Welcome to Webinar 5!

Data Analysis

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Aprovecho Research Center

OSPREY FOUNDATION

Agenda

1. Introduction
2. Energy Calculations
3. Emission Calculations
4. Reviewing a Level 2
5. Standard Values

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1 Introduction

It’s important to understand what is calculated, how it’s calculated, and what range is reasonable so we can

- Understand the results
- Have confidence in the data
- Know when something has gone wrong
- Understand why each part of testing and maintenance is important

Goal: Understand data enough to review results, find errors, and fix metrics

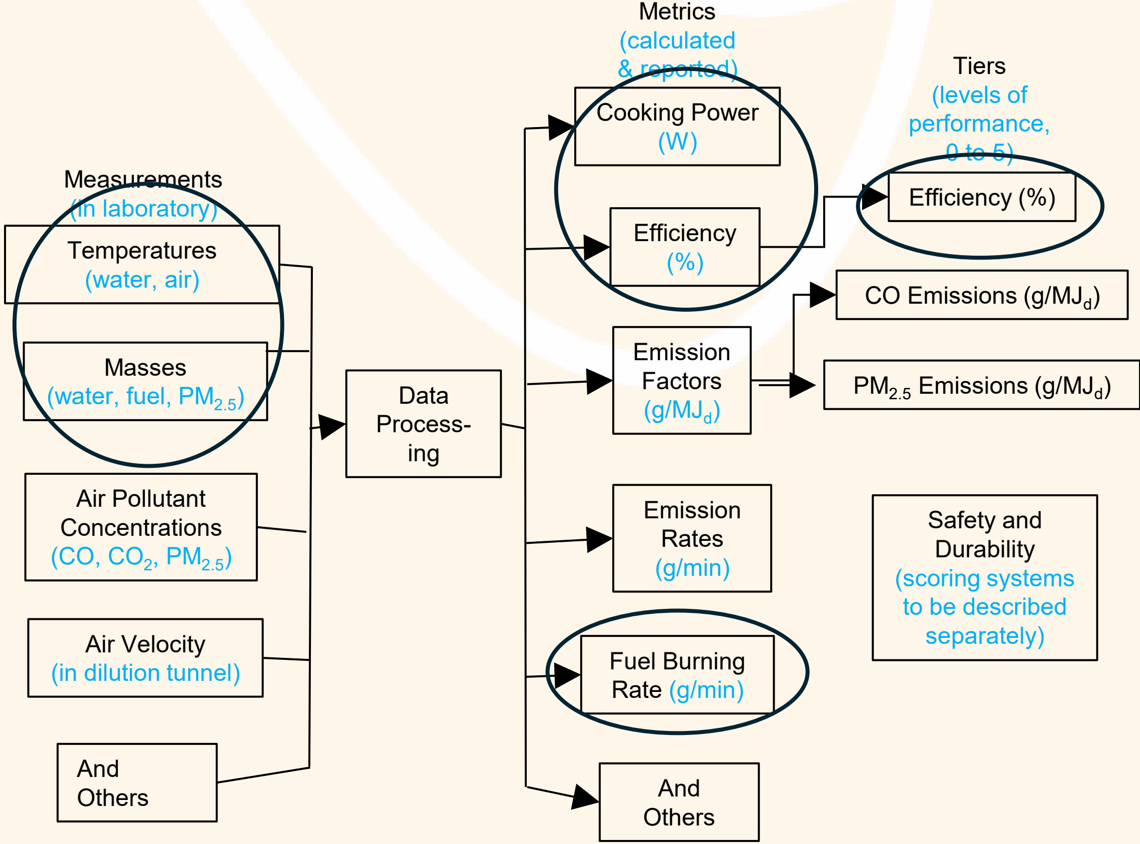
2 Energy Calculations

Energy calculations involve all the values written in the data sheet

- Can be done without a LEMS

Important Metrics:

- Thermal Efficiency
- Charcoal mass and energy productivity
- Firepower
- Cooking power
- Burn rate

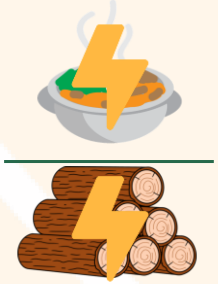


2 Energy Calculations

Thermal Efficiency

What goes into it:

- Initial and final mass of water
- Empty pot weight
- Initial and final temperature of water
- Ambient pressure
- Initial and final mass of fuel
- Final mass of charcoal
- Higher heating value of fuel and charcoal
- Moisture content of fuel
- Fuel and charcoal lower heating value conversion factor



$$TEwith\ char = \frac{\left(C_{p,water} * m_{water} * \Delta T\right) + \left(\Delta m_{water} * H_{vap}\right)}{\left(m_{fuel} * EHV_{fuel}\right) - \left(m_{char} * EHV_{char}\right)}$$

$$TEwithout\ char = \frac{\left(C_{p,water} * m_{water} * \Delta T\right) + \left(\Delta m_{water} * H_{vap}\right)}{\left(m_{fuel} * EHV_{fuel}\right)}$$

2 Energy Calculations

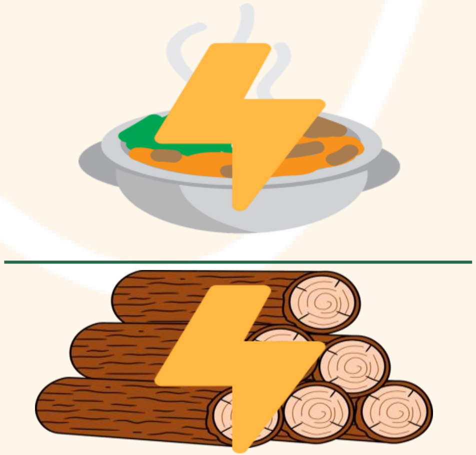
Thermal Efficiency

What is the normal range:

- Most stoves will be between 15-60%
- Charcoal stoves may be higher during low power
- Higher or lower doesn't automatically mean it is incorrect but the values should be examined
- Below 0 or above 100 is wrong

What to do if the value is wrong:

- Look at all the inputs. Compare to written data sheet
- Compare to a similar test. What varies in inputs? Pay attention to water evaporated, charcoal produced, fuel used
- Sometimes a value was entered or written incorrectly.
- Sometimes something in the test went wrong. Water spilling or boiling over, water boiling off, wood counted as charcoal.
- Thermal efficiency with char only valid for wood stoves



2 Energy Calculations

Char Energy and Mass Productivity

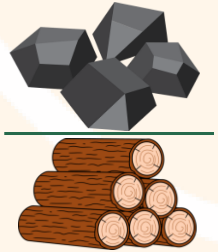
What goes into it:

- Initial and final mass of fuel
- Final mass of charcoal
- Higher heating value of fuel and charcoal
- Moisture content
- Fuel and charcoal lower heating value conversion factor

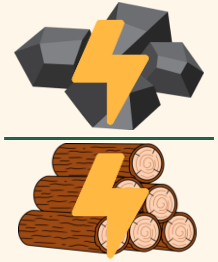
What is the normal range:

- Between 0-50%
- Above 50% doesn't mean it's wrong but it should be evaluated. Did the stove make a lot of charcoal? High char mass productivity correlates to a large difference in the two thermal efficiencies
- Below 0 and above 100 is wrong
- Ignore this metric for charcoal stoves – only valid for wood stoves

$$Char\ mass\ productivity = \frac{m_{char}}{m_{fuel}} * 100$$



$$Char\ energy\ productivity = \frac{m_{char} * EHV_{char}}{m_{fuel} * EHV_{fuel}} * 100$$



2 Energy Calculations

Firepower and Burn rate

What goes into it:

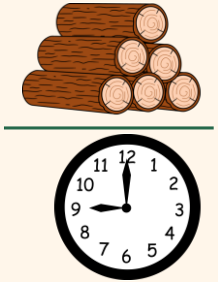
- Initial and final mass of fuel
- Final mass of charcoal
- Higher heating value of fuel and charcoal
- Fuel and charcoal correction value
- Phase start and end time

What is the normal range:

- Wood: 1 to 10 kW
- Charcoal: 0.5 to 6 kW
- High firepower is correlated with higher PM emission rates → high emission factors. If PM data is high, check if firepower was high

$$firepower = \frac{m_{fuel} * EHV_{fuel} - m_{char} * EHV_{char}}{time}$$

$$burn\,rate = \frac{m_{fuel} - m_{char}}{time}$$



2 Energy Calculations

Cooking power

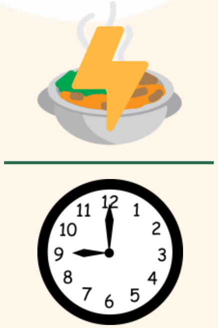
What goes into it:

- Initial and final water mass
- Empty pot weight
- Initial and final water temperature
- Ambient pressure
- Phase start and end times

What is the normal range:

- 0.25 to 6 kW

$$\textit{cooking power} = \frac{\left(C_{p,water} * m_{water} * \Delta T\right) + \left(\Delta m_{water} * H_{vap}\right)}{time}$$



3 Emissions Calculations

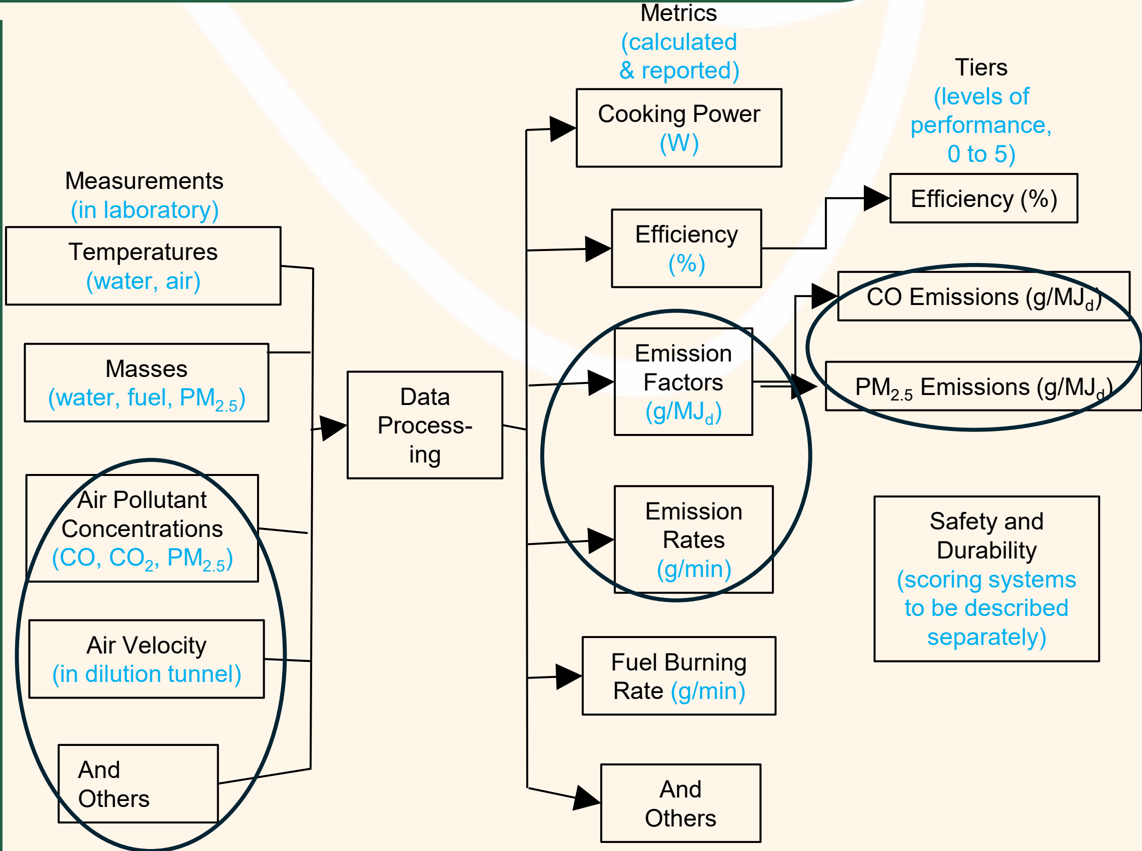
Emission Calculations Involve

- Inputs and outputs from energy calculations
- Emissions data
- Background subtraction methods
- Filter data

A lot more goes into emissions metrics so it's very important to verify the inputs and outputs

Important Metrics:

- Emission Factors
- Emission Rates
- Emissions per MJ Delivered
- Carbon Ratio



3 Emissions Calculations

Emission Rate

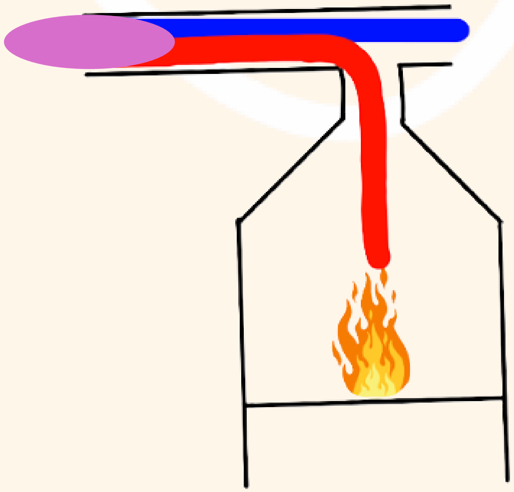
The average concentration of an emissions species multiplied by the average volumetric flow rate through the duct

When we measure concentration, we measure emissions from the stove and the dilution air, that's why having a good background is important

More dilution air = more flow rate

Emission rate is dependent on time

$$\begin{aligned} &emission\ rate(species) \\ &= concentration(species)\ * volumetric\ flow\ rate \end{aligned}$$



3 Emissions Calculations

Emission Rate – Concentration

Converting PPM to g/m^3

Inputs:

- Sensor ppm readings
- Phase start and end times
- Initial and final ambient pressure
- Static pressure in the dilution tunnel (velocity traverse)
- Temperature in the dilution tunnel
- Inputs specifically for PM
- ❑ Tare and gross filter masses
- ❑ Gravimetric flow rate

$$emission\ rate\ (species) = \boldsymbol{concentration\ (species)} * volumetric\ flow\ rate$$

$$concentration(species) = \frac{\boldsymbol{average\ ppm(species)} * MW_{species} * \boldsymbol{P_{duct}}}{\boldsymbol{T_{duct}} * R}$$

$$P_{duct} = \boldsymbol{P_{amb}} - \boldsymbol{static\_pressure\_dil\_tunnel}$$

$$concentration\ PM = \frac{\boldsymbol{m_{gross}} - \boldsymbol{m_{tare}}}{\boldsymbol{time} * \boldsymbol{flow_{grav}}}$$

3 Emissions Calculations

Emission Rate – Volumetric Flow Rate

Inputs:

- Phase start and end times
- Initial and final ambient pressure
- Static pressure in the dilution tunnel (velocity traverse)
- Factory flow cal – determined by duct diameter, 15.3 for all 6” ducts
- Flowgrid cal factory – velocity traverse
- Pressure from flowgrid
- Temperature in the dilution tunnel

$$emission\ rate = concentration\ * \boldsymbol{volumetric\ flow\ rate}$$

$$volumetric\ flow\ rate = \frac{mass\ flow}{density}$$

$$mass\ flow = \boldsymbol{factory\ flow\ cal}\ * \boldsymbol{flowgrid\ cal\ factor}\ * \sqrt{\frac{\boldsymbol{flow}}{\boldsymbol{P_{duct}} * (\boldsymbol{T_{duct}})}}$$

$$density = \frac{MW_{air} * \boldsymbol{P_{duct}}}{R * (\boldsymbol{T_{duct}})}$$

3 Emissions Calculations

Carbon Ratio

The ratio of carbon measured out of the system to carbon into the system

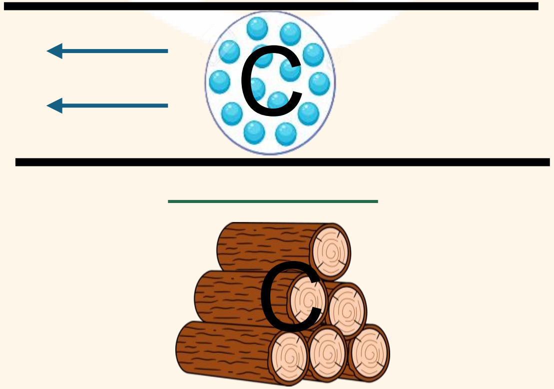
Really good indicator if measurements or calibrations are off

Should be between 0.8 – 1.2

Carbon balance of 1 means all the carbon into the system was captured and measured

Not required by ISO but HIGHLY recommended

$$carbon\ ratio = \frac{C_{out}}{C_{in}}$$



3 Emissions Calculations

Carbon Ratio – Carbon Out

Inputs

- Emission rates
- Phase start and end times
- Filter masses

What goes wrong:

- Flow rate measurements are off
- Not a total capture system
- Sample gas leaks out or dilution air is leaking in
- Calibration of CO and CO2

$$carbon\ ratio = \frac{\boldsymbol{C_{out}}}{C_{in}}$$

$$C_{out} = \frac{\boldsymbol{CO_{tot}} * MW_C}{MW_{CO}} + \frac{\boldsymbol{CO_{2,tot}} * MW_C}{MW_{CO_2}} + 0.91 * \boldsymbol{PM_{tot}}$$

$$m_{tot}(species) = \sum_{end}^{start} ER_{species} * sample\ period$$

3 Emissions Calculations

Carbon Ratio – Carbon In

Inputs

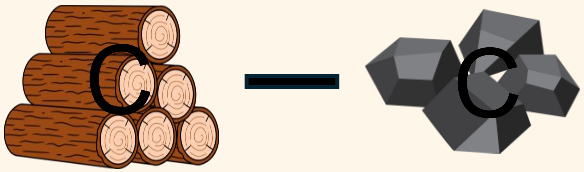
- Carbon fraction fuel
- Start and end mass of fuel
- Moisture content of fuel
- Carbon fraction of charcoal
- Start and end mass of charcoal
- Moisture content of charcoal

What goes wrong:

- Some fuel is input as charcoal
- Masses are wrong
- Carbon fractions are off – more important for charcoal stoves

$$carbon\ ratio = \frac{C_{out}}{\boldsymbol{C_{in}}}$$

$$C_{in} = C_{frac,fuel} * m_{fuel} - C_{frac,char} * m_{char}$$



3 Emissions Calculations

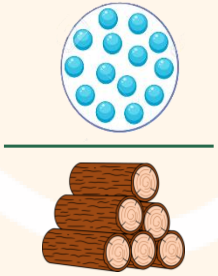
Emission Factors

- The ratio of the mass of emissions and the mass of fuel or energy from fuel
- Reported as per dry fuel mass in ISO but could be per wet fuel as well
- Independent of time

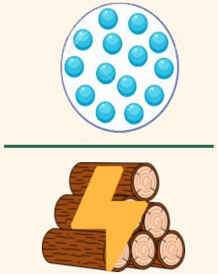
Inputs

- Phase start and end times
- Emission rates
- Initial and final fuel mass
- Fuel moisture content
- Higher heating value of fuel and charcoal
- Fuel and charcoal correction value

$$emission\ factor(fuel) = \frac{m_{tot}}{m_{fuel}}$$



$$emission\ factor(energy) = \frac{m_{tot}}{m_{fuel} * EHV_{fuel}}$$



3 Emissions Calculations

Emissions Per MJ Delivered

- Phase start and end times
- Emission rates
- Initial and final fuel mass
- Fuel moisture content
- Higher heating value of fuel and charcoal
- Fuel and charcoal correction value

- PM: Tier 0 >1030, Tier 5 ≤5 mg/MJd
- CO: Tier 0 >18.3, Tier 5 ≤3.0 g/MJd

$$emission\ per\ MJ\ delivered = \frac{m_{tot}}{useful\ energy\ delivered}$$

$$useful\ energy\ delivered = \left(C_{p,water} * m_{water} * \Delta T\right) + (\Delta m_{water} * H_{vap})$$

4 Reviewing a Level 2

The level 2 report is a valuable tool that allows us to quickly identify potential inconsistencies in our data

Step 1:

- Look at standard deviations and confidence intervals
- Standard deviations tell us how consistent our test results are
- Confidence intervals tell us that based on our data, 90% of retest results would be in the given range
- Small standard deviation/confidence interval: all test values are similar
- Large standard deviation/confidence interval: 1 or more tests values are significantly different and should be looked at
- ISO tiers are based on the conservative end (low for TE and high for CO and PM) of the confidence interval

Metric		Test Sequence Phase				Tier Rating
		High	Medium	Low	Combined	
Thermal Efficiency with char (%)	Mean	26.9	-	60.4	43.7	3
	SD	1.1	-	5.6	2.5	
	90% CI	25.0 - 28.8	-	50.9 - 69.9	39.5 - 47.9	

Stove 1: Really consistent on high power
Standard deviation good on low power but confidence interval is high. A test might be off

Metric		Test Sequence Phase				Tier Rating
		High	Medium	Low	Combined	
Thermal Efficiency without char (%)	Mean	53.5	108.8	67.3	62	0
	SD	30.8	-	29.2	32.6	
	90% CI	1.6 - 105.4	-	18.1 - 116.5	6.9 - 117.0	
Thermal Efficiency with char (%)	Mean	60.8	113.2	74.3	68	0
	SD	35.2	-	38	37.3	
	90% CI	1.4 - 120.2	-	10.2 - 138.4	5.1 - 130.8	

Stove 2: Huge standard deviations and confidence intervals, something is wrong

4 Reviewing a Level 2

Step 2:
Review values between tests for each phase

Are values similar to each other?

Do the ranges make sense?

Does anything look wrong?

Trace values back to inputs

Metric	Units	Mean	SD	Test 1	Test 2	Test 3
Fuel mass, dry	kg	0.2	0	0.2	0.2	0.2
Thermal efficiency with char	%	26.9	1.1	27.8	25.7	27.4
PM2.5 mass per useful energy delivered	mg/MJ	296.1333	125.5806	151.8	380.4	356.2

Stove 1: At high power, all three efficiencies are very similar but one of our PM results are significantly different

Metric	Units	Mean	SD	Test 1	Test 2	Test 3
Fuel mass, dry	kg	0	0	0.1	0	0
Thermal efficiency with char	%	60.4	5.6	53.9	63.8	63.5

Stove 1: At low power we can see why the confidence interval was high, 1 test is 10% lower – what happened?

4 Reviewing a Level 2

Step 3:

Check quality control

- Quality checks should pass
- Non-passing introduces error
- Quality control can take a while but it get easier with practice and saves time in the end
- Quality control is required for ISO

Leak Checks

- Ensures all of the sample get to the sensor box/filter
- Ensures no additional unmeasured dilution air is added

PM2.5 Quality Control			
Gravimetric A Leak Rate	l/min	0.000492	0.000492
Gravimetric A Leak Check	Pass/Fail	PASS	PASS
Gravimetric B Leak Rate	l/min	0.000393	0.000393
Gravimetric B Leak Check	Pass/Fail	PASS	PASS

Dilution Tunnel Quality Control			
Hood Total Capture	pass/fail	PASS	PASS
Flow Grid Calibration Factor	N/A		
Negative Pressure Leak Rate	%	0.000000	0.000000
Negative Pressure Leak Check	pass/fail	PASS	PASS
Positive Pressure Leak Rate	%	0.000000	0.000000
Positive Pressure Leak Check	pass/fail	PASS	PASS
Static Pressure of Dilution Tunnel	N/A		

Gas Sensor Quality Control			
Gas Sensor Leak Rate	l/min	0	0
Gas Sensor Leak Check	Pass/Fail	PASS	PASS

4 Reviewing a Level 2

Step 3:

Check quality control

Bias and Drift Checks

- Checks the calibration of CO and CO2
- Checks that sensors/conditions didn’t drift significantly during testing

	CO	
Zero Bias	%	0.4
Span Bias	%	0.4
Zero Drift	%	0.3
Span Drift	%	-0.6
Zero Bias QC	Pass/Fail	PASS
Span Bias QC	Pass/Fail	PASS
Zero Drift QC	Pass/Fail	PASS
Span Drift QC	Pass/Fail	PASS

4 Reviewing a Level 2

Step 3:

Check quality control

Gravimetric Checks

- Don't take that long
- Check the balance calibration with the calibration weight
- Make sure filter mass difference was high enough (double filters may be needed)
- Make sure gravimetric flow rate didn't decrease
- Track desiccator conditions

High Power			
Mass Scattering Cross Section High Power	m^2/g	0.012	0
Net Filter Weight High Power	g	0.001	0.002
Balance Cal Check High Power	pass/fail	pass	pass
Filter Mass Threshold High Power	pass/fail	PASS	PASS
Tare Sets Till Convergence High Power	#	1	1
Gross Sets Till Convergence High Power	#	1	1
Gravimetric A Flow Rate Check High Power	pass/fail	PASS	PASS
Gravimetric B Flow Rate Check High Power	pass/fail	PASS	PASS
Desicator Temperature High Power	C	28	28
Desicator Relative Humidity High Power	%	32	32

4 Reviewing a Level 2

Step 3:

Check quality control

- Some quality control is automatically entered/calculated from the data
- Dilution tunnel flow check: did the flow rate in the dilution tunnel vary?
- Temperature check: Did the room temperature stay in an acceptable range?

Dilution Tunnel Quality Control				
Hood Total Capture	pass/fail	PASS	PASS	
Flow Grid Calibration Factor	N/A	15.3	15.3	
Static Pressure of Dilution Tunnel	inH2O	0.75	0.75	
High Power				
Dilution Tunnel Average Flow Rate High Power	m^3/sec	0.081	0.081	
Dilution Tunnel Standard Deviation High Power	m^3/sec	0.001	0.001	
Dilution Tunnel Flow Check	pass/fail	PASS	PASS	

Environmental Quality Control			
Initial Wind Speed	m/s	0	0
Final Wind Speed	m/s	0	0
Wind Speed Check	Pass/Fail	PASS	PASS
Initial Room Temperature	C	27	29
Final Room Temperature	C	28	27
Temperature Check	Pass/Fail	PASS	PASS

4 Reviewing a Level 2

Step 4:

Check carbon balance

Step 5:

Fix anything identified and approve

Carbon Balance				
High Power				
Carbon In High Power	g	302.1	306.6	303
Carbon Out High Power	g	302.025	283.934	307.898
Carbon In to Carbon Out	g/g	1	0.926	1.016
Medium Power				
Carbon In Medium Power	g	150.5	149.6	148.7
Carbon Out Medium Power	g	155.004	156.985	160.641
Carbon In to Carbon Out	g/g	1.03	1.049	1.08
Low Power				
Carbon In Low Power	g	107.7	107.7	109.5
Carbon Out Low Power	g	118.795	115.982	117.977
Carbon In to Carbon Out	g/g	1.103	1.077	1.077

Stove 1: Great carbon balances

Carbon Balance				
High Power				
Carbon In High Power	g	196.222	185.279	182.628
Carbon Out High Power	g	115.896	446.621	308.044
Carbon In to Carbon Out	g/g	0.591	2.411	1.687
Medium Power				
Carbon In Medium Power	N/A			
Carbon Out Medium Power	N/A			
Carbon In to Carbon Out	N/A			
Low Power				
Carbon In Low Power	g	62.415	32.661	32.661
Carbon Out Low Power	g	57.785	59.826	99.958
Carbon In to Carbon Out	g/g	0.926	1.832	3.06

Stove 2: Most of these carbon balances are very off

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5 Standard Values

- Gravimetric flowrate: 16.7 LPM can drop by 10% during test phase
- Dilution tunnel pressure: 0.1 – 0.55 inH2O
- Background CO2: 400-1,200 ppm
- Background CO: Around 0 ppm
- FLUEtemp and H2O temp: Similar to ambient temp at start

- Pay attention in filter weighing sheet for large weight range
- Grav reference weight: 500 mg +/- 0.03 mg
- Leak rate: 0.1% of nominal flow
- Gas bias check: +/- 5% of reference gas
- Desiccators: 20-35% humidity

Thank You!

Questions?

Email me at jaden@aprovecho.org

Want a second set of eyes on your data?

Send data and report to me and I’ll look it over

App Cheat Sheet

- P_ambient = ambient pressure
- Hvap = Latent of vaporization
- Fuel_EHV = fuel effective heating value
- Fuel_Cfrac = fuel carbon fraction
- Eff_wo_char = efficiency without char
- Eff_w_char = efficiency with char
- PM/CO/CO2mass = PM/CO/CO2 concentration
- PM/CO/CO2_fuel_dry_mass = emission factor (fuel)
- PM/CO/CO2_fuel_energy = emission factor (energy)
- PM/CO/CO2_useful_eng_deliver = emissions per MJ delivered
- PM/CO/CO2_mass_time = emission rate
- C_Out_In = Carbon ratio
- MSC = Mass scattering cross section
- Vol_flow = volumetric flowrate