals, producing a pressure representing the instantaneous average across the duct. The probes are mounted to the exterior of the duct via a 15 cm x 15 cm mounting plate on one end, with the opposite end secured by a pin support. Two probes are mounted at a 90° angle, per manufacturer specifications [11]. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [12].

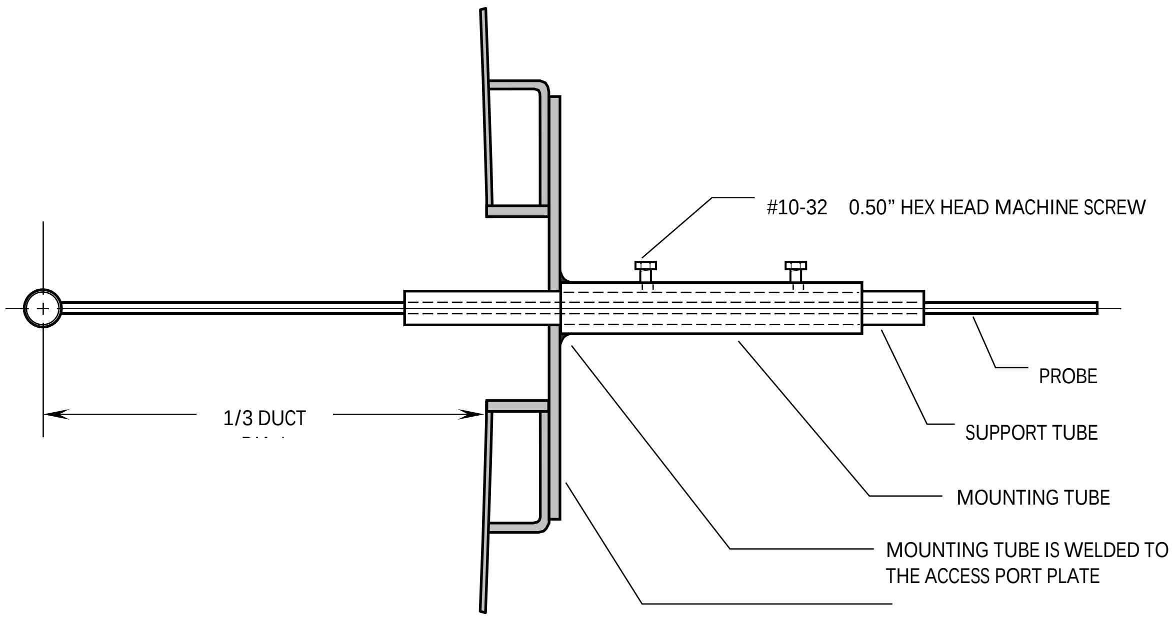

Figure 7: Schematic of the bi-directional probes.

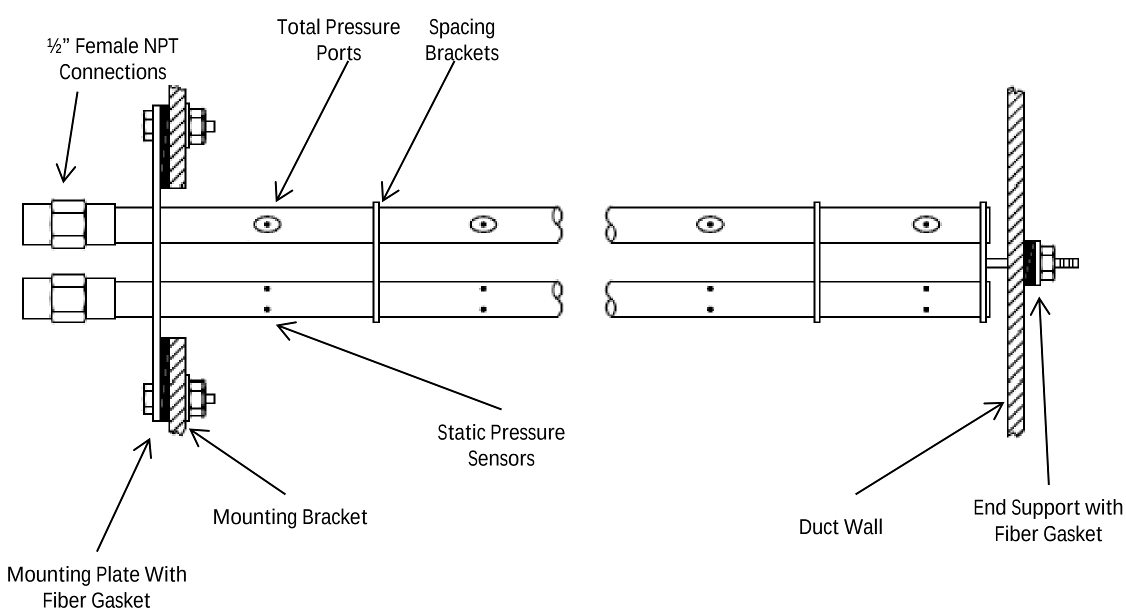

Figure 8: Schematic of the velocity traverse probes [10].

Thermocouple
Two 1.5 mm (0.062 inch) Inconel-sheathed Type K special limits of error (SLE) thermocouples are used to monitor the gas temperature in the 1 MW FPC duct. Type K thermocouples have a peak temperature range of approximately 1250 ºC (2282 ºF). Type-K SLE thermocouple wire has a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. Additional information on thermocouples can be found in the Laboratory Instruction [13].

Smoke Measurement

Smoke is measured in the 1 MW Round FPC using optical density meters (ODMs) [14, 15]. Both laser and white-light ODMs are used in the 1 MW Round FPC. The ODM access ports are located approximately 5 m downstream of the velocity and gas sampling probes.

The laser ODM uses a low-power (0.5 mW) Helium-Neon (HeNe) laser that emits continuous light at 632 nm. The laser ODM uses two photodiode detectors; the main detector is used to measure the beam intensity as it is attenuated by the smoke and fire gases in the FPC. A compensating detector located near the laser head is used to account for changes in the laser output during a test so that these are not erroneously attributed to smoke attenuation by the main detector.

The white-light ODM, which is manufactured by Fire Testing Technology (FTT), uses a broad-band visible (white) light source. The light source consists of a halogen lamp and a series of lenses and apertures that combine to create a nearly collimated beam with a 25 mm diameter at the source. The light receiver uses a silicon photoelectric cell in front of which is a spectral filter to accommodate the human eye. The source and receiver are mounted to a rigid frame on opposite sides of the duct.

Data Acquisition

Data acquisition for the 1 MW Round FPC is achieved using an Allen Bradley (AB) SLC 500 series Programmable Logic Controller (PLC). The system is equipped with a SLC 5/05 processor which has an IP address of 10.243.235.183. The FPC instrumentation and the corresponding FireTOSS tag are listed in Table 2. The PLC is located inside a cabinet on the east wall of a climate controlled instrument shed located on the mezzanine level, above the MBR. This shed houses the data acquisition and gas analysis instrumentation for all of the MBR FPCs.

Table 2. Data Acquisition Setup

Devices Attached	Quantity Measured	FireTOSS Tag
Laser ODM – Main	Light transmission	AB183_AI01_04
Laser ODM – Compensating	Light transmission	AB183_AI01_05
White Light ODM	Light transmission	AB183_AI01_06
Gas Analyzer – O_2	Gas Concentration	AB183_AI03_12
Gas Analyzer – CO_2	Gas Concentration	AB183_AI03_11_F
Gas Analyzer – CO	Gas Concentration	AB183_AI03_13
Pressure Transducer	Pressure	AB183_AI03_09_F
Thermocouple 1	Temperature	AB183_TC10_01
Thermocouple 2	Temperature	AB183_TC10_02

Measurement Range

The practical HRR measurement range for the 1 MW Round FPC is from 10 kW to 1150 kW. This represents a range of HRR values over which the 1 MW FPC has a linear response. The minimum change in HRR that can be resolved with the 1 MW Round FPC is approximately 5 kW. Data from calibration experiments performed over the full measurement range of the FPC are shown in Appendix A.

Calibration

A calibration burner [16] is used to determine the calibration factor, or C Factor, for a FPC. The type of calibration burner is selected based on the desired maximum HRR needed for the calibration. For the 1 MW Round FPC, sand burners [17] are used to determine the C Factor.

Calculations

The calculations used to determine the HRR, and other output quantities, from the FPC are defined in the FPC Laboratory Instruction [1].

Uncertainty and Accuracy

Fire Products Collectors are designed to provide four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production. The uncertainty associated with each of these quantities, calculated from measurements in the 1 MW Round FPC, was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [18], Technical Note 1297 [19], and the NIST Uncertainty Workshop [20]. The analysis outlined below is based primarily on data collected from natural gas fires generated using sand burners; the burner output was fixed for a period of five minutes at progressively increasing HRR levels [1, 17]. Uncertainty was calculated for nominal fire sizes of 100 kW, 500 kW and 1000 kW, representing low, middle and high ends of the operating range.

The combined standard uncertainty for a calculated output y, based on a number (i) of uncorrelated input quantities x_i, is a combination of the uncertainty of each component. It is expressed mathematically by the following equation:

$$u_c(y) = k\sqrt{\sum s_i^2 u(x_i)^2} \quad (1)$$

where:

$u_c(y)$ = Combined standard uncertainty in the output y
$u(x_i)$ = Standard uncertainty of each component x_i
s_i = Sensitivity coefficient associated with each component $(\partial/\partial x_i)$
k = Coverage factor

The expression used to calculate the oxygen consumption HRR is a complex function of multiple variables and physical constants [1, 21]. The formulations used to calculate CHRR, gas species production and smoke production are considerably simpler and use many of the same measured input variables [1]. The approach taken in this analysis was to calculate the uncertainty in the HRR first. This necessitates calculating the standard uncertainty for most of the variables and parameters used in the other output quantities. A spreadsheet formulation was used to apply Equation (1) to perform the uncertainty calculations [22].

Table 3 summarizes the combined standard uncertainty for each output quantity of the 1 MW Round FPC. The HRR, CHRR, CO_2 and CO production rate values are based on data collected from the natural gas calibration burner experiments. Because the natural gas fires produce relatively little smoke, data for the rate of smoke release (RSR) are from separate experiments. The RSR data is from a gasoline pool fire with a peak HRR of approximately 465 kW. Details on how these uncertainty values were determined are provided in the sections that follow.

Table 3. Uncertainty Summary

Quantity	Calculated Value	Combined Standard Uncertainty	Relative Uncertainty
Heat Release Rate (HRR)	500 kW	32	6.4 %
Convective Heat Release Rate	382 kW	23	6.1 %
Mass Production Rate – CO_2	25 g/s	1.5	6.2 %
Mass Production Rate – CO	0.05 g/s	0.01	15.5 %
Rate of Smoke Release – Laser	9.1 m^2/s	0.58	6.3 %

Heat Release Rate

The oxygen consumption heat release rate is calculated according to [1]:

$$HRR = C\left[E\phi - \left(E_{CO} - E\right)\frac{1-\phi}{2}\frac{X_{CO}}{X_{O_2}}\right]\left(\frac{\dot{m}}{1+\phi(\alpha-1)}\right)\left(\frac{MW_{O_2}}{MW_{air}}\right)\left(1-X_{H_2O}^{0}\right)X_{O2}^{0} \qquad (2)$$

The oxygen depletion factor, , in Equation 2 is a function of two co-dependent pairs: the concentrations of oxygen and carbon dioxide in the incoming air and in the product stream $(X_{O_2}, X_{O_2}^0)$ $(X_{CO_2}, X_{CO_2}^0)$. It has been shown that, under these circumstances, the approach to properly account for the uncertainty is to re-write Equation 2 in terms of the raw inputs [18]. Based on this, Equation (2) was broken down into thirty three components and a standard uncertainty was determined for each. Table 4 shows a list of the components along with a brief description.

Table 4: Components used in the oxygen consumption HRR calculation

Component	Description (Units in parentheses)
A_{O_2}	Current output from oxygen analyzer (A)
$A_{O_2,zero}$	Current output from oxygen analyzer flowing zero gas (A)
$A_{O_2,span}$	Current output from oxygen analyzer flowing span gas (A)
$A_{O_2,base}$	Current output from oxygen analyzer during pre-test baseline (A)
$X_{O_2,zero}$	Mole fraction of oxygen in zero gas (A)
$X_{O_2,span}$	Mole fraction of oxygen in span gas (A)
A_{CO_2}	Current output from carbon dioxide analyzer (A)
$A_{CO_2,zero}$	Current output from carbon dioxide analyzer flowing zero gas (A)
$A_{CO_2,span}$	Current output from carbon dioxide analyzer flowing span gas (A)
$A_{CO_2,base}$	Current output from carbon dioxide analyzer during pre-test baseline (A)
$X_{CO_2,zero}$	Mole fraction of carbon dioxide in zero gas (A)
$X_{CO_2,span}$	Mole fraction of carbon dioxide in span gas (A)

Component	Description (Units in parentheses)
A_{CO}	Current output from carbon monoxide analyzer (A)
$A_{CO,zero}$	Current output from carbon monoxide analyzer flowing zero gas (A)
$A_{CO,span}$	Current output from carbon monoxide analyzer flowing span gas (A)
$X_{CO,zero}$	Mole fraction of carbon monoxide in zero gas (A)
$X_{CO,span}$	Mole fraction of carbon monoxide in span gas (A)
$M_{air,dry}$	Molecular weight of dry air (g/mol)
M_{H_2O}	Molecular weight of water (g/mol)
M_{O_2}	Molecular weight of oxygen (g/mol)
E	Net heat release of natural gas per kg of oxygen consumed (kJ/kg)
E_{CO}	Net heat release of carbon monoxide per kg of oxygen consumed (kJ/kg)
α	Volumetric expansion factor (--)
RH	Relative humidity of incoming air (%)
P_{amb}	Ambient pressure (Pa)
T_{amb}	Ambient temperature (K)
C_{bdp}	Bi-directional probe constant (--)
f	Velocity flow shape factor (--)
D	Duct diameter (m)
T_1	Duct temperature at the sampling location (K)
T_2	Duct temperature at the sampling location (K)
$A_{dp,meas}$	Current output from the pressure transducer (A)
$A_{dp,zero}$	Current output from the pressure transducer during pre-test baseline (A)

Variables and constants are grouped in Table 4 according to four primary categories: gas species concentrations, physical constants, ambient conditions and mass flow rate. A discussion of the uncertainty analysis for each category is given below.

Gas Species Concentration

ASTM E 2536 identifies three sources of error that should be considered in the estimation of uncertainty for oxygen measurements in a cone calorimeter: the data acquisition system, random (Type A) scatter in the data signal, and calibration [23]. Instrumentation used in the cone calorimeter is similar to what is used in large scale calorimeter hoods such as the 1 MW FPC. Based on this, these three sources of error were considered for the gas species uncertainty evaluation (O_2, CO_2 and CO) performed here. A fourth source, calibration gas error, was added based on discussions with the instrument retailer [24].

Table 4 lists two components that contribute to gas species measurements: the unscaled analyzer signal (A_i) and the mole fractions in the calibration gases (X_i). The following sections provide details related to the uncertainty estimate for each component.

Analyzer Signal Uncertainty
The uncertainty estimate in the recorded analyzer signal included contributions from the data acquisition hardware and fluctuations in the data. The contribution from data acquisition hardware came from manufacturer's specifications. The uncertainty contribution associated with data fluctuations came from a statistical analysis of the raw signal collected in a calibration burner experiment.

The Servomex gas analyzer used in the 1 MW Round FPC sends an analog 4 – 20 mA signal to an Allen Bradley (AB) SLC 500 series programmable logic controller (PLC) through a 1746 NI16I 16 bit I/O module. Specifications for the AB hardware include a digital resolution of 640 nA and a calibrated accuracy of better than 0.15 % of range [25].

The standard uncertainty associated with fluctuations in the analyzer signal was estimated using the sample standard deviation. Calculations were performed using data recorded when the analyzer output was steady. Analyzer signals listed in Table 4 are divided into two categories: calibration ($A_{i,zero}$, $A_{i,span}$) and experiment (A_i, $A_{i,base}$). For the calibration signal uncertainty, the sample standard deviation was calculated over one minute periods during an 'AUTOCAL' cycle. For the experiment signal uncertainty, the sample standard deviation was calculated during a calibration burner experiment. Statistics were performed for data spanning several minutes.

The combined uncertainty was calculated by combining the data acquisition and statistical components.

Calibration Gas Uncertainty
The 1 MW Round FPC is equipped with a modified Servomex 4100 gas analyzer that contains individual cells to measure each of the three species concentrations. Oxygen concentration is measured in a paramagnetic cell with 0 – 25 % range; CO_2 and CO are measured in non-dispersive infrared (NDIR) cells with peak concentration ranges of 10 % and 1 %, respectively. Each cell is calibrated using zero and span gases. The zero gas and CO / CO_2 span gas come with certifications from the supplier. The oxygen analyzer is spanned with ambient air; the uncertainty estimate for ambient O_2 concentration was taken from the literature [18].

The zero gas is "Zero" grade (99.99 %) nitrogen. Assuming a rectangular distribution, the standard uncertainty is +/- 5.8 x 10^{-5}. The CO/CO_2 span gas is a Primary Standard grade mixture with certified accuracy of 1% for CO and 0.02 % for CO_2. The concentrations of CO and CO_2 in the span gas are nominally 0.8 % and 8 %, respectively, with the balance comprised of N_2. Assuming a rectangular distribution, the standard uncertainties of CO_2 and CO in the span gas are estimated to be 1.2 x 10^{-4} and 4.6 x 10^{-5}, respectively. Laboratory air is used to span the oxygen analyzer; the concentration is taken as 20.95 %. The estimated uncertainty associated with the oxygen span concentration is estimated to be 0.05 % [18]. This estimate was verified through a comparison with a high purity certified O_2/N_2 mixture.

Physical Constants

Physical constants include the molecular weights of oxygen (M_{O_2}), dry air ($M_{air,dry}$) and water (M_{H_2O}), in addition to the volumetric expansion factor (α) and the net heat release per unit mass of oxygen consumed for natural gas (E) and carbon monoxide (E_{CO}). The standard uncertainty of the molecular weights was taken as zero. The standard uncertainties of the remaining constants were based on previous work and summarized in Table 5 [18].

Table 5: Summary of uncertainty in physical constants

Parameter	Value	Standard Uncertainty
α (--)	1.104	0.048
E (kJ/kg O_2)	12550	19.95
E_{CO} (kJ/kg O_2)	17690	10

Ambient Conditions

Ambient conditions are measured using a wall mounted weather station that is permanently housed in the MBR. The weather station measures relative humidity, temperature and absolute pressure. Additional information, including the uncertainty analysis for each of the measured quantities, can be found in the laboratory instruction [26]. Table 6 shows a summary of the standard uncertainty for the ambient temperature, pressure and relative humidity.

Table 6: Ambient conditions uncertainty summary

Quantity	Standard Uncertainty	Quantity
Ta (°C)	0.6	Ta (°C)
Pa (Pa)	115.5	Pa (Pa)

Mass Flow Rate

The mass flow rate is expressed as:

$$\dot{m} = \rho \dot{V} \tag{3}$$

where ρ is the gas density (kg/m^3) and $\dot{V}$ is the volumetric flow rate (m^3/s). The density was expressed in terms of temperature using the ideal gas law:

$$\rho = \rho_{std} \frac{T_{std}}{T} \tag{4}$$

where the standard condition is taken as 300 K and 1 atm. The volumetric flow rate was calculated using:

$$\dot{V} = f\, A\, V \tag{5}$$

where *f* is the flow shape factor, A is the duct area (m^2) and V is the velocity (m/s). The flow shape factor was calculated using data from flow traverse measurements conducted previously [27]. The duct area is a function of the diameter, D (0.65 m). The velocity was calculated according to [6]:

$$V = \sqrt{\frac{2\,\Delta P\,T}{\rho_{std} T_{std}}} \Big/ C_{bdp} \tag{6}$$

where P is the differential pressure measured by the velocity probe (Pa) and T (K) is the temperature inside the duct. C_{bdp} is the bi-directional probe factor that has been shown to be a constant (1.08 ± 5 %) over the range of Reynolds numbers encountered in the duct flow [8]. Combining the above equations and substituting ($T_{std} = 300\ K$, $\rho_{std} = 1.18\ kg/m^3$) yields:

$$\dot{m} = \frac{20.875\ D^2\ f}{C_{bdp}} \sqrt{\frac{\Delta P}{T}} \tag{7}$$

The temperature was taken as the average of two independent measurements at each time step and the differential pressure was expressed as:

$$\begin{aligned} \Delta P &= \Delta P_{meas} - \Delta P_{baseline} \\ &= \left(m_{dp}\, A_{dp} + b_{dp}\right)_{meas} - \left(m_{dp}\, A_{dp} + b_{dp}\right)_{baseline} \end{aligned} \tag{8}$$

where m_{dp} and b_{dp} are the calibration factors for the differential pressure transducer. The differential pressure is corrected by subtracting a baseline value, which is measured in a separate experiment with the transducer cross-ported. Consolidating terms, the differential pressure can be expressed as:

$$\Delta P = m_{dp}\left(A_{dp,meas} - A_{dp,baseline}\right) \tag{9}$$

The calibration constant, m_{dp}, for the pressure transducer was 38920.1 Pa/A. This yields the expression for mass flow rate:

$$\dot{m} = \frac{4118.26\ D^2\ f}{C_{bdp}} \sqrt{\frac{A_{dp,meas} - A_{dp,baseline}}{T}} \tag{10}$$

The standard uncertainty in the diameter measurement was calculated from the standard deviation of five independent measurements. The result was D = 0.654 ± 0.003 m. To account for the duct not being perfectly circular this uncertainty was increased to ± 0.005 m. The standard uncertainty in the flow shape factor (*f*) was estimated based on the standard error in the least squares regression from the traverse data [27]. The standard uncertainty in the temperature measurement (± 1.5 K) was estimated by combining the fundamental error limit of the probe and the sample standard deviation of data calculated during a calibration burner experiment. The standard uncertainty in the average temperature was calculated by combining uncertainties in the individual measurements using Eqn. (1).

The combined standard uncertainty in the pressure transducer data was calculated based on manufacturer's specifications for the data acquisition hardware and pressure transducer, in addition to a statistical analysis of the signal. The data acquisition hardware is the same as what is used for the gas analyzers; the standard uncertainty is 7.1×10^{-8} A. The standard uncertainty for a Setra model 267 pressure transducer is a function of the input range for the instrument; for a device with input range P = 0 – 0.62 kPa (0 – 2.5 inch H_2O) the standard uncertainty is 5.2×10^{-5} A [9]. The uncertainty associated with data fluctuation in the transducer output was calculated from the sample standard deviation collected during a calibration burner experiment. Table 7 shows a summary of the combined standard uncertainty for the pressure measurement for three fire sizes and a baseline.

Table 7: Combined standard uncertainty in the differential pressure measurement.

Fire Size	Combined Standard Uncertainty (A)
Baseline	5.2×10^{-5}
95 KW	1.0×10^{-4}
500 kW	1.2×10^{-4}
1005 kW	1.1×10^{-4}

Summary

Table 8 shows a summary of the uncertainty in the oxygen consumption heat release rate performed for three fire sizes. The first column lists the 33 components (with units in parentheses) that comprise the oxygen consumption HRR calculation, as described in Table 4. For each component, the nominal value obtained for a 500 kW fire is listed in column 2. Column 3 lists the standard uncertainty for each component that was discussed in the preceding sections. Columns 4 – 6 list the sensitivity coefficients calculated for fire sizes of 95 kW, 500 kW and 1005 kW.

Table 8: Summary of HRR uncertainty calculations

Variable / Parameter x_i	Nominal Value	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient $\lvert s_i \rvert$		
			95 kW	500 kW	1005 kW
A_{O_2}	0.01684	1.2 x 10^{-5}	9.2 x 10^{5}	9.2 x 10^{5}	1.1 x 10^{6}
$A_{O_2,zero}$	0.00400	6.2 x 10^{-7}	7.9 x 10^{3}	4.1 x 10^{4}	8.2 x 10^{4}
$A_{O_2,span}$	0.01741	1.8 x 10^{-6}	9.0 x 10^{3}	4.7 x 10^{4}	9.3 x 10^{4}
$A_{O_2,base}$	0.01743	1.5 x 10^{-6}	9.2 x 10^{5}	9.2 x 10^{5}	1.1 x 10^{6}
$X_{O_2,zero}$	0.00000	5.8 x 10^{-5}	5.1 x 10^{2}	2.6 x 10^{3}	5.3 x 10^{3}
$X_{O_2,span}$	0.20950	5.0 x 10^{-4}	5.7 x 10^{2}	3.0 x 10^{3}	6.0 x 10^{3}
A_{CO_2}	0.00482	1.2 x 10^{-5}	7.7 x 10^{4}	7.4 x 10^{4}	8.9 x 10^{4}
$A_{CO_2,zero}$	0.00400	2.3 x 10^{-7}	9.7 x 10^{2}	4.8 x 10^{3}	9.7 x 10^{3}
$A_{CO_2,span}$	0.01680	1.3 x 10^{-6}	8.8 x 10^{2}	4.3 x 10^{3}	8.9 x 10^{3}
$A_{CO_2,base}$	0.00407	1.9 x 10^{-6}	7.7 x 10^{4}	7.5 x 10^{4}	9.0 x 10^{4}
$X_{CO_2,zero}$	0.00000	5.8 x 10^{-5}	1.6 x 10^{2}	7.6 x 10^{2}	1.6 x 10^{3}
$X_{CO_2,span}$	0.08000	1.2 x 10^{-4}	1.4 x 10^{2}	6.9 x 10^{2}	1.4 x 10^{3}
A_{CO}	0.00403	2.6 x 10^{-6}	1.4 x 10^{4}	1.3 x 10^{4}	1.6 x 10^{4}
$A_{CO,zero}$	0.00400	1.4 x 10^{-6}	1.4 x 10^{4}	1.3 x 10^{4}	1.6 x 10^{4}
$A_{CO,span}$	0.01680	1.6 x 10^{-5}	1.2 x 10^{1}	2.8 x 10^{1}	7.8 x 10^{0}
$X_{CO,zero}$	0.00000	5.8 x 10^{-5}	2.2 x 10^{4}	2.1 x 10^{4}	2.6 x 10^{4}
$X_{CO,span}$	0.00800	4.6 x 10^{-5}	2.0 x 10^{1}	4.5 x 10^{1}	1.2 x 10^{2}
$M_{air,dry}$ (g/mol)	28.97	0	0	0	0
M_{H_2O} (g/mol)	18	0	0	0	0
M_{O_2}(g/mol)	32	0	0	0	0
E (kJ/kg)	12550	19.95	7.6 x 10^{-3}	4.0 x 10^{-2}	8.0 x 10^{-2}
E_{CO} (kJ/kg)	17690	10	1.3 x 10^{-5}	3.2 x 10^{-5}	8.9 x 10^{-6}
α (--)	1.104	0.048	9.2 x 10^{-1}	2.5 x 10^{1}	8.0 x 10^{1}
RH (%)	52.2	2.16	2.3 x 10^{-2}	1.2 x 10^{-1}	2.5 x 10^{-1}
P_{amb} (Pa)	101636.2	115.5	1.3 x 10^{-5}	6.0 x 10^{-5}	1.7 x 10^{-4}
T_{amb} (K)	300.9	0.59	7.7 x 10^{-2}	3.7 x 10^{-1}	1.0 x 10^{-0}
C_{bdp}	1.08	0.054	8.4 x 10^{1}	4.4 x 10^{2}	8.9 x 10^{2}
f (--)	1.0822	1.7 x 10^{-2}	8.7 x 10^{1}	4.5 x 10^{2}	9.1 x 10^{2}
D (m)	0.654	0.005	2.9 x 10^{2}	1.5 x 10^{3}	3.1 x 10^{3}
T_1 (K)	409.7	1.5	7.4 x 10^{-2}	3.0 x 10^{-1}	5.4 x 10^{-1}
T_2 (K)	409.2	1.5	7.4 x 10^{-2}	3.0 x 10^{-1}	5.4 x 10^{-1}
$A_{dp,meas}$ (A)	0.00623	1.2 x 10^{-4}	2.8 x 10^{4}	1.1 x 10^{5}	1.3 x 10^{5}
$A_{dp,zero}$ (A)	0.00404	5.2 x 10^{-5}	2.9 x 10^{4}	1.1 x 10^{5}	1.3 x 105

The combined standard uncertainty for each fire size was calculated by combining terms in Table 8 according to Equation 1. The results are summarized in Table 9; the values represent a coverage factor of k = 1. In the case of a normal distribution, this translates to a confidence level of approximately 68%. To obtain a higher confidence level a higher coverage factor can be applied. A coverage factor of k = 2 in a normally distributed population provides a confidence level of approximately 95 %.

Table 9: Combined standard uncertainty in the heat release rate

Fire Size (kW)	Combined Standard Uncertainty (kW)	Relative Uncertainty (%)
95	7	7.2
500	32	6.4
1005	64	6.4

Table 10 shows a list of the variables that contribute most significantly to the combined uncertainty. The HRR is highly sensitive to the oxygen concentration measurements (A_{O_2}, $A_{O_2,base}$) as demonstrated by the large sensitivity factor shown for these variables in Table 8. However, the mass flow terms (C_{bdp}, D, $A_{dp,meas}$) contribute more to the combined uncertainty. These terms account for more than 70 % of the combined uncertainty, with the differential pressure probe factor (C_{bdp}) being dominant.

Table 10: Contribution to the combined uncertainty

Variable / Parameter x_i	Fire Size		
	95 kW	500 kW	1005 kW
A_{O_2} (A)	14.4	11.8	25.2
$A_{O_2,base}$ (A)	4.2	0.2	0.1
$X_{CO,Zero}$ (--)	3.4	0.2	0.1
C_{bdp} (--)	44.4	55.0	56.2
D (m)	4.6	5.7	5.8
$A_{dp,meas}$ (A)	19.0	17.5	4.8
$A_{dp,zero}$ (A)	4.9	3.5	1.1
f (--)	4.5	5.6	5.7

Convective Heat Release Rate

The convective heat release rate (CHRR) is expressed as:

$$\dot{Q}_c = \dot{m}\,(h_2 - h_1) \qquad (11)$$

where $\dot{Q}_c$ is the convective heat release rate (kW), $\dot{m}$ is the mass flow rate (kg/s) and h_1 and h_2 are the enthalpies of the incoming air and product stream, respectively (kJ/kg). The mass flow rate is evaluated in the same manner as in the HRR calculation (Equation 11) and is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The standard uncertainty in each of these is the same as in the HRR analysis.

The enthalpy difference is calculated according to a polynomial fit evaluated over the temperature range:

$$h_2 - h_1 = \left(\alpha T + \beta\frac{T^2}{2} + \gamma\frac{T^3}{3} + \delta\frac{T^4}{4} + \varepsilon\frac{T^5}{5}\right)\Bigg|_{T_1}^{T_2} \qquad (12)$$

where , , , , are fit parameters. Data used to fit the coefficients was taken from two sources [28, 29]. The error associated with the fit parameters is negligible; the uncertainty in enthalpy was assumed to be solely due to error in the temperature measurement[1]. The standard uncertainty in temperature is the same as in the HRR analysis. Table 11 shows a summary of the CHRR and the combined standard uncertainty in the CHRR for each corresponding HRR step; the values represent a coverage factor of k = 1.

Table 11: Convective heat release rate uncertainty summary

HRR (kW)	CHRR (kW)	Combined Uncertainty (kW)	Relative Uncertainty (%)
95	68	5.5	8.1
500	382	23	6.1
1005	733	40	5.5

[1] The polynomial fit parameters used for the enthalpy calculation were those for air.

Gas Species Production

The gas species mass production rate is expressed as:

$$\dot{m}_x = \dot{m}\left(X_x - X_{x,base}\right)\frac{M_x}{M_a} \qquad (13)$$

Where $\dot{m}_x$ is the production rate of species x (kg/s), $\dot{m}$ is the mass flow rate in the exhaust duct (kg/s), X_x and $X_{x,base}$ are the mole fractions of species x in the product stream and the incoming air, respectively (mol/mol), M_x is the molecular weight of species x (g/mol) and M_a is the molecular weight of air (g/mol).

All variables in Equation (13) are evaluated in the same manner as in the HRR calculation (Equation 1). The mass flow rate is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The mole fractions are calculated from the analyzer current and calibration concentrations. The standard uncertainty in each of these is the same as in the HRR analysis.

Table 12 and Table 13 show summaries of the combined uncertainty in the CO_2 and CO production rates, respectively, for three fire sizes. The values represent a coverage factor of k = 1. Relative uncertainty levels in the CO production rate are high at low HRR mainly because of the low CO levels generated by natural gas fires.

Table 12: Combined uncertainty in the CO_2 production rate

HRR (kW)	$\dot{m}_{CO_2}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
95	4.8	0.3	6.8
500	25	1.5	6.2
1005	53	3.2	6.0

Table 13: Combined uncertainty in the CO production rate

HRR (kW)	$\dot{m}_{CO}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
95	0.02	0.01	41.9
500	0.05	0.01	15.5
1005	0.13	0.01	9.0

Smoke Production

The rate of smoke release (RSR) is expressed as:

$$RSR = k\dot{V} \quad (14)$$

where k (m^{-1}) is the optical extinction coefficient measured by the ODM and $\dot{V}$ (m^3/s) is the volumetric flow rate in the exhaust duct.

The standard uncertainty for the extinction coefficient is described in the ODM Technical Reference [15]. For the laser system the relative standard uncertainty is less than 1 % for k > 0.1 m^{-1}; for k > 0.2 m^{-1} the relative uncertainty is less than 0.5 %.

Uncertainty in the volumetric flow rate was calculated in a manner similar to the procedure used for the mass flow rate in the HRR analysis. The volumetric flow rate is a function of the same six quantities as the mass flow rate ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f).

Smoke data was collected from an experiment in which gasoline was the primary fuel. The peak HRR in this experiment was approximately 465 kW; at this fire size the extinction coefficient measured by the laser ODM was approximately 2.3 m^{-1}, yielding a smoke release rate of 9.1 m^2/s. The combined standard uncertainty in the RSR under these conditions was 0.58 m^2/s or 6.3 %.

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Appendix A – Experimental Data

Figure 9 shows heat release rate data from a calibration burner experiment conducted under the 1 MW Round FPC using gas train "C" and a 20 cm square burner [17]. Gas train "C" has a maximum flow rate of 100 SLPM, which for natural gas translates to a peak fire size of approximately 57 kW. The calibration burner was run through a series of 5-minute duration steps with outputs of 0, 5, 15, 30 and 50 kW. Data from the burner is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burner and FPC during each of the seven steps; the average values are plotted together in Figure 10. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 9. The slope of a linear fit through this data is the C-Factor [1].

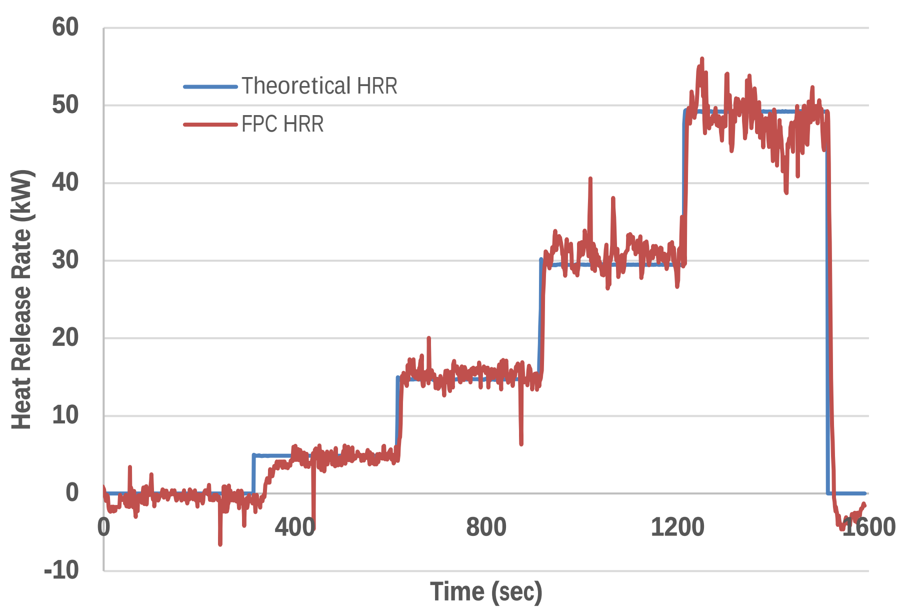

Figure 9: Heat release rate data from a calibration burner experiment under the 1 MW Round FPC.

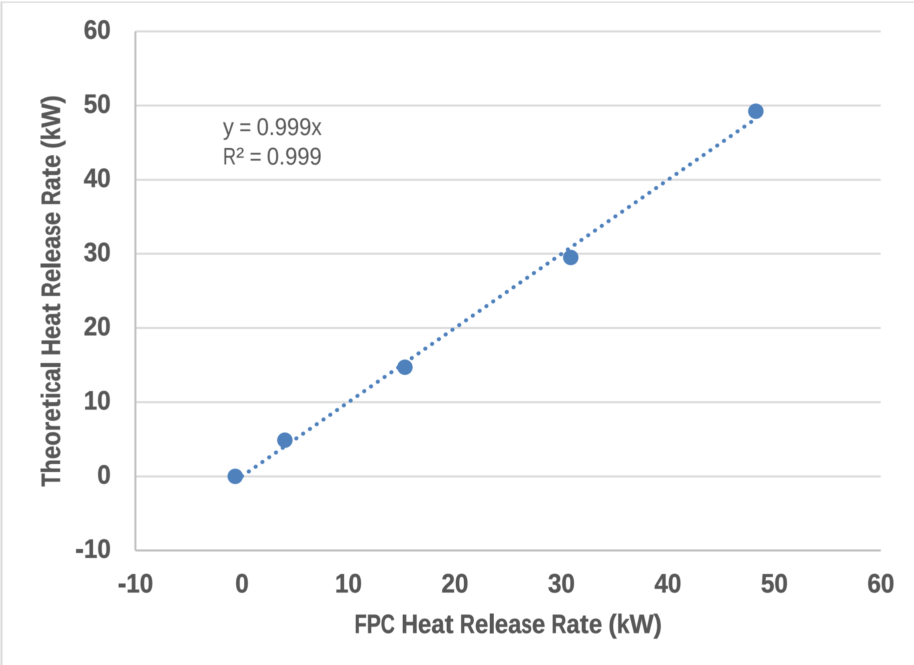

Figure 10: Average theoretical HRR plotted against average FPC HRR for an experiment using gas train "C" and a 20 cm square calibration burner.

Figure 11 shows heat release rate data from a calibration burner experiment conducted under the 1 MW Round FPC using gas trains "A" and "B" and a pair of 41 cm square burners [17]. Gas trains "A" and "B" each have a maximum flow rate of 1000 SLPM, which for natural gas translates to a peak fire size of approximately 570 kW. When run simultaneously they can produce a peak fire size of approximately 1100 kW. The calibration burners were run through a series of 5-minute duration steps with combined outputs of 0, 100, 300, 500, 700, 900 and 1100 kW. Data from the burners is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burners and FPC during each of the nine steps; the average values are plotted together in Figure 12. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 11. The slope of a linear fit through this data is the C-Factor [1].

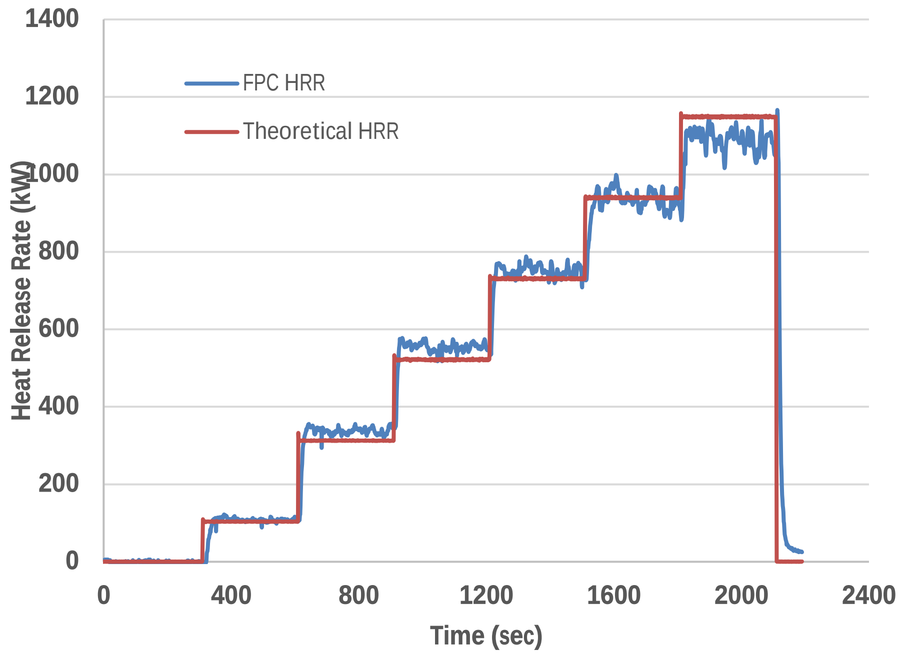

Figure 11: Heat release rate data from a calibration burner experiment under the 1 MW Round FPC.

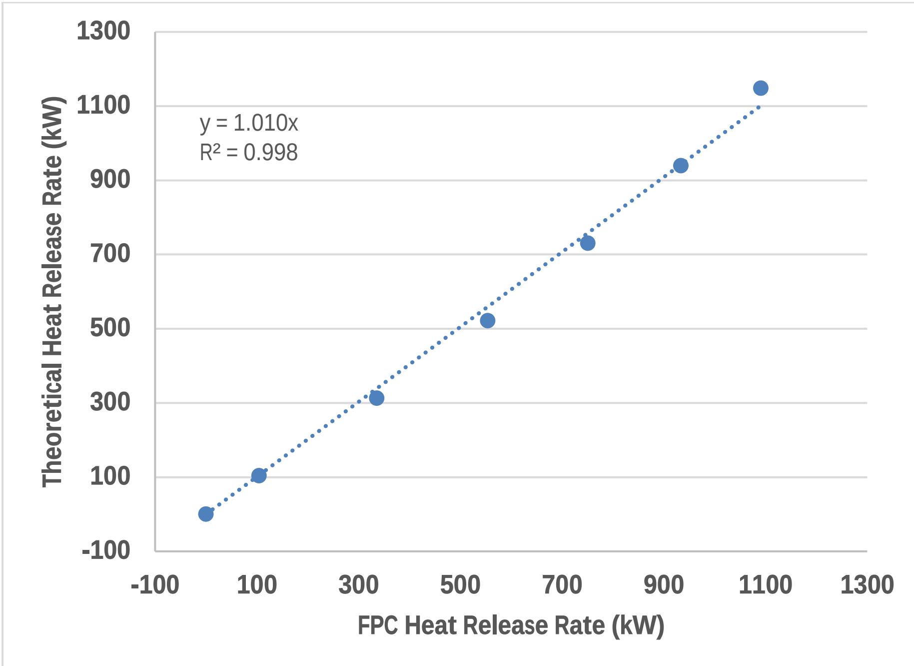

Figure 12: Average theoretical HRR plotted against average FPC HRR for an experiment using gas trains "A" and "B" and a pair of 41 cm square calibration burners.

Scope

This Technical Reference covers the use, design and specifications of the 4 MW Fire Products Collector (FPC) in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

General

The 4 MW FPC collects smoke and other products of combustion generated during fire experiments. A FPC consists of a collection hood connected to an exhaust duct, with air drawn through the duct by one or more variable speed fans. A FPC serves two purposes:

1) To remove combustion products from a laboratory space, and
2) To optimize the flow field for measurement and quantitative analyses of the combustion products.

A FPC provides four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production [1]. When used in conjunction with a weighing device, such as a load cell, the mass loss rate (MLR) of the burning object can be calculated. Gas species yields, smoke yield, and the effective heat of combustion of a burning item can then be calculated based on the MLR.

The 4 MW FPC is located in the north end of the FRL's Medium Burn Room (MBR). Figure 1 shows a photograph of the collection hood for the 4 MW FPC.

Figure 1: 4 MW FPC

Hood and Collection System

Physical Dimensions

Figure 2 shows a plan view schematic of the 4 MW FPC collection hood in the MBR. The 5.8 m diameter collection hood transitions to a circular exhaust duct with an internal diameter of 1.35 m. A 0.82 m diameter orifice plate is located in the horizontal section of the duct, downstream of the 90° bend approximately 3.2 m from the centerline of the vertical section. The orifice enhances mixing of the fire products prior to reaching the instrumentation locations. The exhaust duct has a vertical run of approximately 7.3 m before transitioning to a horizontal run above the MBR ceiling. The base of the collection hood is 7.1 m above the MBR floor; however skirts can be added to reduce the height to 4.2 m.

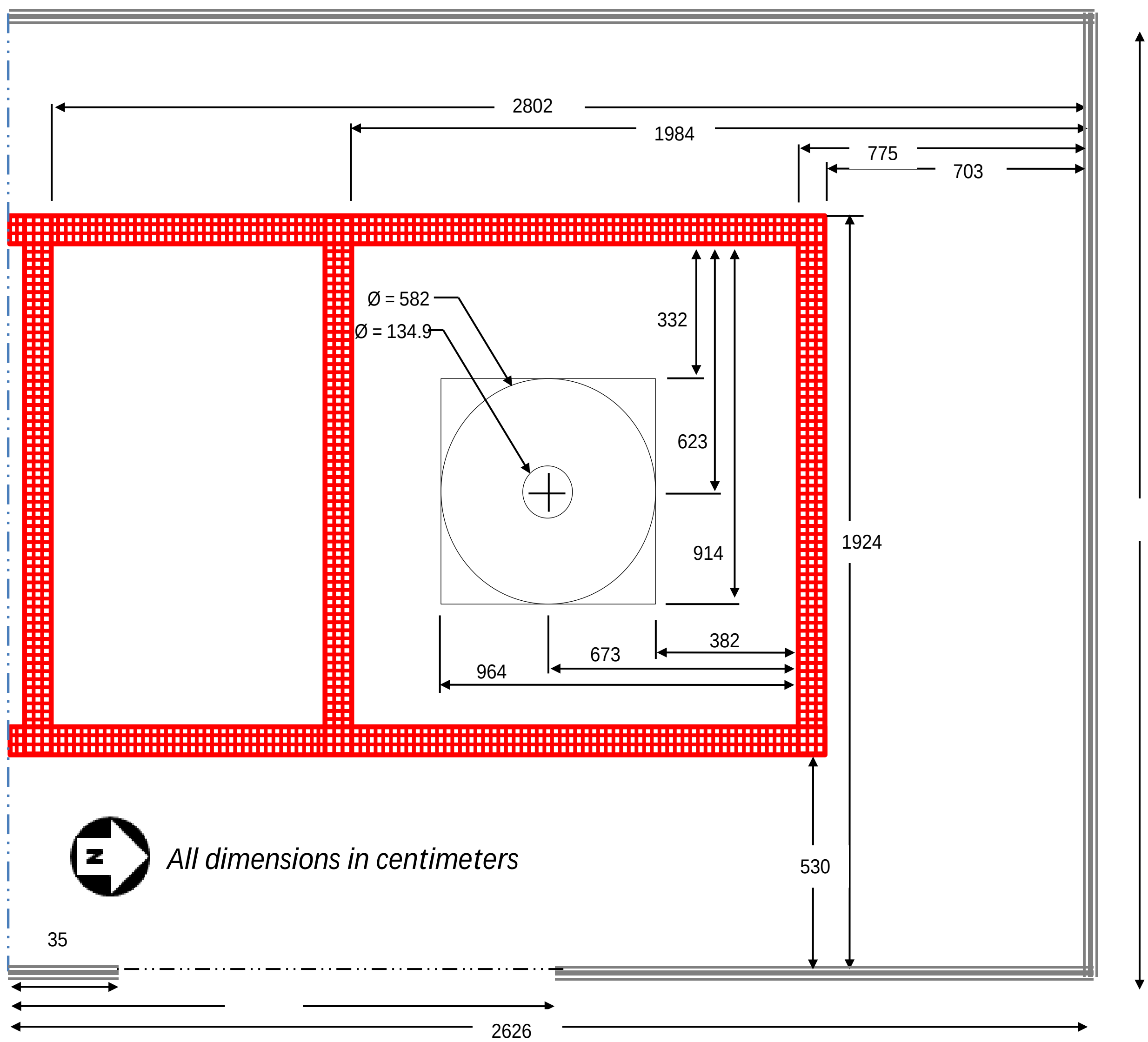

Figure 2: Plan view of 4 MW FPC in the MBR.

Instrument Locations

Instruments are located in the horizontal run of the FPC exhaust duct as shown in Figure 3. The first two instrument stations are located approximately 7.3 m and 7.7 m downstream of the inlet orifice, and are used for flow measurement. The first flow measurement station is the averaging velocity probes and the second includes the bidirectional probes. The gas sampling probe is located approximately 0.3 m downstream of the bi-directional probe station. The laser smoke measurement station is located approximately 0.3 m downstream of the sampling probe.

Flow Control

Flow in the FPC is controlled by a system of variable speed fans and actuated dampers that are programmed to maintain a fixed mass flow rate. The system is operated by a PC in the FRL Control Room. The FRL FPC's were designed to flow 6.8 kg/s (12,000 SCFM) per 1 MW heat release rate; the design flow rate of the 4 MW FPC is 27.2 kg/s.

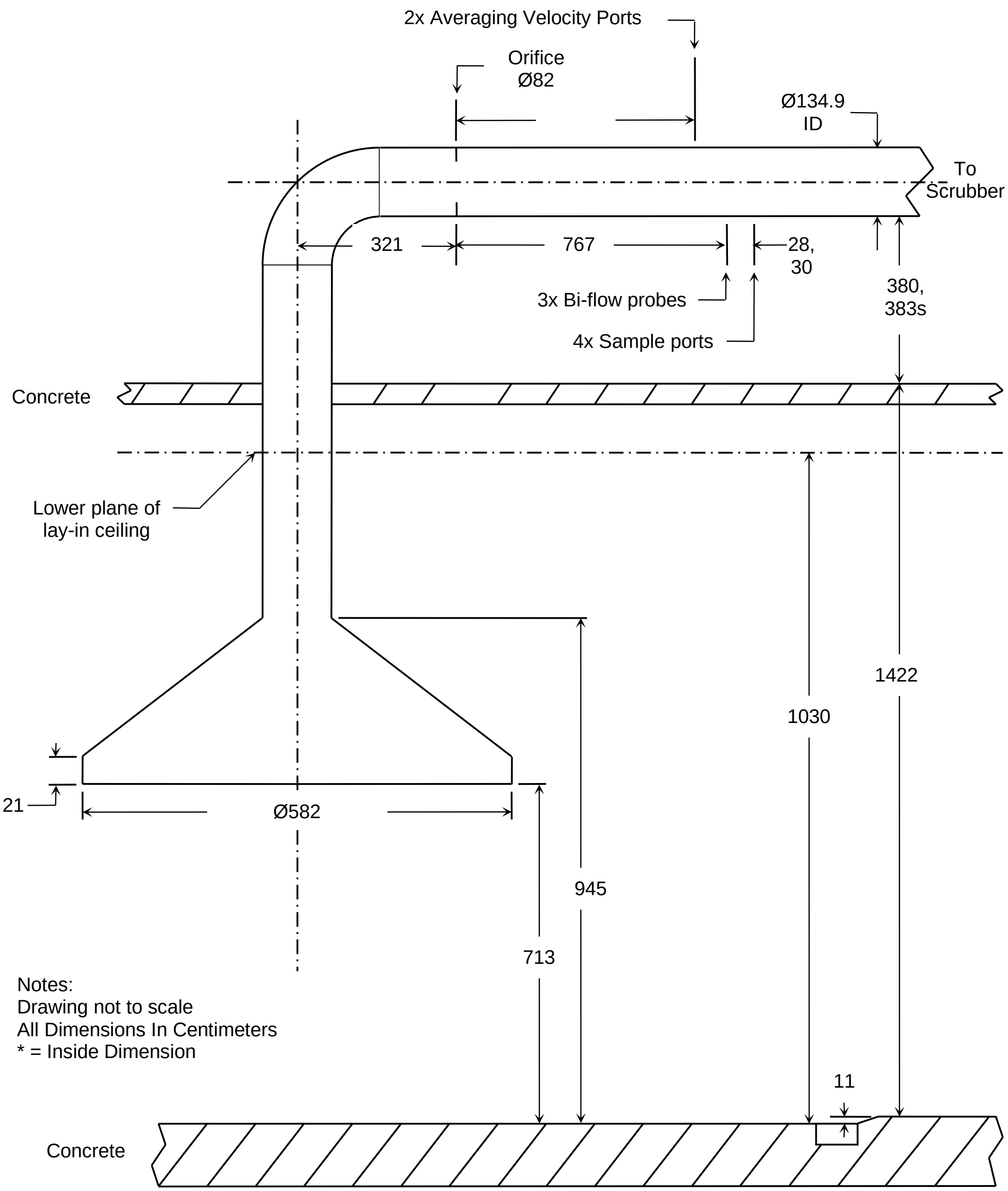

Figure 3: Elevation view of 4 MW FPC in the MBR

Instrumentation

The 4 MW FPC is equipped with instrumentation to measure gas species concentrations, temperature, velocity, and smoke concentration.

Gas Species Measurement

The system of instrumentation used to measure gas species concentrations consists of a gas sampling probe located in the duct, tubing to transport the sample, a pump, sample conditioning equipment, and a gas analyzer.

Figure 4 shows a schematic of the gas sampling probe layout used in the 4 MW FPC. The gas sampling probe consists of two stainless steel tubes with a radial offset of 90° and an axial offset of approximately 5.1 cm (2 inch) between centerlines. Each tube has an outside diameter of 19.1 mm (0.75 inch) and contains 26 sampling holes positioned at 50 mm (2 inch) intervals. The sampling holes have diameters of either 3 mm or 4 mm. Figure 5 shows a detailed schematic of the gas sampling probe.

The gas sampling probe is installed with one tube oriented vertically and the other oriented horizontally with the sampling holes facing downstream; the tubes overlap at the center of the exhaust duct. The probe is located in 8 m downstream of the inlet orifice. Sample is drawn from both ends of each tube and transported to the gas analysis rack through a single 9.5 mm (3/8 inch) diameter Teflon gas sampling line.

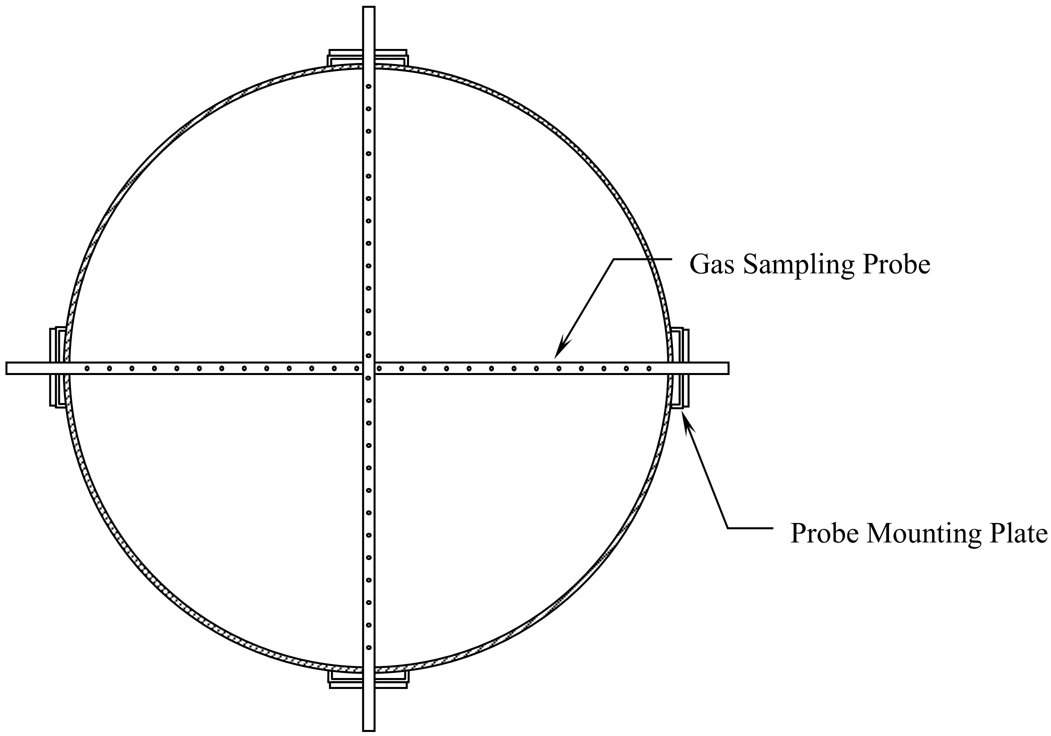

Figure 4. Schematic of the gas sampling probe mounted in the duct

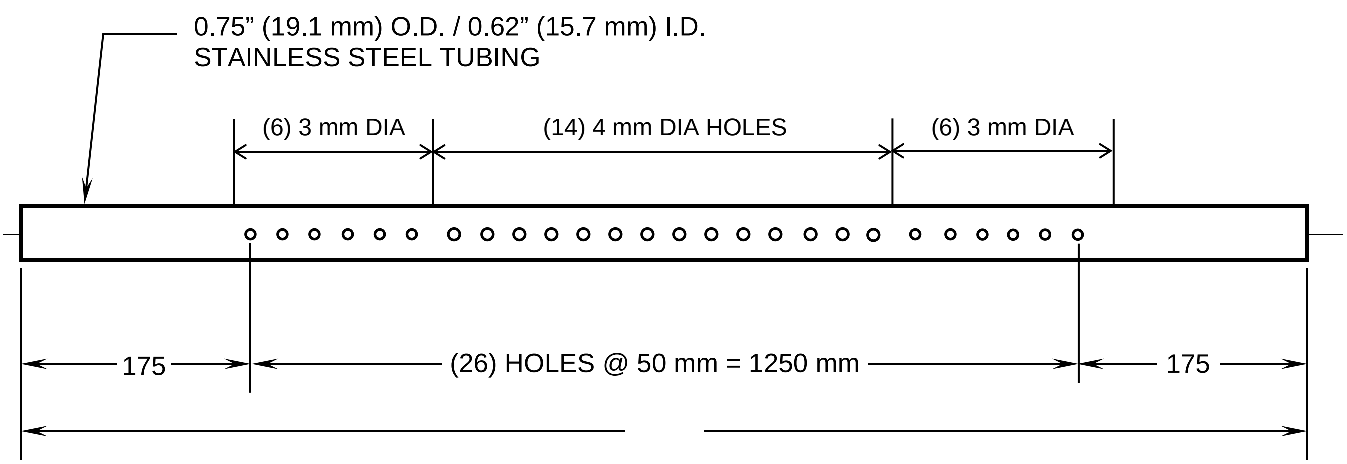

Figure 5. Detailed schematic of the gas sampling probe showing hole locations

Tubing from the gas sampling probe is connected to a gas analysis rack constructed by Fire Testing Technology Limited (FTT), shown in Figure 6. This rack, located in a conditioned space on the mezzanine level above the MBR, includes a Servomex 4100C Xentra gas analyzer, gas train, pressure and flow control, filtering, and moisture removal.

Figure 6: Photo of the 4 MW FPC gas analysis rack

The gas analyzer is configured to measure oxygen, carbon monoxide and carbon dioxide. Table 1 lists the output range for these three gas species measured for the 4 MW FPC. Additional details on the gas analyzer rack are provided elsewhere [2 - 4].

A delay exists between the time that the gas sample is extracted from the duct and the time it reaches the analyzer. This delay time is determined by introducing a step-change in gas composition flowing past the gas sampling probe and monitoring the output of the analyzer for change in measured gas concentration. The delay time used in each experiment is documented in the FireTOSS datasheet. The gas analyzer was modified by Servomex to permit higher sample flow rates in order to reduce the sample delay times [4, 5].

Table 1. Servomex 4100C gas species measurement ranges.

Gas Species	Range
Oxygen (O_2)	0 – 25 %
Carbon Dioxide (CO_2)	0 – 10 %
Carbon Monoxide (CO)	0 – 1 %

Flow Measurement

The flow of gases in the duct is measured using a pressure transducer, velocity probe, and thermocouple. Details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6].

Pressure Transducer

A Setra model 267 pressure transducer with a range of 0 – 620 Pa (0 – 2.5 inches of water) and an output of 4 – 20 mA is used for differential pressure measurement in the 4 MW FPC [7]. The transducer is connected to the differential pressure probes through a set of valves that can be closed to facilitate baseline readings and probe purging.

Velocity Probe

Velocity measurements in the 4 MW FPC are performed using a pair of bi-directional probes [8]. Figure 7 shows a schematic of the probe. The probe consists of two ports; one facing upstream and the other downstream. The differential pressure measured between the two ports is used to calculate the velocity at the probe location. A flow shape factor is applied to calculate the average duct velocity. The probes are mounted to the exterior of the duct via a 19 cm diameter mounting plate. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [9].

The 4 MW FPC duct is equipped with additional velocity probes. A pair of VOLU-probe/1SS Stainless Steel Pitot Airflow Traverse Probes [10] is mounted approximately 39 cm upstream of the bi-directional probes, as shown in Figure 3. Figure 8 shows a schematic of the probe. The probe consists of two manifolds; one each for static and total pressure measurement. Each manifold has pressure ports spaced at equal area intervals, producing a pressure representing the instantaneous average across the duct. The probes are mounted to the exterior of the duct via a 15 cm x 15 cm mounting plate on one end, with the opposite end secured by a pin support. Two probes are mounted at a 90° angle, per manufacturer specifications [11]. All components are constructed of stainless steel. Additional details on the use of differential pressure probes for velocity measurements are contained in the Laboratory Instruction [6] and Technical Reference [12].

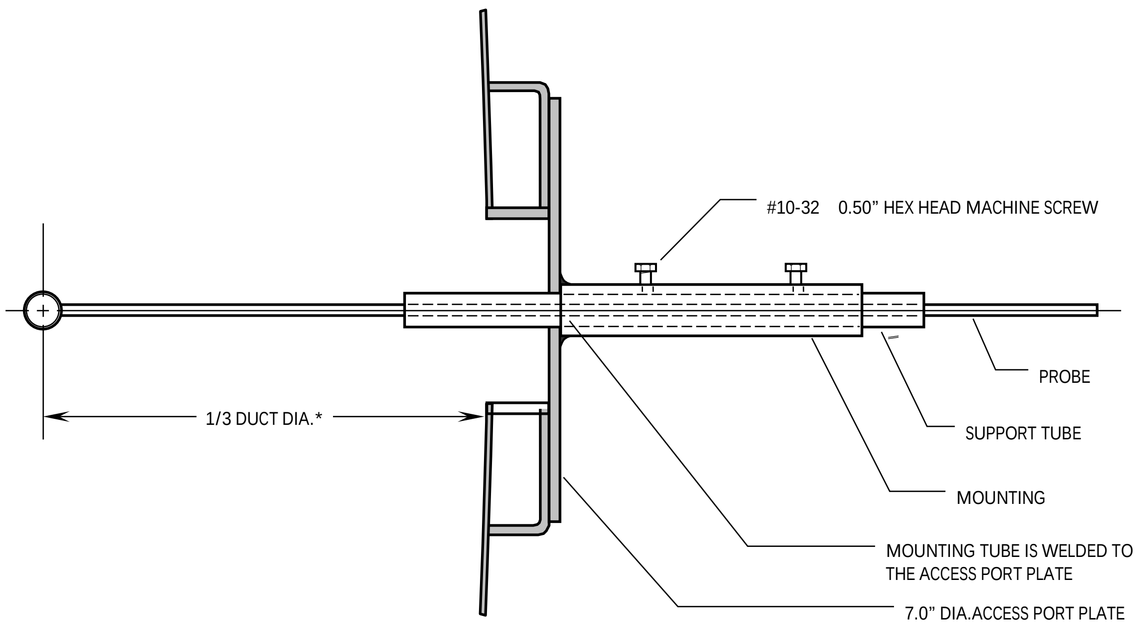

Figure 7: Schematic of the bi-directional probes.

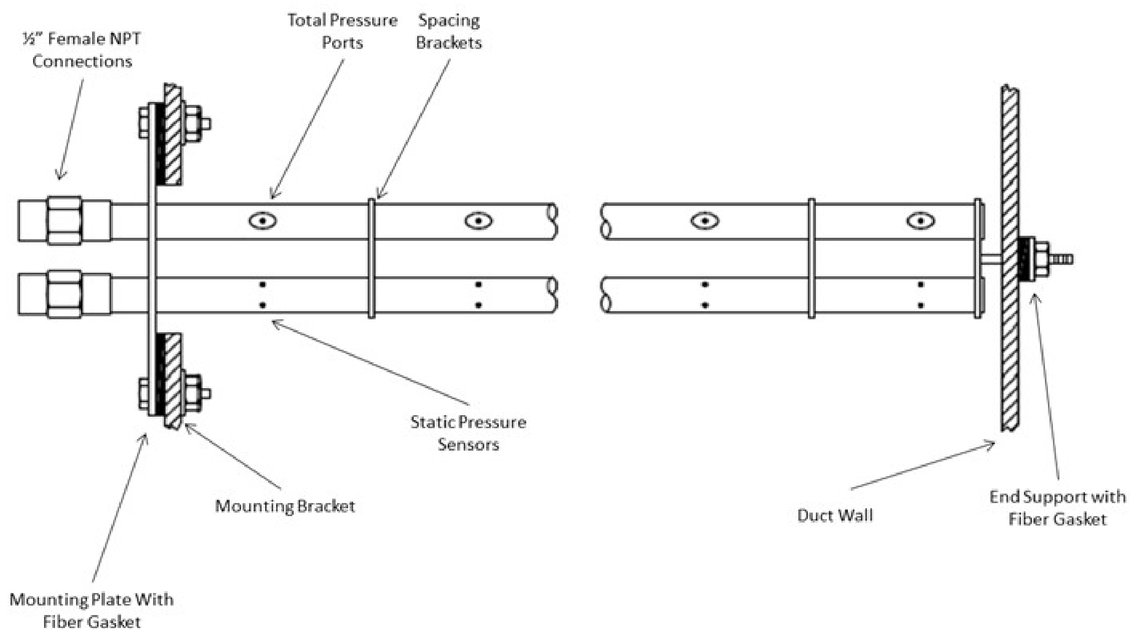

Figure 8: Schematic of the Voluprobe/1SS [10]

Thermocouple

Two 1.5 mm (0.062 inch) Inconel-sheathed Type K special limits of error (SLE) thermocouples are used to monitor the gas temperature at each bi-directional probe location in the 4 MW FPC duct. Type K thermocouples have a peak temperature range of approximately 1250 ºC (2282 ºF). Type-K SLE thermocouple wire has a minimum accuracy of the greater of 1.1ºC or 0.4% of the temperature reading over 0ºC. Additional information on thermocouples can be found in the Laboratory Instruction [13].

Smoke Measurement

Smoke is measured in the 4 MW FPC using laser optical density meters (ODMs) [14, 15]. The ODM access ports are located approximately 0.3 m downstream of the gas sampling probes.

The laser ODM uses a low-power (0.5 mW) Helium-Neon (HeNe) laser that emits continuous light at 632 nm. The laser ODM uses two photodiode detectors; the main detector is used to measure the beam intensity as it is attenuated by the smoke and fire gases in the FPC. A compensating detector located near the laser head is used to account for changes in the laser output during a test so that these are not erroneously attributed to smoke attenuation by the main detector.

Data Acquisition

Data acquisition for the 4 MW FPC is achieved using an Allen Bradley (AB) SLC 500 series Programmable Logic Controller (PLC). Instruments are connected to the FireTOSS network through a SLC 5/05 processor, with an IP address of 10.243.235.183. The FPC instrumentation and the corresponding FireTOSS tag are listed in Table 2. The SLC 500 is located on the east wall of a compartment located on the mezzanine level, above the MBR. This compartment houses the data acquisition and gas analysis instrumentation for all of the MBR FPCs.

Table 2. Data Acquisition Setup

Devices Attached	Quantity Measured	FireTOSS Tag
Laser ODM – Main	Light transmission	AB183_AI01_00
Laser ODM – Compensating	Light transmission	AB183_AI01_01
White Light ODM	Light transmission	AB183_AI01_02
Gas Analyzer – O_2	Gas Concentration	AB183_AI03_04
Gas Analyzer – CO_2	Gas Concentration	AB183_AI03_03_F
Gas Analyzer – CO	Gas Concentration	AB183_AI03_05
Bi-directional probe Pressure Transducer	Pressure	AB183_AI03_00_F

Devices Attached	Quantity Measured	FireTOSS Tag
Bi-directional probe Pressure Transducer	Pressure	AB183_AI03_01_F
Thermocouple 1	Temperature	AB183_TC09_01
Thermocouple 2	Temperature	AB183_TC09_02
Thermocouple 3	Temperature	AB183_TC09_03
Thermocouple 4	Temperature	AB183_TC09_04

Measurement Range

The practical HRR measurement range for the 4 MW FPC is from approximately 50 kW to 5600 kW. This range represents a range of HRR values over which the 4 MW FPC has a linear response. The minimum change in HRR that can be resolved with the 4 MW FPC is approximately 25 kW. Data from calibration experiments performed over the full measurement range of the FPC are shown in Appendix A.

Calibration

A calibration burner [16] is used to determine the calibration factor, or C Factor, for a FPC. The type of calibration burner is selected based on the desired maximum HRR needed for the calibration. For the 4 MW FPC, a natural gas tube burner [17] is used to determine the C Factor.

Calculations

The calculations used to determine the HRR, and other output quantities, from the FPC are defined in the FPC Laboratory Instruction [1].

Uncertainty and Accuracy

Fire Products Collectors are designed to provide four primary quantities: heat release rate (HRR), convective heat release rate (CHRR), gas species production and smoke production. The uncertainty associated with each of these quantities, calculated from measurements in the 4 MW FPC, was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [18], Technical Note 1297 [19], and the NIST Uncertainty Workshop [20]. The analysis outlined below is based primarily on data collected from natural gas fires generated using the FRL tube burner; the burner output was fixed for a period of five minutes at progressively increasing HRR levels [1, 17]. Uncertainty was calculated for nominal fire sizes of 400 kW, 2600 kW and 5400 kW, representing low, middle and high ends of the operating range.

The combined standard uncertainty for a calculated output y, based on a number (i) of uncorrelated input quantities x_i, is a combination of the uncertainty of each component. It is expressed mathematically by the following equation:

$$u_c(y) = k\sqrt{\sum s_i^2 u(x_i)^2} \quad (1)$$

where:

$u_c(y)$ = Combined standard uncertainty in the output y
$u(x_i)$ = Standard uncertainty of each component x_i
s_i = Sensitivity coefficient associated with each component $(\partial/\partial x_i)$
k = Coverage factor

The expression used to calculate the oxygen consumption HRR is a complex function of multiple variables and physical constants [1, 21]. The formulations used to calculate CHRR, gas species production and smoke production are considerably simpler and use many of the same measured input variables [1]. The approach taken in this analysis was to calculate the uncertainty in the HRR first. This necessitates calculating the standard uncertainty for most of the variables and parameters used in the other output quantities. A spreadsheet formulation was used to apply Equation (1) to perform the uncertainty calculations [22].

Table 3 summarizes the combined standard uncertainty for each output quantity of the 4 MW FPC. The HRR, CHRR, CO_2 and CO production rate values are based on data collected from the natural gas calibration burner experiments. Because the natural gas fires produce relatively little smoke, data for the rate of smoke release (RSR) are from a separate experiment. The RSR data is from an upholstered furniture fire with a peak HRR of approximately 5500 kW. Details on how these uncertainty values were determined are provided in the sections that follow.

Table 3. Uncertainty Summary

Quantity	Calculated Value	Combined Standard Uncertainty	Relative Uncertainty
Heat Release Rate (HRR)	2565 kW	149	5.8 %
Convective Heat Release Rate	2077 kW	110	5.3 %
Mass Production Rate – CO_2	108 g/s	5.7	5.3 %
Mass Production Rate – CO	0.72 g/s	0.11	14.9 %
Rate of Smoke Release – Laser	122 m^2/s	7.2	5.9 %

Heat Release Rate

The oxygen consumption heat release rate is calculated according to [1]:

$$HRR = C\left[E\phi - \left(E_{CO} - E\right)\frac{1-\phi}{2}\frac{X_{CO}}{X_{O_2}}\right]\left(\frac{\dot{m}}{1+\phi(\alpha-1)}\right)\left(\frac{MW_{O_2}}{MW_{air}}\right)\left(1-X^0_{H_2O}\right)X^0_{O2} \quad (2)$$

The oxygen depletion factor, , in Equation 2 is a function of two co-dependent pairs: the concentrations of oxygen and carbon dioxide in the incoming air and in the product stream $(X_{O_2}, X^0_{O_2})$ $(X_{CO_2}, X^0_{CO_2})$. It has been shown that, under these circumstances, the approach to properly account for the uncertainty is to re-write Equation 2 in terms of the raw inputs [18]. Based on this, Equation (2) was broken down into thirty four components and a standard uncertainty was determined for each. Table 4 shows a list of the components along with a brief description.

Table 4: Components used in the oxygen consumption HRR calculation

Component	Description (Units in parentheses)
A_{O_2}	Current output from oxygen analyzer (A)
$A_{O_2,zero}$	Current output from oxygen analyzer flowing zero gas (A)
$A_{O_2,span}$	Current output from oxygen analyzer flowing span gas (A)
$A_{O_2,base}$	Current output from oxygen analyzer during pre-test baseline (A)
$X_{O_2,zero}$	Mole fraction of oxygen in zero gas (A)
$X_{O_2,span}$	Mole fraction of oxygen in span gas (A)
A_{CO_2}	Current output from carbon dioxide analyzer (A)
$A_{CO_2,zero}$	Current output from carbon dioxide analyzer flowing zero gas (A)
$A_{CO_2,span}$	Current output from carbon dioxide analyzer flowing span gas (A)
$A_{CO_2,base}$	Current output from carbon dioxide analyzer during pre-test baseline (A)
$X_{CO_2,zero}$	Mole fraction of carbon dioxide in zero gas (A)
$X_{CO_2,span}$	Mole fraction of carbon dioxide in span gas (A)
A_{CO}	Current output from carbon monoxide analyzer (A)
$A_{CO,zero}$	Current output from carbon monoxide analyzer flowing zero gas (A)
$A_{CO,span}$	Current output from carbon monoxide analyzer flowing span gas (A)
$X_{CO,zero}$	Mole fraction of carbon monoxide in zero gas (A)
$X_{CO,span}$	Mole fraction of carbon monoxide in span gas (A)
$M_{air,dry}$	Molecular weight of dry air (g/mol)
M_{H_2O}	Molecular weight of water (g/mol)

Component	Description (Units in parentheses)
M_{O_2}	Molecular weight of oxygen (g/mol)
E	Net heat release of natural gas per kg of oxygen consumed (kJ/kg)
E_{CO}	Net heat release of carbon monoxide per kg of oxygen consumed (kJ/kg)
α	Volumetric expansion factor (--)
RH	Relative humidity of incoming air (%)
P_{amb}	Ambient pressure (Pa)
T_{amb}	Ambient temperature (K)
C_{bdp}	Bi-directional probe constant (--)
f	Velocity flow shape factor (--)
D	Duct diameter (m)
T_1	Duct temperature at sampling location 1 (K)
T_2	Duct temperature at sampling location 2 (K)
$A_{dp,meas1}$	Current output from pressure transducer at sampling location 1(A)
$A_{dp,meas2}$	Current output from pressure transducer at sampling location 2(A)
$A_{dp,zero}$	Current output from the pressure transducer during pre-test baseline (A)

Variables and constants are grouped in Table 4 according to four primary categories: gas species concentrations, physical constants, ambient conditions and mass flow rate. A discussion of the uncertainty analysis for each category is given below.

Gas Species Concentration

ASTM E 2536 identifies three sources of error that should be considered in the estimation of uncertainty for oxygen measurements in a cone calorimeter: the data acquisition system, random (Type A) scatter in the data signal, and calibration [23]. Instrumentation used in the cone calorimeter is similar to what is used in large scale calorimeter hoods such as the 4 MW FPC. Based on this, these three sources of error were considered for the gas species uncertainty evaluation (O_2, CO_2 and CO) performed here. A fourth source, calibration gas error, was added based on discussions with the instrument retailer [24].

Table 4 lists two components that contribute to gas species measurements: the unscaled analyzer signal (A_i) and the mole fractions in the calibration gases (X_i). The following sections provide details related to the uncertainty estimate for each component.

Analyzer Signal Uncertainty

The uncertainty estimate in the recorded analyzer signal included contributions from the data acquisition hardware and fluctuations in the data. The contribution from data acquisition hardware came from manufacturer's specifications. The uncertainty contribution associated with data fluctuations came from a statistical analysis of the raw signal collected in a calibration burner experiment.

The Servomex gas analyzer used in the 4 MW FPC sends an analog 4 – 20 mA signal to an Allen Bradley (AB) SLC 500 series programmable logic controller (PLC) through a 1746 NI16I 16 bit I/O module. Specifications for the AB hardware include a digital resolution of 640 nA and a calibrated accuracy of better than 0.15 % of range [25].

The standard uncertainty associated with fluctuations in the analyzer signal was estimated using the sample standard deviation. Calculations were performed using data recorded when the analyzer output was steady. Analyzer signals listed in Table 4 are divided into two categories: calibration ($A_{i,zero}$, $A_{i,span}$) and experiment (A_i, $A_{i,base}$). For the calibration signal uncertainty, the sample standard deviation was calculated over one minute periods during an ‘AUTOCAL’ cycle. For the experiment signal uncertainty the sample standard deviation was calculated during a calibration burner experiment. Statistics were performed for data spanning several minutes.

The combined uncertainty was calculated by combining the data acquisition and statistical components.

Calibration Gas Uncertainty
The 4 MW FPC is equipped with a modified Servomex Xentra 4100 gas analyzer that contains individual cells to measure each of the three species concentrations. Oxygen concentration is measured in a paramagnetic cell with 0 – 25 % range; CO_2 and CO are measured in non-dispersive infrared (NDIR) cells with peak concentration ranges of 10 % and 1 %, respectively. Each cell is calibrated using zero and span gases. The zero gas and CO / CO_2 span gas come with certifications from the supplier. The oxygen analyzer is spanned with ambient air; the uncertainty estimate for ambient O_2 concentration was taken from the literature [18].

The zero gas is “Zero” grade (99.99 %) nitrogen. Assuming a rectangular distribution, the standard uncertainty is +/- 5.8 x 10^{-5}. The CO/CO_2 span gas is a Primary Standard grade mixture with certified accuracy of 1% for CO and 0.02 % for CO_2. The concentrations of CO and CO_2 in the span gas are nominally 0.8 % and 8 %, respectively, with the balance comprised of N_2. Assuming a rectangular distribution, the standard uncertainties of CO_2 and CO in the span gas are estimated to be 1.2 x 10^{-4} and 4.6 x 10^{-5}, respectively. Laboratory air is used to span the oxygen analyzer; the concentration is taken as 20.95 %. The estimated uncertainty associated with the oxygen span concentration is estimated to be 0.05 % [18]. This estimate was verified through a comparison with a high purity certified O_2/N_2 mixture.

Physical Constants
Physical constants include the molecular weights of oxygen (M_{O_2}), dry air ($M_{air,dry}$) and water (M_{H_2O}), in addition to the volumetric expansion factor (α) and the net heat release per unit mass of oxygen consumed for natural gas (E) and carbon monoxide (E_{CO}). The standard uncertainty

of the molecular weights was taken as zero. The standard uncertainties of the remaining constants were based on previous work and summarized in Table 5 [18].

Table 5: Summary of uncertainty in physical constants

Parameter	Value	Standard Uncertainty
α (--)	1.104	0.048
E (kJ/kg O_2)	12550	19.95
E_{CO} (kJ/kg O_2)	17690	10

Ambient Conditions

Ambient conditions are measured using a wall mounted weather station that is permanently housed in the MBR. The weather station measures relative humidity, temperature and absolute pressure. Additional information, including the uncertainty analysis for each of the measured quantities, can be found in the laboratory instruction [28]. Table 6 shows a summary of the standard uncertainty for the ambient temperature, pressure and relative humidity.

Table 6: Ambient conditions uncertainty summary

Quantity	Standard Uncertainty
T_a (°C)	0.6
P_a (Pa)	115.5
RH (%)	2.2

Mass Flow Rate

The mass flow rate is expressed as:

$$\dot{m} = \rho \, \dot{V} \tag{3}$$

where ρ is the gas density (kg/m^3) and $\dot{V}$ is the volumetric flow rate (m^3/s). The density was expressed in terms of temperature using the ideal gas law:

$$\rho = \rho_{std} \frac{T_{std}}{T} \tag{4}$$

where the standard condition is taken as 300 K and 1 atm. The volumetric flow rate was calculated using:

$$\dot{V} = f\,A\,V \tag{5}$$

where f is the flow shape factor, A is the duct area (m^2) and V is the velocity (m/s). The flow shape factor was calculated using data from flow traverse measurements conducted previously [29]. The duct area is a function of the diameter, D (1.35 m). The velocity was calculated according to [6]:

$$V = \sqrt{\frac{2\,\Delta P\,T}{\rho_{std} T_{std}}} \Big/ C_{bdp} \tag{6}$$

where P is the differential pressure measured by the velocity probe (Pa) and T (K) is the temperature inside the duct. C_{bdp} is the bi-directional probe factor that has been shown to be a constant (1.08 ± 5 %) over the range of Reynolds numbers encountered in the duct flow [8]. Combining the above equations and substituting ($T_{std} = 300\ K$, $\rho_{std} = 1.18\ kg/m^3$) yields:

$$\dot{m} = \frac{20.875\,D^2\,f}{C_{bdp}} \sqrt{\frac{\Delta P}{T}} \tag{7}$$

The temperature was taken as the average of four independent measurements at each time step and the differential pressure was expressed as:

$$\Delta P = \Delta P_{meas} - \Delta P_{baseline} = \left(m_{dp}\,A_{dp} + b_{dp}\right)_{meas} - \left(m_{dp}\,A_{dp} + b_{dp}\right)_{baseline} \tag{8}$$

where m_{dp} and b_{dp} are the calibration factors for the differential pressure transducer. The differential pressure is corrected by subtracting a baseline value, which is measured in a separate experiment with the transducer cross-ported. Consolidating terms, the differential pressure can be expressed as:

$$\Delta P = m_{dp}\left(A_{dp,meas} - A_{dp,baseline}\right) \tag{9}$$

The calibration constant, m_{dp}, for the pressure transducer was 38920.1 Pa/A. This yields the expression for mass flow rate:

$$\dot{m} = \frac{4118.26\,D^2\,f}{C_{bdp}} \sqrt{\frac{A_{dp,meas} - A_{dp,baseline}}{T}} \tag{10}$$

The standard uncertainty in the diameter measurement was calculated from the standard deviation of six independent measurements. The result was D = 1.349 ± 0.002 m. To account for the duct not being perfectly circular this uncertainty was increased to ± 0.005 m. The standard uncertainty in the flow shape factor (*f*) was estimated based on the standard error in the least squares regression from the traverse data [29]. The standard uncertainty in the each temperature measurement was estimated by combining the fundamental error limit of the probe and the sample standard deviation of data calculated during a calibration burner experiment. The standard uncertainty in the average temperature was calculated by combining uncertainties in the individual measurements using Eqn. (1).

The combined standard uncertainty in the pressure transducer data was calculated based on manufacturer's specifications for the data acquisition hardware and pressure transducer, in addition to a statistical analysis of the signal. The data acquisition hardware is the same as what is used for the gas analyzers; the standard uncertainty is 7.1×10^{-8} A. The standard uncertainty for a Setra model 267 pressure transducer is a function of the input range for the instrument; for a device with input range P = 0 – 0.62 kPa (0 – 2.5 inch H_2O) the standard uncertainty is 5.2×10^{-5} A [12]. The uncertainty associated with data fluctuation in the transducer output was calculated from the sample standard deviation collected during a calibration burner experiment. Table 7 shows a summary of the combined standard uncertainty for the pressure measurement for three fire sizes and a baseline.

Table 7: Combined standard uncertainty in the differential pressure measurement.

Fire Size	Combined Standard Uncertainty (A)
Baseline	5.2×10^{-5}
370 KW	3.0×10^{-4}
2565 kW	2.6×10^{-4}
5370 kW	3.0×10^{-4}

Summary

Table 8 shows a summary of the uncertainty in the oxygen consumption heat release rate performed for three fire sizes. The first column lists the 26 components (with units in parentheses) that comprise the oxygen consumption HRR calculation, as described in Table 4. For each component, the nominal value obtained for a 2565 kW fire is listed in column 2. Column 3 lists the standard uncertainty for each component that was discussed in the preceding sections. Columns 4 – 6 list the sensitivity coefficients calculated for fire sizes of 370 kW, 2565 kW and 5370 kW.

Table 8: Summary of HRR uncertainty calculations

Variable / Parameter x_i	Nominal Value	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient $\lvert s_i \rvert$		
			370 kW	2565 kW	5370 kW
A_{O_2}	0.01699	9.9×10^{-6}	6.9×10^{6}	6.4×10^{6}	5.8×10^{6}
$A_{O_2,zero}$	0.00400	1.2×10^{-6}	3.2×10^{4}	2.1×10^{5}	4.3×10^{5}
$A_{O_2,span}$	0.01741	1.0×10^{-6}	3.5×10^{4}	2.4×10^{5}	5.0×10^{5}
$A_{O_2,base}$	0.01743	1.2×10^{-6}	6.9×10^{6}	6.4×10^{6}	5.9×10^{6}
$X_{O_2,zero}$	0.00000	5.8×10^{-5}	2.1×10^{3}	1.3×10^{5}	2.8×10^{4}
$X_{O_2,span}$	0.20950	5.0×10^{-4}	2.2×10^{3}	1.5×10^{5}	3.2×10^{4}
A_{CO_2}	0.00454	4.4×10^{-6}	5.7×10^{5}	5.2×10^{5}	4.5×10^{5}
$A_{CO_2,zero}$	0.00400	2.2×10^{-7}	4.6×10^{3}	2.2×10^{4}	4.6×10^{4}
$A_{CO_2,span}$	0.01680	8.1×10^{-7}	4.3×10^{3}	1.9×10^{4}	4.2×10^{4}
$A_{CO_2,base}$	0.00406	1.4×10^{-6}	5.7×10^{5}	5.2×10^{5}	4.6×10^{5}
$X_{CO_2,zero}$	0.00000	5.8×10^{-5}	7.3×10^{2}	3.5×10^{3}	7.4×10^{3}
$X_{CO_2,span}$	0.08000	1.2×10^{-4}	6.9×10^{2}	3.1×10^{3}	6.7×10^{3}
A_{CO}	0.00402	3.3×10^{-6}	1.0×10^{5}	9.3×10^{4}	8.4×10^{4}
$A_{CO,zero}$	0.00400	6.5×10^{-7}	1.0×10^{5}	9.3×10^{4}	8.4×10^{4}
$A_{CO,span}$	0.01680	7.9×10^{-6}	2.8×10^{2}	1.1×10^{2}	2.5×10^{2}
$X_{CO,zero}$	0.00000	5.8×10^{-5}	1.6×10^{5}	1.5×10^{5}	1.3×10^{5}
$X_{CO,span}$	0.00800	4.6×10^{-5}	4.5×10^{2}	1.8×10^{2}	4.0×10^{2}
$M_{air,dry}$ (g/mol)	28.97	0	0	0	0
M_{H_2O} (g/mol)	18	0	0	0	0
M_{O_2}(g/mol)	32	0	0	0	0
E (kJ/kg)	12550	19.95	3.0×10^{-2}	2.0×10^{-1}	4.3×10^{-1}
E_{CO} (kJ/kg)	17690	10	3.1×10^{-4}	1.2×10^{-4}	2.8×10^{-4}
α (--)	1.104	0.048	1.9×10^{0}	9.6×10^{1}	4.5×10^{2}
RH (%)	47.01	2.16	8.5×10^{-2}	3.4×10^{-1}	7.1×10^{-1}
P_{amb} (Pa)	100105	115.5	4.8×10^{-5}	1.6×10^{-4}	3.3×10^{-4}
T_{amb} (K)	291.41	0.44	2.9×10^{-1}	1.0×10^{0}	2.1×10^{0}
C_{bdp}	1.08	0.054	3.3×10^{2}	2.3×10^{3}	4.7×10^{3}
f (--)	1.0825	8.0×10^{-3}	3.4×10^{2}	2.4×10^{3}	4.9×10^{3}
D (m)	1.349	0.005	5.5×10^{2}	3.8×10^{3}	8.0×10^{3}
T_1 (K)	378.26	1.13	2.9×10^{-1}	1.7×10^{0}	2.8×10^{0}
T_2 (K)	378.07	1.12	3.0×10^{-1}	1.7×10^{0}	2.8×10^{0}
$A_{dp,meas,1}$ (A)	0.00903	2.5×10^{-4}	1.9×10^{4}	1.2×10^{5}	2.3×10^{5}

Variable / Parameter x_i	Nominal Value	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient $\lvert s_i \rvert$		
			370 kW	2565 kW	5370 kW
$A_{dp,meas,2}$ (A)	0.00946	2.8 x 10^{-4}	1.8 x 10^{4}	1.2 x 10^{5}	2.3 x 10^{5}
$A_{dp,zero}$ (A)	0.00404	5.2 x 10^{-5}	3.8 x 10^{4}	2.5 x 10^{5}	4.6 x 10^{5}

The combined standard uncertainty for each fire size was calculated by combining terms in Table 8 according to Equation 1. The results are summarized in Table 9; the values represent a coverage factor of k = 1. In the case of a normal distribution, this translates to a confidence level of approximately 68%. To obtain a higher confidence level a higher coverage factor can be applied. A coverage factor of k = 2 in a normally distributed population provides a confidence level of approximately 95 %.

Table 9: Combined standard uncertainty in the heat release rate

Fire Size (kW)	Combined Standard Uncertainty (kW)	Relative Uncertainty (%)
370	29	7.8
2565	149	5.8
5370	301	5.6

Table 10 shows a list of the variables that contribute most significantly to the combined uncertainty. The HRR is highly sensitive to the oxygen concentration measurements (A_{O_2}, $A_{O_2,base}$) as demonstrated by the large sensitivity factor shown for these variables in Table 8. As the fire size increases, the terms associated with the mass flow become more significant (C_{bdp}, D, $A_{dp,meas}$). These terms account for more than 84 % of the combined uncertainty at 5370 kW, with the differential pressure probe factor (C_{bdp}) being dominant.

Table 10: Contribution to the combined uncertainty

Variable / Parameter x_i	Fire Size		
	370 kW	2565 kW	5370 kW
A_{O_2} (A)	35.7 %	17.9 %	12.1 %
$A_{O_2,base}$ (A)	5.7 %	0.3 %	0.1 %
$X_{CO,Zero}$ (--)	10.5 %	0.3 %	0.1 %
C_{bdp} (--)	37.3 %	67.6 %	72.2 %
D (m)	0.9 %	1.6 %	1.8 %
$A_{dp,meas}$ (A)	7.7 %	9.2 %	10.4 %

Convective Heat Release Rate

The convective heat release rate (CHRR) is expressed as:

$$\dot{Q}_c = \dot{m}\,(h_2 - h_1) \qquad (11)$$

where $\dot{Q}_c$ is the convective heat release rate (kW), $\dot{m}$ is the mass flow rate (kg/s) and h_1 and h_2 are the enthalpies of the incoming air and product stream, respectively (kJ/kg). The mass flow rate is evaluated in the same manner as in the HRR calculation (Equation 11) and is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The standard uncertainty in each of these is the same as in the HRR analysis.

The enthalpy difference is calculated according to a polynomial fit evaluated over the temperature range:

$$h_2 - h_1 = \left(\alpha T + \beta\frac{T^2}{2} + \gamma\frac{T^3}{3} + \delta\frac{T^4}{4} + \varepsilon\frac{T^5}{5}\right)\Bigg|_{T_1}^{T_2} \qquad (12)$$

where , , , , are fit parameters. Data used to fit the coefficients was taken from two sources [30,31]. The error associated with the fit parameters is negligible; the uncertainty in enthalpy was assumed to be solely due to error in the temperature measurement[1]. The standard uncertainty in temperature is the same as in the HRR analysis. Table 11 shows a summary of the CHRR and the combined standard uncertainty in the CHRR for each corresponding HRR step; the values represent a coverage factor of k = 1.

Table 11: Convective heat release rate uncertainty summary

HRR (kW)	CHRR (kW)	Combined Uncertainty (kW)	Relative Uncertainty (%)
370	322	24	7.4
2565	2077	110	5.3
5370	4343	227	5.2

Gas Species Production

The gas species mass production rate is expressed as:

[1] The polynomial fit parameters used for the enthalpy calculation were those for air.

$$\dot{m}_x = \dot{m}\left(X_x - X_{x,base}\right)\frac{M_x}{M_a} \qquad (13)$$

Where $\dot{m}_x$ is the production rate of species x (kg/s), $\dot{m}$ is the mass flow rate in the exhaust duct (kg/s), X_x and $X_{x,base}$ are the mole fractions of species x in the product stream and the incoming air, respectively (mol/mol), M_x is the molecular weight of species x (g/mol) and M_a is the molecular weight of air (g/mol).

All variables in Equation (13) are evaluated in the same manner as in the HRR calculation (Equation 1). The mass flow rate is a function of six quantities ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f). The mole fractions are calculated from the analyzer current and calibration concentrations. The standard uncertainty in each of these is the same as in the HRR analysis.

Table 12 and Table 13 show summaries of the combined uncertainty in the CO_2 and CO production rates, respectively, for three fire sizes. The values represent a coverage factor of k = 1. Relative uncertainty levels in the CO production rate are high mainly because of the low CO levels generated by natural gas fires.

Table 12: Combined uncertainty in the CO_2 production rate

HRR (kW)	$\dot{m}_{CO_2}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
370	23	1.5	6.6
2565	108	5.7	5.3
5370	249	13.2	5.3

Table 13: Combined uncertainty in the CO production rate

HRR (kW)	$\dot{m}_{CO}$ (g/s)	Combined Uncertainty (g/s)	Relative Uncertainty (%)
370	0.06	0.24	369
2565	0.72	0.11	14.9
5370	1.2	0.11	9.8

Smoke Production

The rate of smoke release (RSR) is expressed as:

$$RSR = k\dot{V} \qquad (14)$$

where k (m^{-1}) is the optical extinction coefficient measured by the ODM and $\dot{V}$ (m^3/s) is the volumetric flow rate in the exhaust duct.

The standard uncertainty for the extinction coefficient is described in the ODM Technical Reference [15]. For the laser system the relative standard uncertainty is less than 1 % for k > 0.1 m^{-1}; for k > 0.2 m^{-1} the relative uncertainty is less than 0.5 %.

Uncertainty in the volumetric flow rate was calculated in a manner similar to the procedure used for the mass flow rate in the HRR analysis. The volumetric flow rate is a function of the same six quantities as the mass flow rate ($A_{dp,meas}$, $A_{dp,baseline}$, D, T, C_{bdp}, f).

Smoke data was collected from an experiment in which upholstered furniture was the primary fuel. The peak HRR in this experiment was approximately 5500 kW; at this fire size the extinction coefficient measured by the laser ODM was 5.0 m^{-1}, yielding a smoke release rate of 122 m^2/s. The combined standard uncertainty in the RSR under these conditions was 7.2 m^2/s or 5.9 %.

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Appendix A – Experimental Data

Figure 9 shows heat release rate data from a calibration burner experiment conducted under the 4 MW FPC using the natural gas tube burner [17]. The burner was run through a series of 5-minute duration steps with outputs of 0, 50, 100, 300, 500, 700, 900 and 1100 kW. Data from the burner is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burner and FPC during each of the eight steps; the average values are plotted together in Figure 10. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 9. The slope of a linear fit through this data is the C-Factor [1].

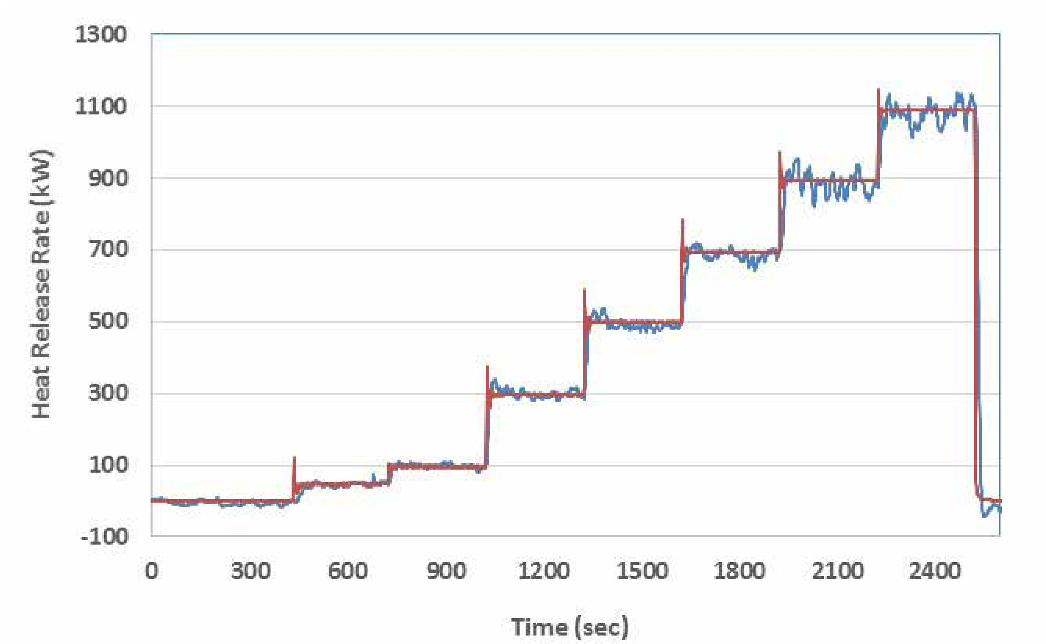

Figure 9: Heat release rate data from a calibration burner experiment under the 4 MW FPC.

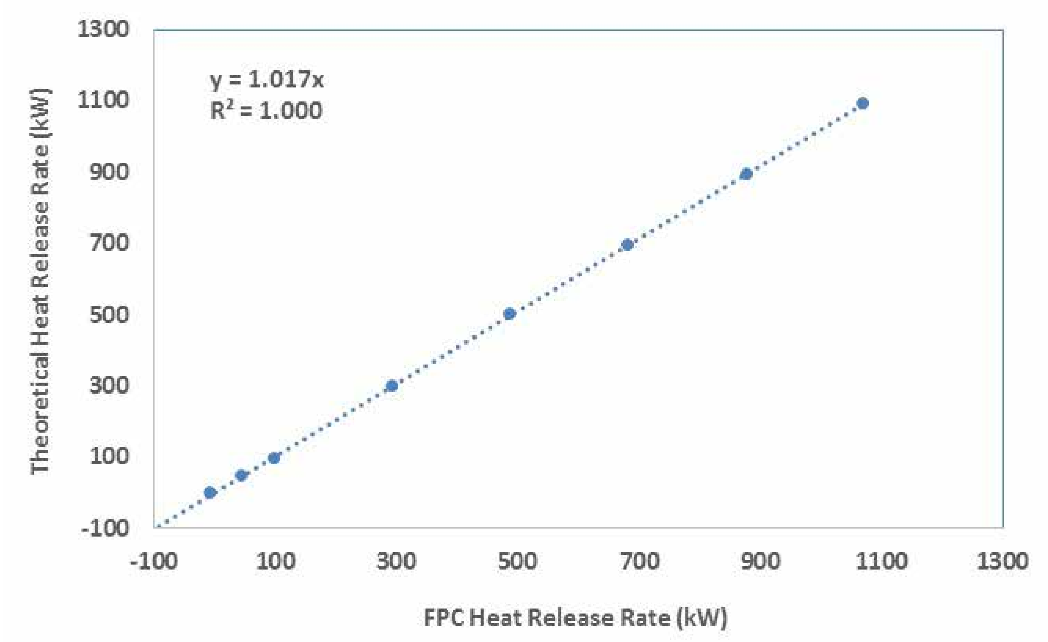

Figure 10: Average theoretical HRR plotted against average FPC HRR for an experiment using the natural gas tube burner.

Figure 11 shows heat release rate data from a calibration burner experiment conducted under the 4 MW FPC using the natural gas tube burner [17]. The burner was run through a series of 5-minute duration steps with nominal outputs of 0, 750, 1450, 2450, 3450, 4400 and 5400 kW. Data from the burners is labeled "Theoretical HRR" in the chart. Calculated HRR from FPC measurements is plotted on the same chart.

Average HRR values were calculated for the burner and FPC during each of the seven steps; the average values are plotted together in Figure 12. This chart shows the average theoretical HRR plotted against the average FPC HRR calculated for each step in Figure 11. The slope of a linear fit through this data is the C-Factor [1].

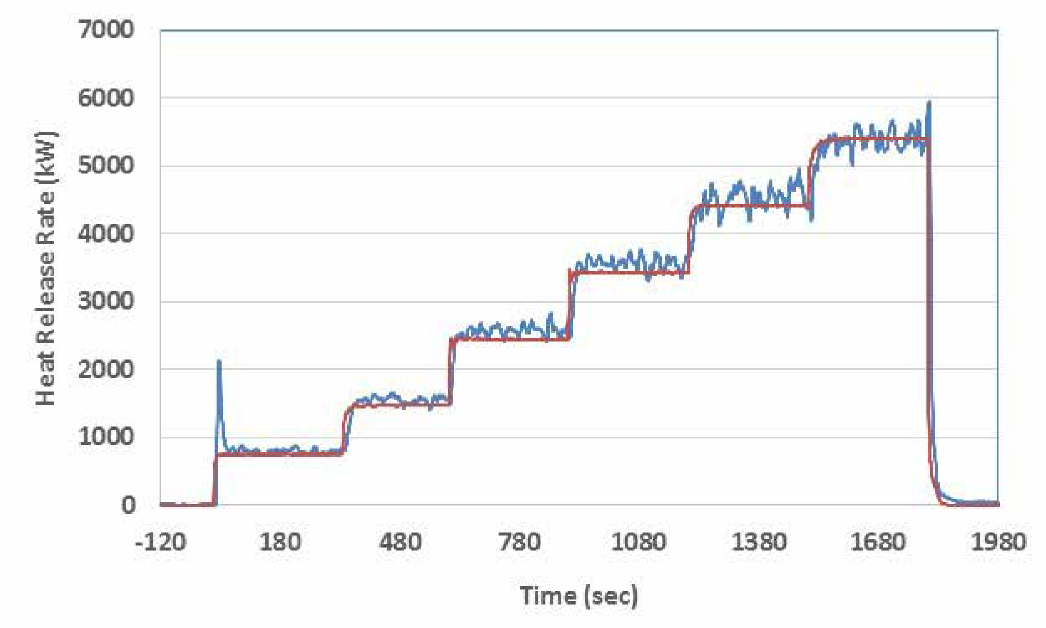

Figure 11: Heat release rate data from a calibration burner experiment under the 4 MW FPC.

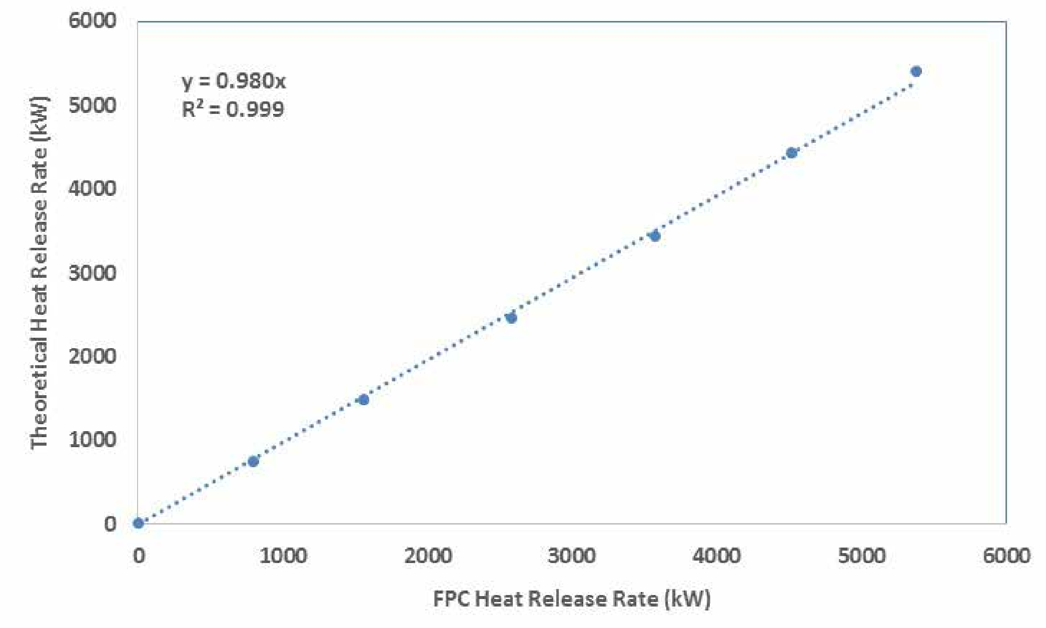

Figure 12: Average theoretical HRR plotted against average FPC HRR for an experiment using the natural gas tube burner.

Scope

This Technical Reference covers the use, design and specifications of white light and laser Optical Density Meters (ODM) in the large scale Fire Product Collectors (FPC) at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Optical Density Meters (ODMs) are used to perform smoke measurements in the exhaust duct of a fire product collector. Smoke measurements are performed for a variety of reasons including toxicity assessment, visibility calculation, and model validation. Optical density meters measure the attenuation of a light beam passing along a fixed path length through a particulate and gaseous medium. The FPC ODMs used at the ATF FRL are categorized as laser and white light systems.

LASER SYSTEM

The basic elements of the laser system are a laser and two photodiode detectors. The hardware is configured so that the laser and compensating detector are mounted to one side of the FPC duct, while the main detector is mounted on the other side of the duct, directly opposite the laser. A schematic of the setup is shown in Figure 1 (Note that the mounting bracket design may vary). Additional components include beam splitters, diffusers, filter housings, optical density filters, amplifier and power supply modules. The laser system is designed in accordance with ASTM E 1354, NFPA 286 and NFPA 289 fire test standards [1,2,3].

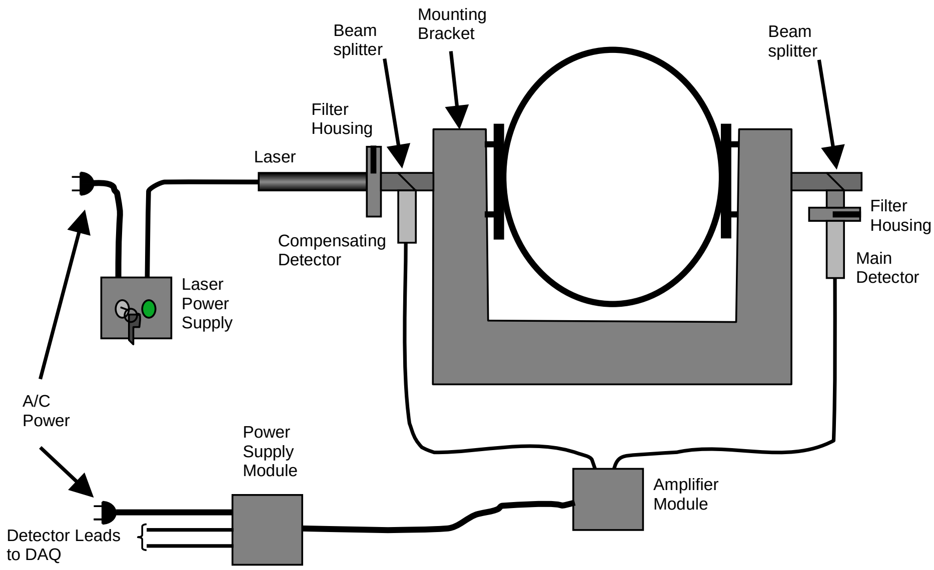

Figure 1: Layout of laser smoke measurement equipment.

Laser

The light source is a 0.5 mW Heluim-Neon (HeNe) laser that emits at 632.8 nm (Melles Griot 05-LHP-494-249 or similar) [4]. Figure 2 shows a photo of a typical laser mounted to an assembly that includes a filter housing, beam splitter, diffuser and compensating detector.

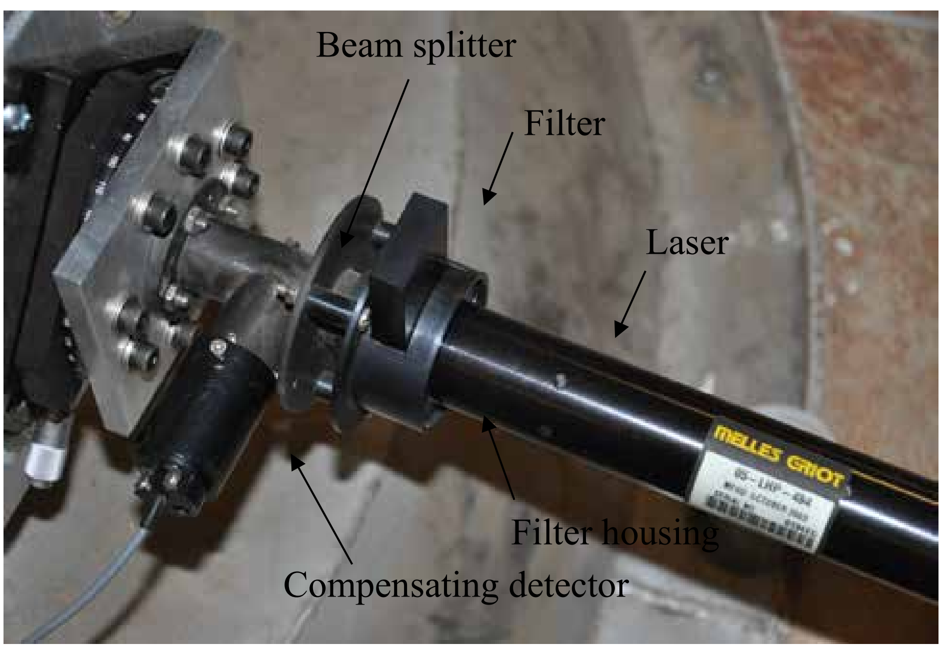

Figure 2: Laser assembly

Detectors

The laser system is equipped with two silicon photodiode detectors: both a main and a compensating (Hamamatsu S1336-44BK) [5]. The main detector is mounted to the side of the duct directly opposite the laser, shown in Figure 3. The signal from the main detector is used to calculate the quantities described in the Lab Instruction [6]. The compensating detector is mounted to the same side of the duct as the laser head (Figure 2). The purpose of a compensating detector is to act as a reference for variations in the laser source intensity so that the main detector signal can be corrected.

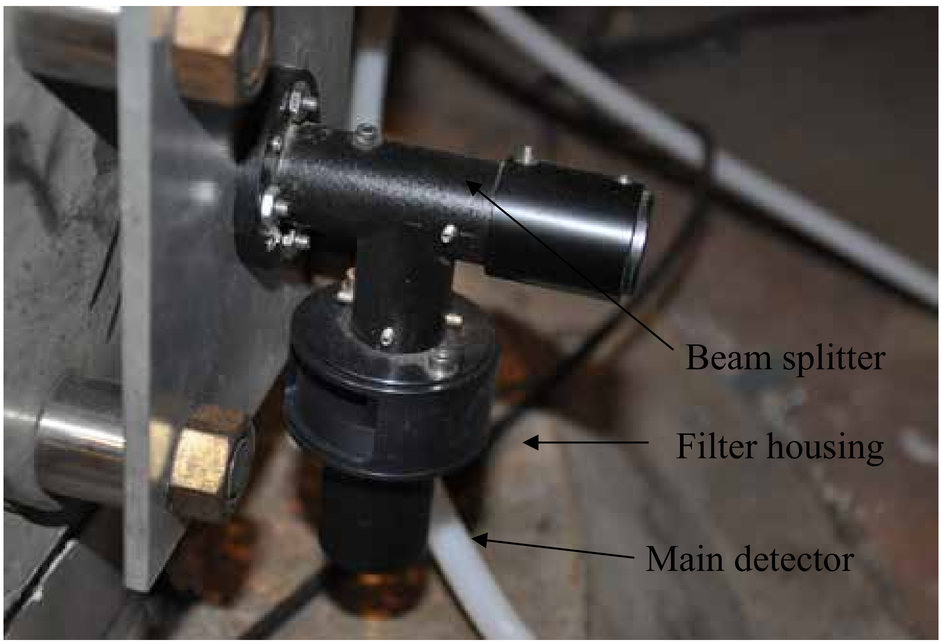

Figure 3: Main detector assembly

Beam Splitter

The system includes two non polarizing cube beam splitters, located along the laser path adjacent to each detector (Melles Griot 03-BSL-043) [7]. Each beam splitter nominally transmits 50% of the incident light, redirecting the remaining light at a 90° angle to the detector.

Filter Housing

There is a filter housing mounted along the laser path adjacent to both detectors. The filter housings are machined with a slot to accommodate an optical density filter during balancing and calibration procedures. A sliding cover can be used to cover the slot when a filter is not in use.

Optical Density Filters

Optical density filters can be used to calibrate the laser ODM. Two Coherent neutral density filters (models 36-5338 and 36-5387), with nominal optical densities of 0.3 and 0.8 are provided

[8]. Figure 4 shows a photo of typical filters. In addition to the filters, a blank insert is also provided for use in the system balancing procedure. The laser ODM balancing and calibration procedures are described in the "FireTOSS Calculations" section.

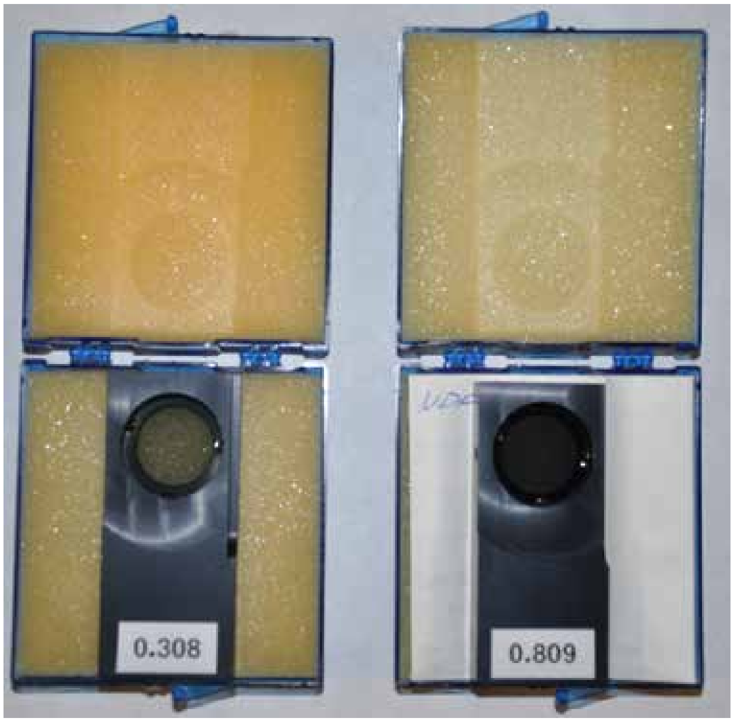

Figure 4: Optical density filters

Diffuser

The front surface of each detector is covered by a diffuser. The diffuser scatters the incident light over a larger area on the detector surface. This makes system alignment more forgiving but also reduces the light intensity reaching the detector.

Amplifier and Power Supply

The detector output is amplified by adjusting the gain on the amplifier module, shown in Figure 5. The power supply module, shown in Figure 6, connects to the amplifier module and also has junctions to connect the detector outputs to the data acquisition system.

Figure 5: Photodiode amplifier module

Figure 6: Laser ODM power supply module

WHITE LIGHT

The basic elements of the white light system are a control unit, a light source, and a light receiver. The system used by the FRL is manufactured by Fire Testing Technology (FTT), and conforms to DIN 50055 [9]. The hardware is configured so that the light source is mounted to one side of the FPC duct, while the light receiver is mounted on the other side of the duct, directly opposite the source. A schematic of the setup is shown in Figure 7 (note that the mounting bracket design may vary).

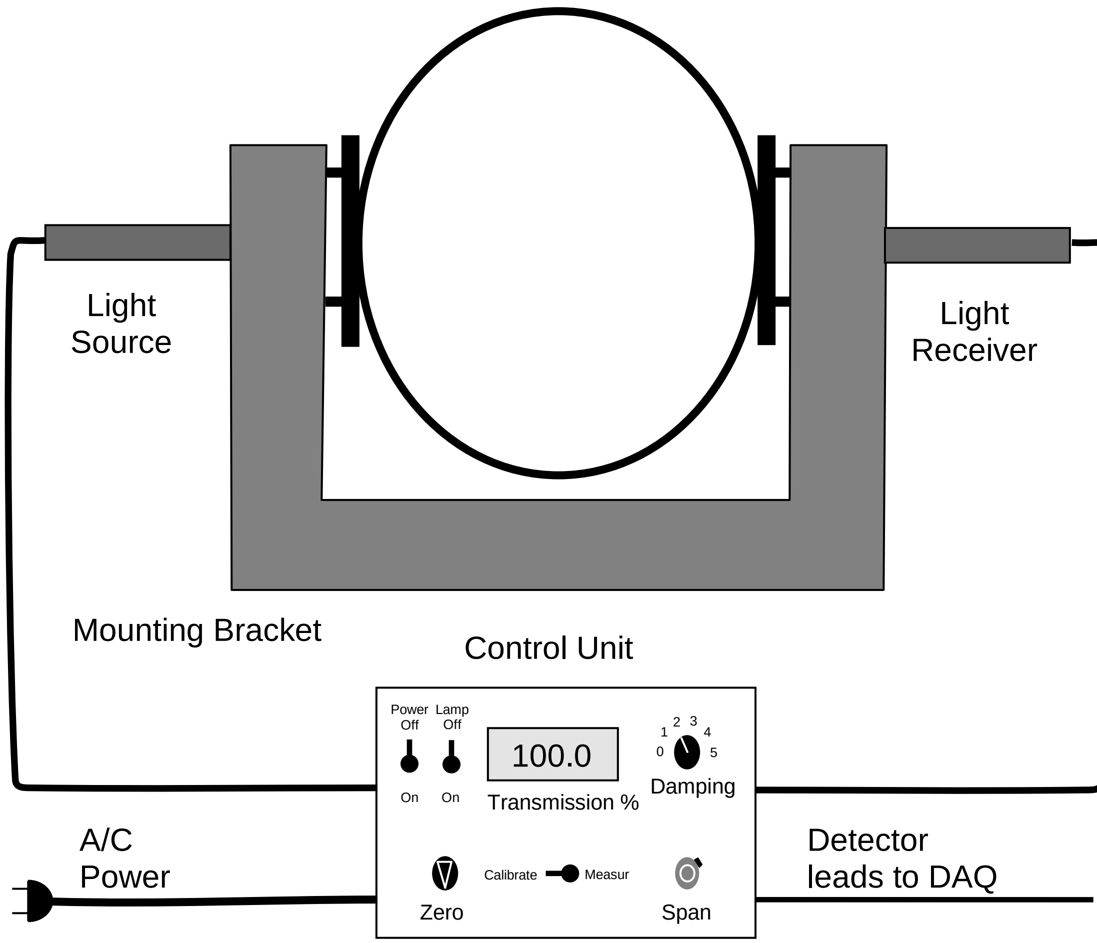

Figure 7: Layout of white light smoke measurement equipment.

Control Unit

The control unit interface includes the main power switch, the lamp power switch, the zero and span controls, damping adjustment and a LED display [9]. Figure 8 shows a photo of the control unit. The display can be toggled between calibration mode and measurement mode. The damping setting adjusts the 95% time constant of the amplifier. Table 1 shows the time constant associated with each setting option.

Figure 8: White light ODM control module

Table 1: Damping levels for white light ODM

Damping Level	Time Constant in s ± 10%
0	0.75
1	1.6
2	2.5
3	4.0
4	6.0
5	8.0

Light Source

The light source consists of a halogen lamp and a series of lenses and apertures that combine to create a nearly collimated beam with a 25 mm diameter at the outlet. It is also equipped with an adjustable aperture to reduce the luminous intensity if necessary [9]. Figure 9 shows a photo of the source module.

Figure 9: Source module for white light ODM

Light Receiver

The Light Receiver consists of an achromatic lens system with a focal depth of approximately 80mm and a silicon photoelectric cell in front of which is a spectral filter to accommodate the human eye. A ground glass plate in front of the spectral filter scatters the incident light in the focal plane of the lens. The unit is fitted with an amplifier [9]. Figure 10 shows a photo of the white light receiver module.

Figure 10: Receiver module for white light ODM

Optical Density Filters

Optical density filters can be used to calibrate the laser ODM. Five filters, with nominal optical densities of 0.1, 0.3, 0.5, 1.0 and 2.0 are provided. Figure 11 shows a photo of a typical filter. During a calibration procedure the filter is placed in front of the light receiving module between two guides welded to the mounting frame.

Figure 11: Filter for white ODM

FireTOSS Calculations

Optical density meters are used in FPC experiments to calculate the following quantities: extinction coefficient, optical density per meter, rate of smoke release and total smoke released. If an experiment is conducted using a weighing device the smoke yield can also be calculated. The theory behind these calculations is provided elsewhere [6]. The calculations outlined in this document describe how the amplified photodiode and photocell voltages are used to calculate engineering quantities.

LASER SYSTEM

Zeroing and Balancing

The first step in the laser calculation is to zero and balance the system. Zeroing is accomplished by recording the amplified detector outputs with the laser beam blocked; this yields V_0 for each detector ($V_{0,main}$ and $V_{0,comp}$). Likewise, the system is balanced by recording the amplified detector signals with no obstructions in the laser path. This yields $V_{1,main}$ and $V_{1,comp}$ [10].

The next step is to normalize the amplified detector readings for both the main and compensating detectors to produce a signal that varies between zero and one. The data arrays are normalized according to Equation 1.1:

$$V_n = \frac{V_{raw} - V_0}{V_1 - V_0} \quad (1.1)$$

Where V_{raw} is the detector data array. V_n is the calculated for the main and compensating detectors to produce $V_{n,main}$ and $V_{n,comp}$, respectively.

Calibration

System calibration is used to calculate the correction factor, f, used in the extinction coefficient calculation [10]. Calibration is performed on the main detector by placing a neutral density filter in the housing and recording the detector output. The measured optical density is then calculated using Equation 1.2,

$$OD_{meas} = \log\left(\frac{V_{n,comp}}{V_{n,main}}\right) \tag{1.2}$$

where $V_{n,main}$ is calculated based on V_{raw} with the filter in place. The correction factor is the ratio of the filter optical density to the measured optical density, as shown in Equation 1.3.

$$f = \frac{OD_{filter}}{OD_{meas}} \tag{1.3}$$

The factor should be close to 1, and is assumed to be 1 if calibration is not performed.

Extinction Coefficient

The extinction coefficient, k (m^{-1}), is defined by Equation 1.4:

$$k = f \cdot \frac{1}{L} \ln\left(\frac{V_{n,comp}}{V_{n,main}}\right) \tag{1.4}$$

Where L is the path length traversed through the attenuating medium. The optical density per meter, rate of smoke release and total smoke released are all derived from the extinction coefficient [6].

WHITE LIGHT SYSTEM

The white light calculations are similar to the laser calculations, with the exception that the signal is not normalized as in Equation 1.1.

Zeroing and Spanning

The white light FPC ODM is equipped with zero and span controls. The system is zeroed with the light source either blocked or turned off. The system is then spanned with the light source powered on and unobstructed. The span setting is adjusted such that the display reads 100.0 with no smoke present in the light path.

Calibration

The system is calibrated by placing three neutral density filters independently in front of the detector, normal to the light path. If the measured transmittance varies from the calibrated filter transmittance by more than 2%, then a correction factor, f_w, will be used to adjust the measured values.

Extinction Coefficient

The white extinction coefficient, k_w (m^{-1}) follows from Equation 1.4:

$$k_w = f_w \frac{1}{L} \ln\left(\frac{V_1 - V_0}{V_{raw} - V_0}\right) \qquad (1.5)$$

Where V_0 and V_1 are the photocell zero and span voltage, respectively. V_{raw} is the photocell data array measured during an experiment and L is the path length traversed through the attenuating medium.

Uncertainty and Accuracy

The uncertainty of the optical density measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [11], Special Publication 1007 [12], and the NIST Uncertainty Workshop [13]. The combined standard uncertainty of the measurements is a combination of the uncertainty of its components, including voltage, path length and the filter optical density,among other factors, and is given by the following equation:

$$u_C(k) = \sqrt{\sum s_i^2 u(x_i)^2} \qquad (1.6)$$

where:

$u_c(k)$ = Combined standard uncertainty of the extinction coefficient
$u(x_i)$ = Standard uncertainty of each extinction coefficient component
s_i = Sensitivity coefficient $(\partial y/\partial x_i)$

Due to the relatively large number of variables involved in the laser calculation, a numerical approach was used to evaluate Equation 1.6 [14].

LASER

A spreadsheet formulation was used to apply Equation 1.6 to calculate the combined standard uncertainty in the laser extinction coefficient as represented by Equations 1.1 – 1.4 [14]. The laser extinction coefficient (k) is a function of nine variables:

$V_{raw,main}$	Raw voltage from the main detector (V)
$V_{1,main}$	Span voltage from the main detector (V)
$V_{0,main}$	Zero voltage from the main detector (V)
$V_{filter,main}$	Voltage from the main detector with the filter in place (V)
$V_{raw,comp}$	Raw voltage from the compensating detector (V)
$V_{1,comp}$	Span voltage from the compensating detector (V)
$V_{0,comp}$	Zero voltage from the compensating detector (V)
OD_{filter}	Optical density of the filter (--)
L	Laser path length (m)

The uncertainties in the voltages were estimated based on a statistical evaluation of detector output during an experiment. The standard uncertainty for each measurement was calculated according to Equation (1.7) [13].

$$u = \frac{S}{\sqrt{n}} \tag{1.7}$$

where:

S = Standard deviation of the measurements in a sample
n = Number of measurements in the sample

Similarly, the combined uncertainty in the path length measurement was based on the resolution of the measuring device and a statistical evaluation based on multiple measurements. The standard uncertainty in the measurement was estimated as 1.9×10^{-3} m.

The uncertainty of the neutral density filters was estimated based on the measured optical density. The filters are calibrated to a tolerance of 0.001 OD. Assuming a rectangular probability distribution the standard uncertainty was calculated by dividing the filter error by $\sqrt{3}$ [11]. This yields a standard uncertainty for the filters of $\pm 5.8 \times 10^{-4}$ OD.

The relative combined standard uncertainty in the extinction coefficient is approximately 10.5 % at an extinction coefficient of 0.01 m^{-1}. The relative uncertainty decreases rapidly as the extinction coefficient increases, however, falling below 2 % at an extinction coefficient of 0.05 m^{-1}. Figure 12 shows a chart of this trend.

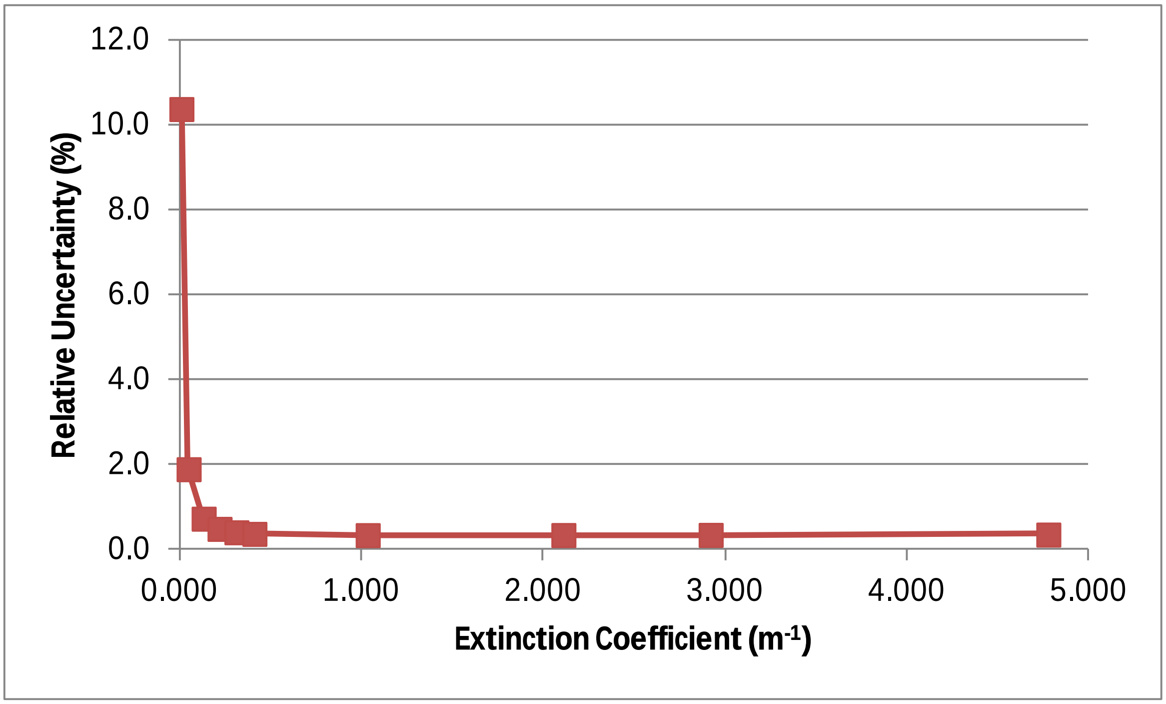

Figure 12: Relative combined standard uncertainty in laser extinction coefficient

WHITE LIGHT

Uncertainty for the white light system was calculated in a way that was similar to the laser system calculation. A spreadsheet formulation was used to apply Equation 1.6 to calculate the combined standard uncertainty in the extinction coefficient as represented by Equation 1.5 [14].

The uncertainties in the voltages were estimated based on a statistical evaluation of detector output during an experiment. The path length uncertainty was taken to be the same as what was calculated for the laser system.

The filter uncertainty was based on manufacturer specifications. The white light ODM uses UQG Optics neutral density filters. The calibrated accuracy of these filters is ±1.0 % [15]. It can be assumed that this error maintains a rectangular probability distribution and the standard uncertainty was calculated by dividing the filter error by $\sqrt{3}$ [11].

The relative combined standard uncertainty in the white extinction coefficient displayed a trend similar to the laser system. The relative uncertainty is approximately 12 % for an extinction coefficient of 6 x 10^{-4} m^{-1}. The relative uncertainty decreases rapidly as the extinction coefficient increases, however, falling below 1 % at an extinction coefficient of 0.01 m^{-1}. Figure 13 shows a chart of this trend.

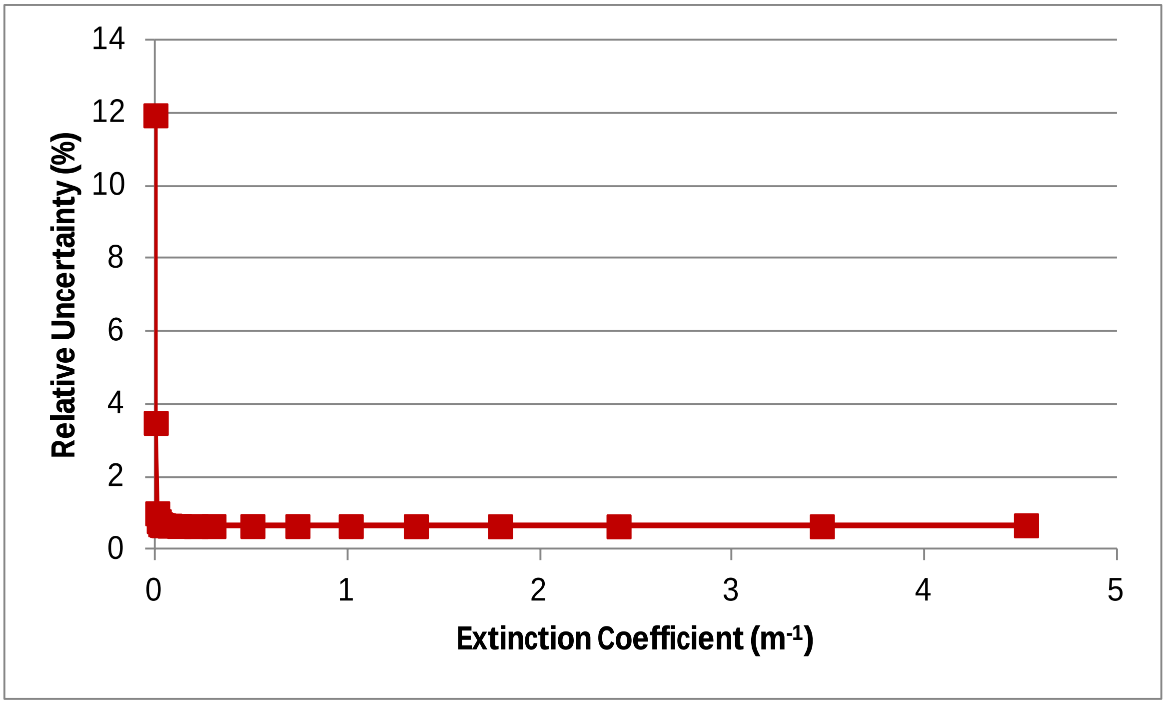

Figure 13: Relative combined standard uncertainty in white extinction coefficient

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Scope

This Technical Reference covers the use, design and specifications of Servomex 4100 Gas Species Analyzers (Servomex Analyzers) used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Servomex analyzers are used in experiments to determine the concentration of a gas species in a mixture of gases. Servomex analyzers are utilized remotely from the measurement location with a continuous sample drawn from the measurement location and pumped through the analyzers via tubing. The sample is pre-treated prior to reaching the analyzers to remove particulate materials and moisture that can damage the analyzers. This pre-treatment is accomplished through a series of particulate filters, cold traps and Drierite filters. To reduce the transit time between the sampling point and the analyzer, a by-pass flow is incorporated into the sampling apparatus.

ANALYZER DESCRIPTION

The Servomex analyzer is configured to measure oxygen, carbon monoxide and carbon dioxide. The analyzers feature two different analyzer types, paramagnetic and infrared absorption.

Oxygen (O_2) measurement utilizes the paramagnetic principle which uses the response of the gas in a varying magnetic field to determine the presence and concentration of a paramagnetic species (oxygen) in the mixture. The paramagnetic analyzer is configured to measure oxygen concentrations of 0-25%. The O_2 measurement is calibrated using nitrogen gas for the zero measurement and ambient air for the high measurement.

Carbon monoxide (CO) and carbon dioxide (CO_2) measurement utilizes an infrared absorption principle, which measures the absorption of infrared light over a wavelength range to determine the presence and concentration of species, in the mixture. The infrared analyzer is configured to measure CO concentrations of 0-1% and CO_2 concentrations of 0-10%. The CO/CO_2 measurements are calibrated using nitrogen gas for the zero measurements and a 0.8% CO/8% CO_2 gas mixture with a nitrogen balance for the high measurements.

Figure 1: Servomex 4100 Gas Purity Analyzer

RACK DESCRIPTION

The Servomex analyzers are located in racks constructed by Fire Testing Technology Limited. The rack includes the analyzer, gas train, pressure and flow control, filtering and moisture removal, power switches, and a mode selection dial which controls how the analyzer measures and calibrates.

Figure 2. Rack housing of Servomex Analyzer

DATA ACQUISITION

Servomex 4100 analyzers produce a current output over the 4-20 mA range. The current output is typically recorded using the FRL's Data Acquisition System (DAQ). To collect the output with a voltage channel, a 250 ohm resistor can be placed in parallel with the signal to convert the output signal to 1-5 volts.

Uncertainty and Accuracy

The uncertainty of the Servomex analyzers was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [1], Special Publication 1007 [2] and the NIST Uncertainty Workshop [3]. Each type of analyzer, which includes the paramagnetic O_2, infrared CO, and infrared CO_2, has unique errors. The errors of the gas analyzer at the specified ranges are given by Servomex [4] and are listed in Table 1. Note that most conservative (largest) errors assumed.

Table 1. Errors associated with the Servomex 4100 Gas Purity Analyzers

Types of Error	Paramagnetic (O_2: 0-25%)	Infrared (CO: 0-1%)	Infrared (CO_2: 0-10%)
Intrinsic Error	<0.15%	0.01%	0.1%
Linearity Error	<0.1%	0.01%	0.1%
Repeatability	<0.1%	0.01%	0.1%
Zero Drift	0.1%	0.02%	0.2%
Span Drift	0.1%	0.01%	0.1%
Output Fluctuation	<0.1%	0.01%	0.1%
Inlet Sample Pressure Effect	<0.5%	<0.03%	<0.3%
Sample Flow Effect	<0.5%	<0.03%	<0.3%

It can be assumed that the errors have a rectangular probability distribution, in which case the standard uncertainty is computed by the following equation [1]:

$$u(x) = \frac{e}{\sqrt{3}} \qquad (1.1)$$

where:

$u(x)$ = Standard uncertainty
e = Error/accuracy of the measurement

Where more than one type or uncertainty is present for a measurement, the values can be combined in quadrature to achieve a combined uncertainty, using the following equation [1-3]:

$$u_C(\mathrm{X}) = \sqrt{\sum \mathrm{u}(\mathrm{x_i})^2} \qquad (1.2)$$

where:

$u_c(X)$ = Combined standard uncertainty
$u(x_i)$ = Standard uncertainty component, as calculated by equation 1.1

Using Equation 1.2 with the values from Table 1, the following combined standard uncertainties were calculated:

Paramagnetic (O_2):	0.44%
Infrared (CO):	0.03%
Infrared (CO_2):	0.30%

References

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Scope

This Technical Reference covers the use, design and specifications of Siemens Oxymat 61 oxygen analyzers used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Oxygen analyzers are used in experiments to determine the concentration of oxygen in a mixture of gases. Oxygen analyzers are utilized remotely from the measurement location with a continuous sample drawn from the measurement location and pumped through the analyzers via tubing. The sample is pre-treated prior to reaching the analyzers to remove particulate materials and moisture that can damage the analyzers. This pre-treatment is accomplished through a series of filters, cold traps and desiccant filters. To reduce the transit time between the sampling point and the analyzer, a by-pass flow is incorporated into the sampling apparatus.

ANALYZER DESCRIPTION

The Oxymat 61 utilizes the paramagnetic principle which uses the response of the gas in a varying magnetic field to determine the presence and concentration of a paramagnetic species (oxygen) in the mixture. The paramagnetic analyzer is configured to measure oxygen concentrations of 0-25% [1]. The O_2 measurement is calibrated using zero grade nitrogen gas for the zero measurement and ambient air for the span measurement, which is 20.95%.

Figure 1: Siemens Oxymat 61 Analyzer

CART DESCRIPTION

The Oxymat 61 analyzers are located in mobile carts. The cart includes the analyzer, gas train, pressure and flow control, filtering and moisture removal, power switches, and a gas selection dials which controls how the analyzer measures and calibrates.

Figure 2. Cart housing of Siemens Oxymat 61 Analyzer

DATA ACQUISITION

Oxymat 61 analyzers produce a current output over the 4-20 mA range. The current output can be converted to a voltage output by placing a resistor in parallel with the signal. For example, the typical setup used by the FRL is to place a 250 ohm precision resistor in line to convert the output signal to 1-5 VDC.

Uncertainty and Accuracy

ASTM E2536 describes the procedure for assessing uncertainty in fire tests, which is based on the law of propagation of uncertainty [2]. In this approach, the combined standard uncertainty for a calculated output y, based on a number (i) of uncorrelated input quantities x_i, is a combination of the uncertainty of each component. The standard uncertainties are evaluated independently and combined through an analytical expression for the result. It is expressed mathematically by the following equation [2-5]:

$$u_c(y) = k\sqrt{\sum s_i^2 u(x_i)^2} \tag{0.1}$$

where:

$u_c(y)$ = Combined standard uncertainty in the output y
$u(x_i)$ = Standard uncertainty of each component x_i
s_i = Sensitivity coefficient associated with each component $(\partial/\partial x_i)$
k = Coverage factor

For measurements of time varying data such as temperature, pressure and gas concentration, E2536 identifies three components of error that should be considered: measurement error in the data acquisition system, noise in the recorded signal, and sensor calibration [2]. These are the sources that were considered for present analysis. The following sections provide details related to each component.

DATA ACQUISITION UNCERTAINTY

The FRL uses Yokogawa SMARTDAC+ GM10 data loggers paired with GX90XA I/O modules. The Siemens gas analyzers are typically connected to voltage channels with 6 VDC range. Specifications for the Yokogawa hardware include a calibrated accuracy of 0.01 % of range (6V) ±2 mV [6]. The resulting standard uncertainty, assuming a rectangular error distribution, is 1.5 mV.

ANALYZER SIGNAL UNCERTAINTY

The Oxymat 61 produces an analog 4-20 mA signal that is converted to a voltage in the 1-5 VDC range by passing through a 250 ohm resistor. The uncertainty estimate in the recorded analyzer signal included contributions from signal noise (Type A) and error associated with the resistor. The contribution associated with noise in the data came from a statistical analysis of the raw analyzer signal. The contribution from the resistor came from manufacturer specifications.

The standard uncertainty associated with noise in the analyzer signal was estimated using the sample standard deviation [2-5]. Statistics were performed on a data set where the analyzer output was steady for several minutes. The resulting standard uncertainty was 31 ppm, which corresponds to ±1.9   A using scaling for the 0-25% range setting.

To incorporate the uncertainty associated with the resistor, the conversion from current to voltage through Ohm's law was applied:

$$V = I \times R \quad (0.2)$$

where:

V = Voltage
I = Current
R = Resistance

To evaluate the combined uncertainty of the analyzer and resistor, Equation 1.1 was applied to Equation 1.2 (with k=1). The combined standard uncertainty in the analyzer voltage, $u_c(V)$, is then:

$$u_c(V) = \sqrt{(R)^2(u(I))^2 + (I)^2(u(R))^2} \tag{0.3}$$

The 250 ohm resistor has an accuracy of 0.25 ohm, which corresponds to a standard uncertainty of 0.14 ohm when a rectangular distribution is assumed. For an output of 0.0174 A (corresponding to an ambient O_2 reading in the 0-25% range setting), the combined standard uncertainty in the analyzer is:

$$u_c(V) = \sqrt{(250)^2(0.0000019)^2 + (0.0174)^2(0.14)^2} = \underline{0.0026\ V}$$

The standard uncertainties in the data acquisition system and the analyzer are combined through the root sum squared (RSS) method [2,3,5]:

$$u_c = \sqrt{(0.0015)^2 + (0.0026)^2} = 3\ mV$$

CALIBRATION UNCERTAINTY

The Siemens Oxymat 61 is equipped with a paramagnetic cell that produces a linear output. A two point calibration is performed daily using zero and span gases. The zero gas is “Zero” grade (99.99 %) bottled nitrogen. Assuming a rectangular distribution, the standard uncertainty of the zero gas is +/- 5.8 x 10^{-5} mol/mol. Laboratory air is used to span the oxygen analyzer; the concentration is taken as 20.95 %. The uncertainty associated with the oxygen span concentration is estimated to be 0.05 % O_2 [4]. This estimate was verified through a comparison with a high purity certified O_2/N_2 mixture.

The oxygen concentration is calculated from the following relationship:

$$X_{O2} = m_{O2} * V_{O2} + b_{O2} \tag{0.4}$$

Where V_{O2} is the measured voltage and m_{O2} and b_{O2} are the calibration coeffoeients:

$$m_{O2} = \frac{X_{O2_{span}} - X_{O2_{zero}}}{V_{O2_{span}} - V_{O2_{zero}}} \tag{0.5}$$

and

$$b_{O2} = X_{O2_{zero}} + m_{O2} * V_{O2_{zero}} \tag{0.6}$$

These combine to the following:

$$X_{O2} = \frac{X_{O2_{span}} - X_{O2_{zero}}}{V_{O2_{span}} - V_{O2_{zero}}} * \left(V_{O2} - V_{O2_{zero}}\right) + X_{O2_{zero}} \quad (0.7)$$

Equation 1.1 is applied to Eqn. 1.7 to calculate the combined expanded uncertainty in the oxygen mole fraction, $u(X_{O2})$. Due to algebraic complexity of the resulting expression, the calculation was performed using a spreadsheet method [7]. Using the standard uncertainties derived in this analysis, and assuming a coverage factor of k=1, the combined uncertainty is 0.06% O_2, or approximately 560 ppm.

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Technical Reference

Siemens Ultramat 23

TR016C

Contents

Scope

This Technical Reference covers the use, design and specifications of Siemens Ultramat 23 gas analyzers used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Carbon Monoxide/Carbon Dioxide (CO/CO_2) analyzers are used in experiments to determine the concentration of CO and CO_2 in a mixture of gases. CO/CO_2 analyzers are utilized remotely from the measurement location with a continuous sample drawn from the measurement location and pumped through the analyzers via tubing. The sample is pre-treated prior to reaching the analyzers to remove particulate materials and moisture that can damage the analyzers. This pre-treatment is accomplished through a series of soot filters, cold traps and desiccant filters. To reduce the transit time between the sampling point and the analyzer, a by-pass flow is incorporated into the sampling apparatus.

ANALYZER DESCRIPTION

The Ultramat 23 utilizes an infrared absorption principle, which measures the absorption of infrared light over a wavelength range to determine the presence and concentration of species, in the mixture. The infrared analyzer is configured to measure CO concentrations of 0-5% and CO_2 concentrations of 0-25%. [1] The CO/CO_2 measurements are calibrated using zero grade nitrogen gas for the zero measurements and a 0.8% CO/8% CO_2 gas mixture for the span measurements.

Figure 1: Siemens Ultramat 23 Analyzer

CART DESCRIPTION

The Ultramat 23 analyzers are located in mobile carts. The cart includes the analyzer, gas train, pressure and flow control, filtering and moisture removal, power switches, and a gas selection dials which controls how the analyzer measures and calibrates.

Figure 2. Cart housing of Siemens Ultramat 23 Analyzer

DATA ACQUISITION

Ultramat analyzers produce a current output of 4-20 mA. The current output can be converted to a voltage output by placing a resistor in parallel with the signal. For example, the typical setup used by the FRL is to place a 250 ohm resistor in parallel to convert the output signal to 1-5 volts.

Uncertainty and Accuracy

ASTM E2536 describes the procedure for assessing uncertainty in fire tests, which is based on the law of propagation of uncertainty [2]. In this approach, the combined standard uncertainty for a calculated output y, based on a number (i) of uncorrelated input quantities x_i, is a combination of the uncertainty of each component. The standard uncertainties are evaluated independently and combined through an analytical expression for the result. It is expressed mathematically by the following equation [2-5]:

$$u_c(y) = k\sqrt{\sum s_i^2 u(x_i)^2} \tag{1.1}$$

where:

$u_c(y)$	=	Combined standard uncertainty in the output y
$u(x_i)$	=	Standard uncertainty of each component x_i
s_i	=	Sensitivity coefficient associated with each component $(\partial/\partial x_i)$
k	=	Coverage factor

For measurements of time varying data such as temperature, pressure and gas concentration, E2536 identifies three components of error that should be considered: measurement error in the data acquisition system, noise in the recorded signal, and sensor calibration [2]. These are the sources that were considered for present analysis. The following sections provide details related to each component.

DATA ACQUISITION UNCERTAINTY

The FRL uses Yokogawa SMARTDAC+ GM10 data loggers paired with GX90XA I/O modules. The Siemens gas analyzers are typically connected to voltage channels with 6 VDC range. Specifications for the Yokogawa hardware include a calibrated accuracy of 0.01 % of range (6V) ±2 mV [6]. The resulting standard uncertainty, assuming a rectangular error distribution, is 1.5 mV.

ANALYZER SIGNAL UNCERTAINTY

The Ultramat 23 produces analog 4-20 mA signals that are converted to voltage in the 1-5 VDC range by passing through a 250 ohm resistor. The uncertainty estimate in the recorded analyzer signal included contributions from signal noise (Type A) and error associated with the resistor. The contribution associated with noise in the data came from a statistical analysis of the raw analyzer signal. The contribution from the resistor came from manufacturer specifications.

The standard uncertainty associated with noise in the analyzer signal was estimated using the sample standard deviation [2-5]. Statistics were performed on a data set where the analyzer output was steady for several minutes. The resulting standard uncertainties were 12 ppm for CO and 37 ppm for CO_2 which correspond to ±3.8   A and ±2.3   A, respectively, using scaling for the typical range settings.

To incorporate the uncertainty associated with the resistor, the conversion from current to voltage through Ohm's law was applied:

$$V = I \times R \tag{1.2}$$

where:

V = Voltage
I = Current
R = Resistance

To evaluate the combined uncertainty of the analyzer and resistor, Eqn. 1.1 was applied to Eqn. 1.2 (with k=1). The combined standard uncertainty in the analyzer voltage, $u_c(V)$, is then:

$$u_c(V) = \sqrt{(R)^2\big(u(I)\big)^2 + (I)^2\big(u(R)\big)^2} \tag{1.3}$$

The 250 ohm resistor has an accuracy of 0.25 ohm, which corresponds to a standard uncertainty of 0.14 ohm when a rectangular distribution is assumed. For ambient concentrations and typical range settings (0 – 5% for CO and 0 – 25% for CO_2), the combined standard uncertainty in the analyzer is 1.1 mV and 0.8 mV for CO and CO_2, respectively.

The standard uncertainties in the data acquisition system and the analyzer are combined through the root sum squared (RSS) method [2, 3, 5]. For CO the result is:

$$u_c = \sqrt{(0.0015)^2 + (0.0008)^2} = \underline{1.9\ mV}$$

Similarly, for CO_2 the result is 1.7 mV.

CALIBRATION UNCERTAINTY

The Siemens Ultramat 23 is equipped with non-dispersive infrared (NDIR) cells that produce a linear output. A two point calibration is performed daily using zero and span gases. The zero gas is "Zero" grade (99.99 %) bottled nitrogen. Assuming a rectangular distribution, the standard uncertainty of the zero gas is +/- 5.8 x 10^{-5} mol/mol. The span gas is typically a blend consisting nominally of 8% CO_2, 0.8% CO with the balance itrogen. For a primary standard mixture, the standard uncertainties in the CO_2 and CO are 0.012 % and 0.005 %, respectively.

The gas concentration is calculated from the following relationship:

$$X_i = m_i * V_i + b_i \tag{1.4}$$

Where *i* represents CO or CO_2, V_i is the measured voltage and m_i and b_i are the calibration coeffoeients:

$$m_i = \frac{X_{i_{span}} - X_{i_{zero}}}{V_{i_{span}} - V_{i_{zero}}} \tag{1.5}$$

and

$$b_i = X_{i_{zero}} + m_i * V_{i_{zero}} \tag{1.6}$$

These combine to the following:

$$X_i = \frac{X_{i_{span}} - X_{i_{zero}}}{V_{i_{span}} - V_{i_{zero}}} * \left(V_i - V_{i_{zero}}\right) + X_{i_{zero}} \tag{1.7}$$

Equation 1.1 is applied to Eqn. 1.7 to calculate the combined expanded uncertainty in the mole fraction, $u(X_i)$. Due to algebraic complexity of the resulting expression, the calculation was performed using a spreadsheet method [7]. Using the standard uncertainties derived in this analysis, and assuming a coverage factor of k=1, the combined uncertainties for are 0.053 % CO and 0.052 % CO_2, or approximately 530 ppm and 520 ppm, respectively.

References

1. "Ultramat 23: Gas Analyzers for IR-Absorbing Gases and Oxygen Manual, Operating Instructions," Siemens, 2005.
2. ASTM E2536-09, *Standard Guide for Assessment of Measurement Uncertainty in Fire Tests*, ASTM International, West Conshohocken, Pennsylvania, 2015.
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5. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.
6. "SMARTDAC+ Data Acquisition and Control, Data Acquisition System GM," Yokogawa, 2014
7. Kragten, J., "Calculating Standard Deviations and Confidence Intervals with a Universally Applicable Spreadsheet Technique", *Analyst*, Vol. 119, pp 2161 – 2165, October, 1994.

Scope

This Technical Reference covers the use, design and specifications of the Sartorius-Scale-450 kg scale used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

The Sartorius-Scale-450 kg weighing device is used primarily for mass measurements up to a capacity of 450 kg (1000 lb_m). This scale offers a modular design incorporating the use of four load cells, a weighing platform, and an indicator unit. The components of Sartorius-Scale-450 kg weighing device are calibrated as one unit in accordance with manufacturer and ATF specifications.

Load Cell

The Sartorius-Scale-450 kg uses four load cells (GWT Type 011462/500 lb) each with a capacity of 225 kg (500 lb_m). Two load cells are loaded in compression and two load cells are loaded in tension, allowing for a maximum measurement capacity of 450 kg (1000 lb_m). The load cells respond to an applied load positioned on a weighing platform and relays an electrical response to a Sartorius model PR6130 Cable Junction Box. The responses from the four load cells are then combined into a single analog electrical signal and transmitted to the indicator unit.

Weighing Platform

The Sartorius-Scale-450 kg uses a Sartorius model CAPPU-1000KK-LU weighing platform with a 91.4 cm x 91.4 cm (36 inch x 36 inch) steel load plate. The platform must be leveled manually by the user prior to testing to reduce measurement errors caused by the angular orientation of the scale. Adjusting the supports on each of the corners of the weighing platform raises or lowers each corner if the scale is used on an uneven surface.

Indicator

The Sartorius-Scale-450 kg uses a Sartorius Combics 3 model CIS3-U indicator unit to provide a digital display of the analog electrical output signal from the load cells. The indicator offers a maximum readability of 0.02 kg (0.05 lb_m) at a 450 kg (1000 lb_m) capacity. The indicator also contains functions that zero, tare, and offset mass measurements to the full capacity defined by the indicator.

CONNECTING TO THE DATA ACQUISITION

The Sartorius Combics 3 indicator allows for transmitting data to the data acquisition (DAQ) system by means of a network cable connected to a FireTOSS jack.

Uncertainty

The measurement uncertainty was determined using guidelines in the National Institute of Standards and Technology (NIST) Technical Note 1297 [1], Special Publication 1007 [2], and the NIST Uncertainty Workshop [3]. The uncertainty of mass measurements includes the allowable uncertainty, random uncertainty, and combined uncertainty.

ALLOWABLE UNCERTAINTY

The allowable uncertainty is determined from allowable tolerances provided in the manufacturer's specifications [4] and NIST Handbook 44 [5]. The allowable tolerances defined by the manufacturer are:

the linearity as ± 0.05 kg (0.1 lb_m)

the repeatability as ± 0.07 kg (0.15 lb_m)

Additional tolerance requirements for the weighing device provided by NIST Handbook 44 are:

the tolerance as ± 0.23 kg (0.5 lb_m)

the zero balance as ± 0.23 kg (0.5 lb_m)

the sensitivity as ± 0.05 kg (0.1 lb_m)

the temperature effect on the minimum dead load output as ± 0.02 kg (0.05 lb_m) over a temperature change of 5°C (9°F)

The error associated with each tolerance, *T*, assumes a rectangular probably distribution and can be calculated by dividing the tolerance by $\sqrt{3}$ [1]. The allowable uncertainty, U_A, can be calculated by combining the error components in quadrature using Equation 1.1.

$$\boldsymbol{U_A} = \sqrt{\sum \left(\frac{T}{\sqrt{3}}\right)^2} \qquad (1.1)$$

The allowable uncertainty for the weighing device is ± 0.19 kg (± 0.43 lb_m) or ± 0.04 % of a 450 kg (1000 lb_m) capacity.

RANDOM UNCERTAINTY

The random uncertainty, U_R, is determined from random errors that occur naturally during operation. The errors are determined using sample measurements taken during typical test conditions. The random uncertainty is calculated by applying the standard deviation, *S*, and the number of measurements, *n*, in a sample to Equation 1.2.

$$U_R = \frac{S}{\sqrt{n}} \tag{1.2}$$

The random uncertainty is based on a sample containing 600 measurements of a 90 kg (200 lb_m) mass. The random uncertainty for the weighing device is ± 0.00 kg (0.00 lb_m) or 0 % of a 450 kg (1000 lb_m) capacity.

COMBINED UNCERTAINTY

The combined uncertainty, U_C, is determined from the combining the allowable uncertainty and random uncertainty in quadrature. The combined uncertainty is calculated using Equation 1.3.

$$U_C = \sqrt{\left(U_A{}^2 + U_R{}^2\right)} \tag{1.3}$$

The combined uncertainty for the weighing device is ± 0.19 kg (± 0.43 lb_m) or ± 0.04 % of a 450 kg (1000 lb_m) capacity.

References

1. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, 1993.
2. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, Gaithersburg, MD, 2003.
3. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.

4. McGovern, M., "Satorius_CAPP4U-1000KK-LU_Loadcell_GWT011462.xls", Sartorius AG, February 17, 2011
5. "Handbook 44: Specifications, Tolerances, and Other Technical Requirements for Weighing Devices," National Institute of Standards and Technology, Gaithersburg, MD, 2010.

Scope

This Technical Reference covers the use, design and specifications of the Sartorius-Scale-30 kg scale used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

The Sartorius-Scale-30 kg weighing device is used primarily for mass measurements up to a capacity of 30 kg (60 lb_m). This scale offers a modular design incorporating the use of a load cell, a weighing platform, and an indicator unit. The components of Sartorius-Scale-30 kg weighing device are calibrated as one unit in accordance with manufacturer and ATF specifications.

Load Cell

The Sartorius-Scale-30 kg uses one Sartorius load cell (model 03167124) with a capacity of 30 kg (60 lb_m). The load cell responds to an applied load positioned on a weighing platform and relays an electrical response to a junction box with amplifier. The electrical signal is then transmitted to the indicator unit.

Weighing Platform

The Sartorius-Scale-30 kg uses a Sartorius model CAPP1U-50DD-LU weighing platform with a 45.7 cm x 45.7 cm (18 inch x 18 inch) stainless steel load plate. The platform is NEM4/IP65 to withstand everyday washdown environments. The platform must be leveled manually by the user prior to testing to reduce measurement errors caused by the angular orientation of the scale. Adjusting the supports on each of the corners of the weighing platform raises or lowers each corner if the scale is used on an uneven surface.

Indicator

The Sartorius-Scale-30 kg uses a Sartorius Combics 2 Model CAISL2-U indicator unit to provide a digital display of the analog electrical output signal from the load cell. The indicator offers a maximum readability of 0.001 kg (0.002 lb_m) at a 30 kg (60 lb_m) capacity. The indicator also contains functions that zero, tare, and offset mass measurements to the full capacity defined by the indicator.

CONNECTING TO THE DATA ACQUISITION

The Sartorius Combics 2 indicator allows for transmitting data to the data acquisition (DAQ) system by means of a network cable connected to a FireTOSS jack.

Uncertainty

The uncertainty of the mass measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [1], Special Publication 1007 [2], and the NIST Uncertainty Workshop [3]. The uncertainty of mass measurements includes the allowable uncertainty, random uncertainty, and combined uncertainty.

ALLOWABLE UNCERTAINTY

The allowable uncertainty is determined from allowable tolerances provided in the manufacturer's specifications and NIST Handbook 44. The allowable tolerances defined by the manufacturer [4] are:

the linearity as ± 0.0045 kg (0.01 lb_m)

the span as ± 0.0045 kg (0.01 lb_m)

the off-center load eccentricity as ± 0.0091 kg (0.02 lb_m)

the reproducibility as ± 0.0045 kg (0.01 lb_m)

Additional tolerance requirements for the weighing device provided by NIST Handbook 44 [5] are:

the tolerance as ± 0.0025 kg (0.0055 lbm)

the zero balance as ± 0.0015 kg (0.0331 lbm)

the sensitivity as ± 0.0010 kg (0.0022 lbm)

the temperature effect on the minimum dead load output as ± 0.0005 kg (0.0011 lbm) over a temperature change of 5°C (9°F)

The error associated with each tolerance, *T*, assumes a rectangular probably distribution and can be calculated by dividing the tolerance by $\sqrt{3}$ [1]. The allowable uncertainty, U_A, can be calculated by combining the error components in quadrature using Equation 1.1.

$$\boldsymbol{U_A} = \sqrt{\sum \left(\frac{\boldsymbol{T}}{\sqrt{3}}\right)^2} \tag{1.1}$$

The allowable uncertainty for the weighing device is ± 0.0112 kg (0.0247 lb_m) or ± 0.04% of a 30 kg capacity.

RANDOM UNCERTAINTY

The random uncertainty, U_R, is determined from random errors that occur naturally during operation. The errors are determined using sample measurements taken during typical test conditions. The random uncertainty is calculated by applying the standard deviation, *S*, and the number of measurements, *n*, in a sample to Equation 1.2.

$$U_R = \frac{S}{\sqrt{n}} \tag{1.2}$$

The random uncertainty is based on a sample containing 600 measurements of a 22.7 kg (50 lb_m) mass. The random uncertainty for the weighing device is ± 0.0002 kg (0.0004 lb_m) or 0.00% of a 30 kg capacity.

COMBINED UNCERTAINTY

The combined uncertainty, U_C, is determined from the combining the allowable uncertainty and random uncertainty in quadrature. The combined uncertainty is calculated using Equation 1.3.

$$U_C = \sqrt{\left(U_A{}^2 + U_R{}^2\right)} \tag{1.3}$$

The combined uncertainty for the Sartorius-Scale-30 kg weighing device is ± 0.0112 kg (0.0247 lb_m) or ± 0.04% of a 30 kg capacity.

References

1. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, 1993.
2. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, Gaithersburg, MD, 2003.
3. Guthrie, W. & Liu, H., "Hands-on Workshop on Estimating and Reporting Measurement Uncertainty," National Institute of Standards and Technology, Presentation given to CPSC, 2007.
4. "Service Manual Satorius Combics 1 Combics 2", Publication Number WCI5005-e03104, Sartorius AG, Goettingen, Germany, October 2003

5. "Handbook 44: Specifications, Tolerances, and Other Technical Requirements for Weighing Devices," National Institute of Standards and Technology, Gaithersburg, MD, 2010.

Scope

This Technical Reference covers the use, design and specifications of the Sartorius-Scale-150 kg scale used in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

The Sartorius-Scale-150 kg weighing device is used primarily for mass measurements up to a capacity of 150 kg (300 lb_m). This scale offers a modular design incorporating the use of a load cell, a weighing platform, and an indicator unit. The components of Sartorius-Scale-150 kg weighing device are calibrated as one unit in accordance with manufacturer and ATF specifications.

Load Cell

The Sartorius-Scale-150 kg uses one load cell (model 03167124) with a capacity of 150 kg (300 lb_m). The load cell responds to an applied load positioned on a weighing platform and relays an electrical response to a junction box with amplifier. The electrical signal is then transmitted to the indicator unit.

Weighing Platform

The Sartorius-Scale-150 kg uses a Sartorius model CAPP1U-250GG-LU weighing platform with a 61 cm x 61 cm (24 inch x 24 inch) stainless steel load plate. The platform is NEM4/IP65 to withstand everyday washdown environments. The platform must be leveled manually by the user prior to testing to reduce measurement errors caused by the angular orientation of the scale. Adjusting the supports on each of the corners of the weighing platform raises or lowers each corner if the scale is used on an uneven surface.

Indicator

The Sartorius-Scale-150 kg uses a Sartorius Combics 2 Model CAIS2-U indicator unit to provide a digital display of the analog electrical output signal from the load cell. The indicator offers a maximum readability of 0.005 kg (0.01 lb_m) at a 150 kg (300 lb_m) capacity. The indicator also contains functions that zero, tare, and offset mass measurements to the full capacity defined by the indicator.

CONNECTING TO THE DATA ACQUISITION

The Sartorius Combics 2 indicator allows for transmitting data to the data acquisition (DAQ) system by means of a network cable connected to a FireTOSS jack.

Uncertainty

The uncertainty of the mass measurements was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Technical Note 1297 [1], Special Publication 1007 [2], and the NIST Uncertainty Workshop [3]. The uncertainty of mass measurements includes the allowable uncertainty, random uncertainty, and combined uncertainty.

ALLOWABLE UNCERTAINTY

The allowable uncertainty is determined from allowable tolerances provided in the manufacturer's specifications and NIST Handbook 44. The allowable tolerances defined by the manufacturer [4] are:

the linearity as ± 0.0227 kg (0.05 lb_m)

the span as ± 0.0454 kg (0.1 lb_m)

the off-center load eccentricity as ± 0.0454 kg (0.1 lb_m)

the reproducibility as ± 0.0227 kg (0.05 lb_m)

Additional tolerance requirements for the weighing device provided by NIST Handbook 44 [5] are:

the tolerance as ±0.0100 kg (0.0220 lb_m)

the zero balance as ± 0.0750 kg (0.165 lb_m)

the sensitivity as ± 0.0040 kg (0.009 lb_m)

the temperature effect on the minimum dead load output as ± 0.0020 kg (0.004 lb_m) over a temperature change of 5˚C (9˚F)

The error associated with each tolerance, *T*, assumes a rectangular probably distribution and can be calculated by dividing the tolerance by $\sqrt{3}$ [1]. The allowable uncertainty, U_A, can be calculated by combining the error components in quadrature using Equation 1.1.

$$\boldsymbol{U_A} = \sqrt{\sum \left(\frac{\boldsymbol{T}}{\sqrt{3}}\right)^2} \qquad (1.1)$$

The allowable uncertainty for the weighing device is ± 0.0607 kg (0.114 lb_m) or ± 0.002% of a 150 kg capacity.

RANDOM UNCERTAINTY

The random uncertainty, U_R, is determined from random errors that occur naturally during operation. The errors are determined using sample measurements taken during typical test conditions. The random uncertainty is calculated by applying the standard deviation, S, and the number of measurements, n, in a sample to Equation 1.2.

$$U_R = \frac{S}{\sqrt{n}} \qquad (1.2)$$

The random uncertainty is based on a sample containing 600 measurements of a 90.7 kg (200 lb_m) mass. The random uncertainty for the weighing device is ± 0.00 kg (0.00 lb_m) or 0 % of a 150 kg capacity.

COMBINED UNCERTAINTY

The combined uncertainty, U_C, is determined from the combining the allowable uncertainty and random uncertainty in quadrature. The combined uncertainty is calculated using Equation 1.3.

$$U_C = \sqrt{(U_A{}^2 + U_R{}^2)} \qquad (1.3)$$

The combined standard uncertainty for the Sartorius-Scale-150 kg is ± 0.0607 kg (0.114 lb_m) or ± 0.002 % of a 150 kg capacity.

References

1. Taylor, B. N., & Kuyatt, C. E., "NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, 1993.
2. Bryant, A.R., Ohlemiller, T.J., Johnsson, E.L, Hamins, A., Grove, B.S., Guthrie, W.F., Maranghides, A., Mulholland, G.W., "Special Publication 1007," National Institute of Standards and Technology, Gaithersburg, MD, 2003.
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