CTM Operation and Fueling Workgroup

- Agenda
  - Role call
  - Review results of Washington State Cordwood Stove Protocol Project
  - Discuss next steps

Washington State Stove Protocol

Lisa Rector

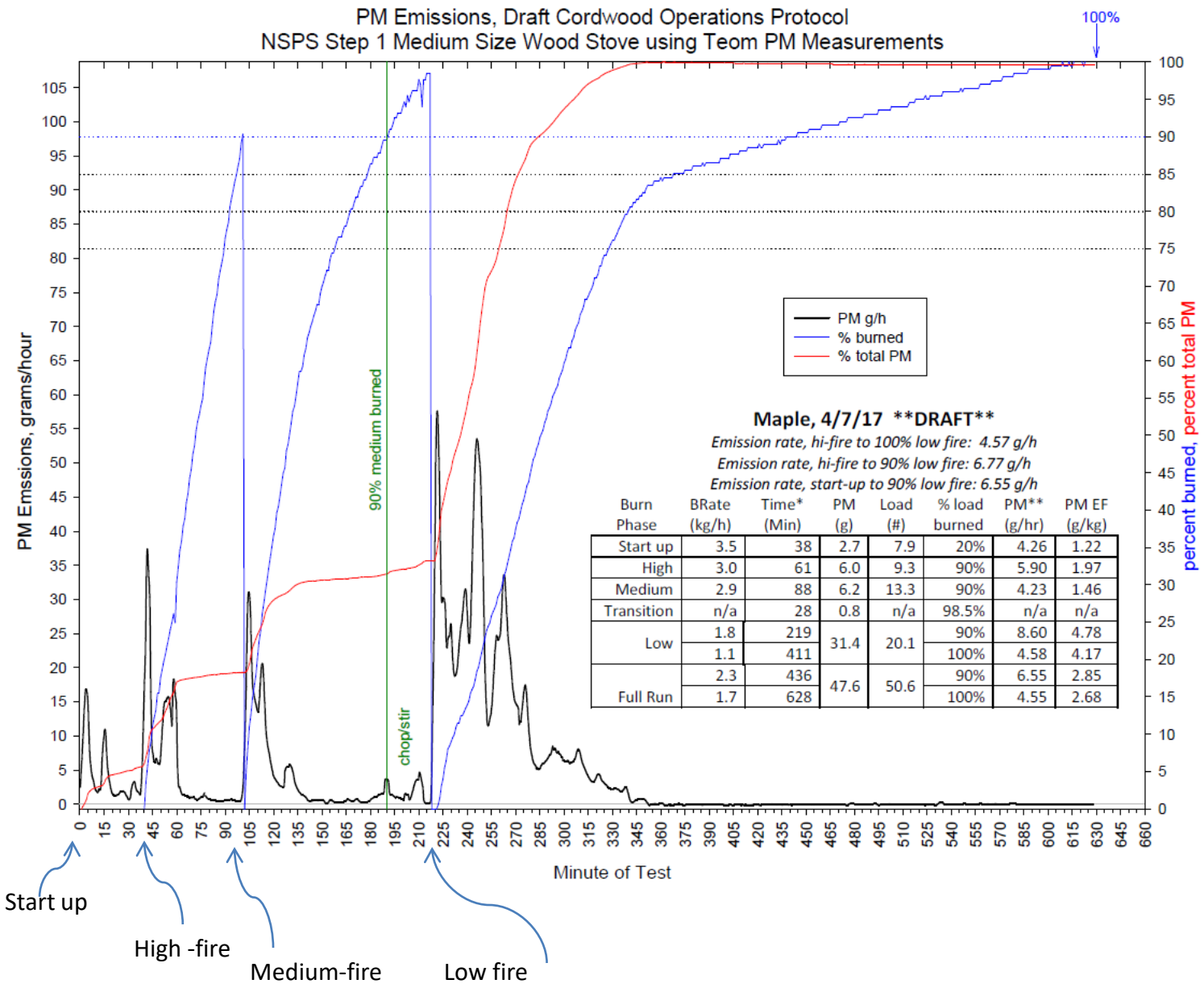
June 1, 2017

Overarching Goals

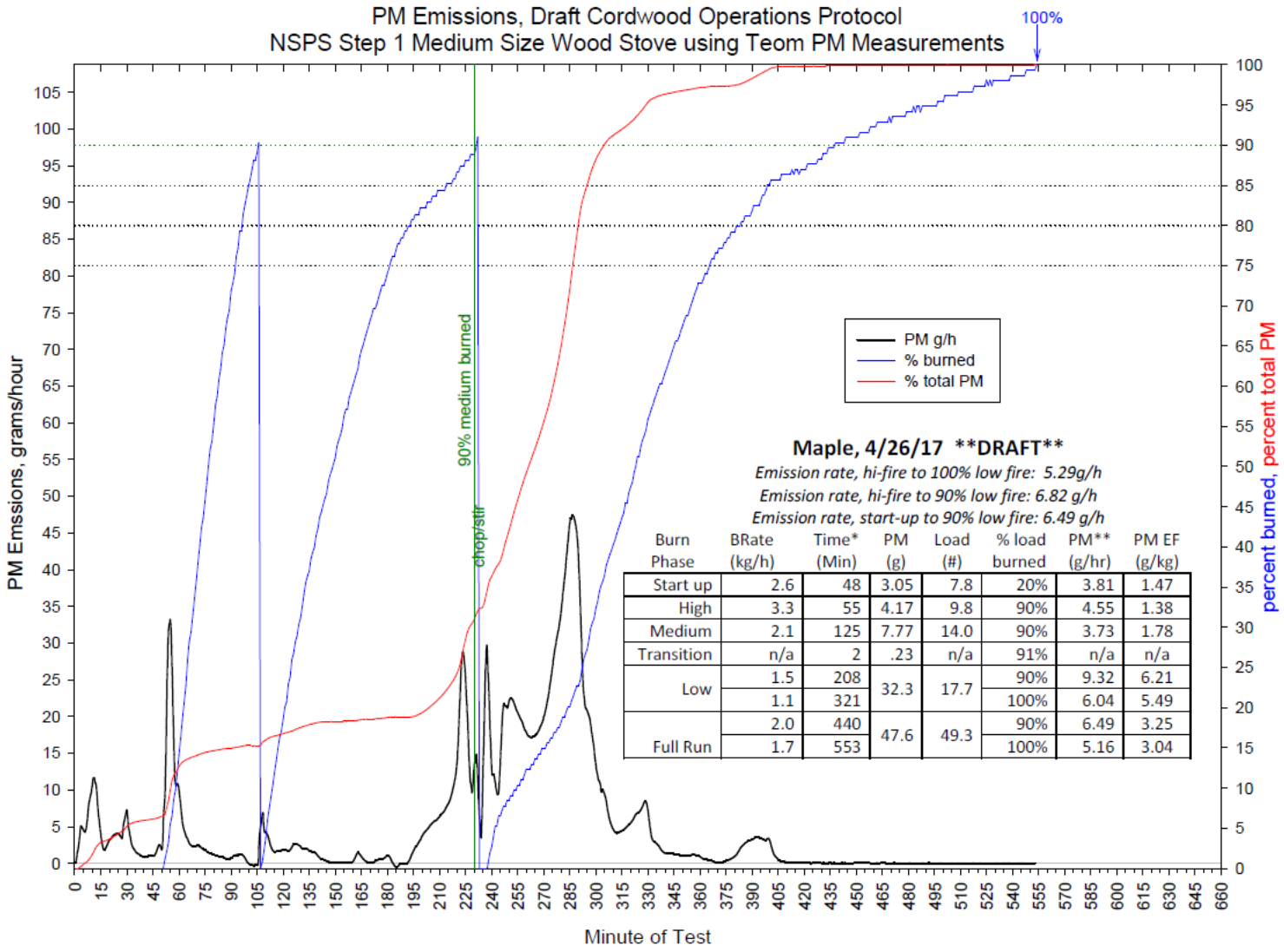
- Reflect typical loading patterns
- Reflect typical operating patterns
- Address variability by completing multiple runs of the same protocol

Protocol Overview

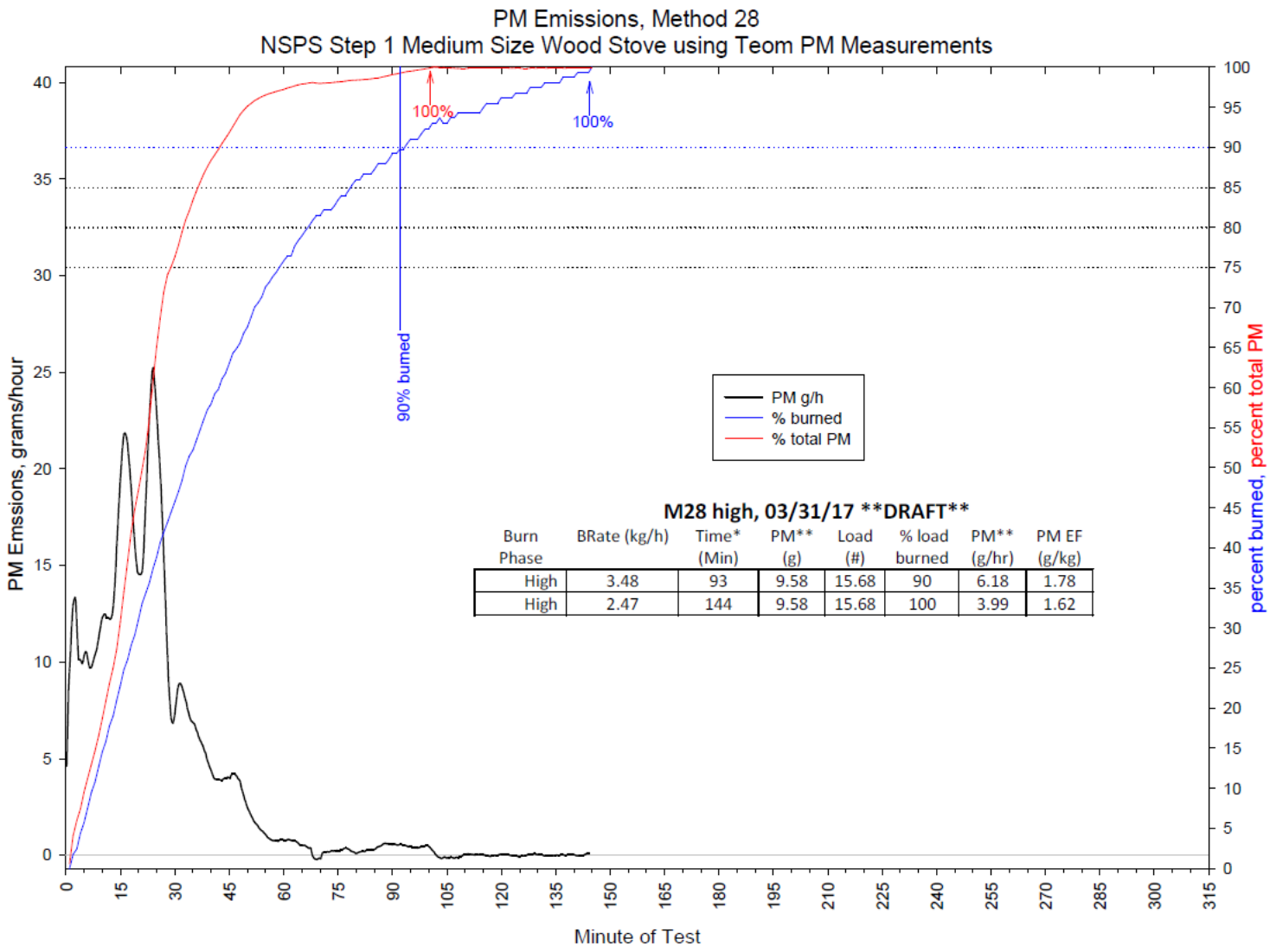
- Compress entire protocol into a single day test
  - Burn phases: startup, high, medium, medium-low transition, and low
    - Phases attempt to reflect common daily user practices such as start-up and reloads.
    - Phases end when 90% of fuel charge is burned.
    - Three reloads during the protocol, with different coal bed weights.
  - Piece sizes vary with phase:
    - Start-up kindling and starter – 4 lb/ft^3
    - High-fire: small pieces – 5 lb/ft^3
    - Medium-fire: large pieces – 7 lb/ft^3
    - Low-fire: mix of small and medium pieces – based on firebox capacity – min of 9 lb/ft^3



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.5	38	2.7	7.9	20%	4.26	1.22
High	3.0	61	6.0	9.3	90%	5.90	1.97
Medium	2.9	88	6.2	13.3	90%	4.23	1.46
Transition	n/a	28	0.8	n/a	98.5%	n/a	n/a
Low	1.8	219	31.4	20.1	90%	8.60	4.78
	1.1	411			100%	4.58	4.17
Full Run	2.3	436	47.6	50.6	90%	6.55	2.85
	1.7	628			100%	4.55	2.68

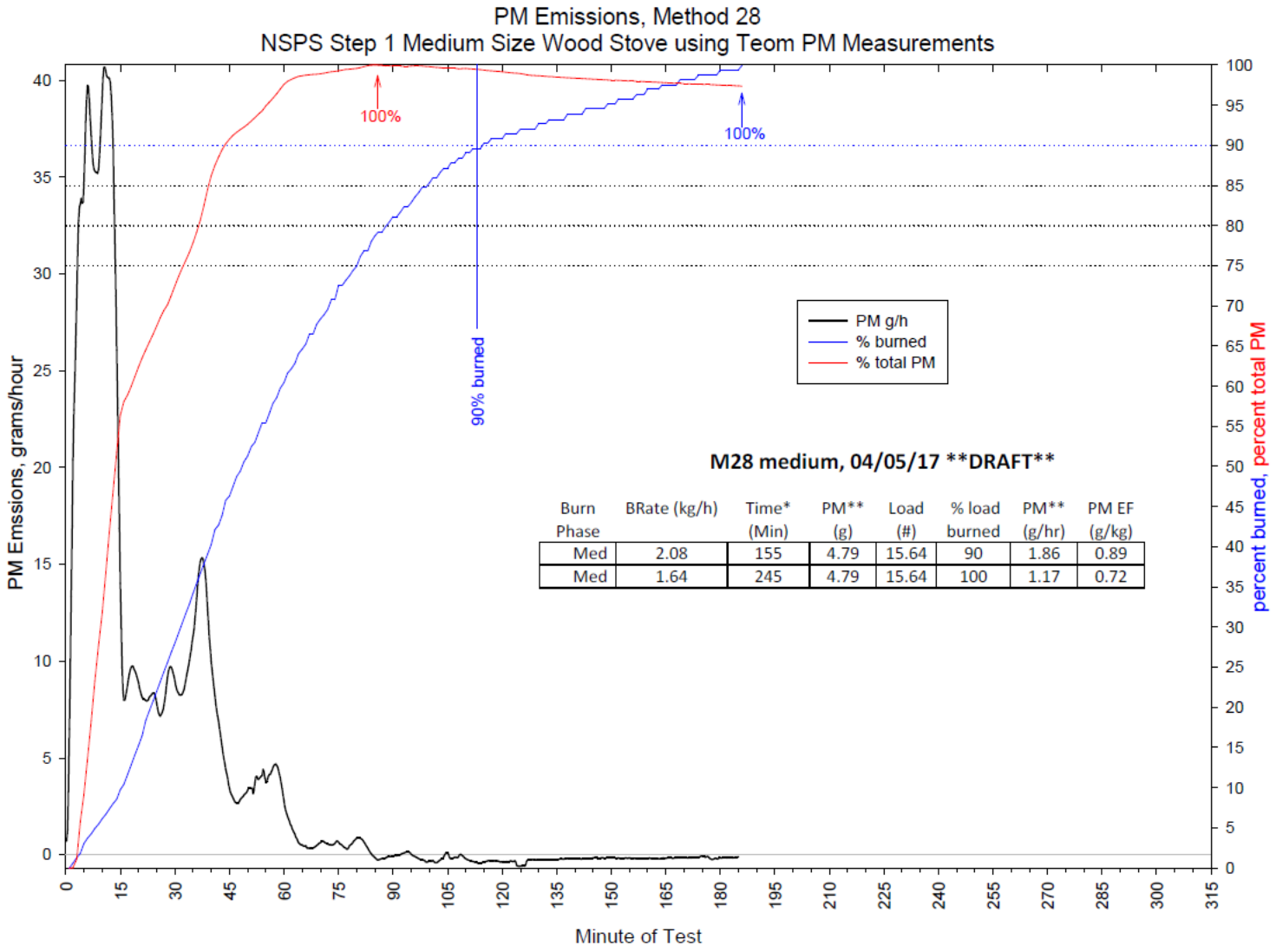


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.6	48	3.05	7.8	20%	3.81	1.47
High	3.3	55	4.17	9.8	90%	4.55	1.38
Medium	2.1	125	7.77	14.0	90%	3.73	1.78
Transition	n/a	2	.23	n/a	91%	n/a	n/a
Low	1.5	208	32.3	17.7	90%	9.32	6.21
	1.1	321			100%	6.04	5.49
Full Run	2.0	440	47.6	49.3	90%	6.49	3.25
	1.7	553			100%	5.16	3.04

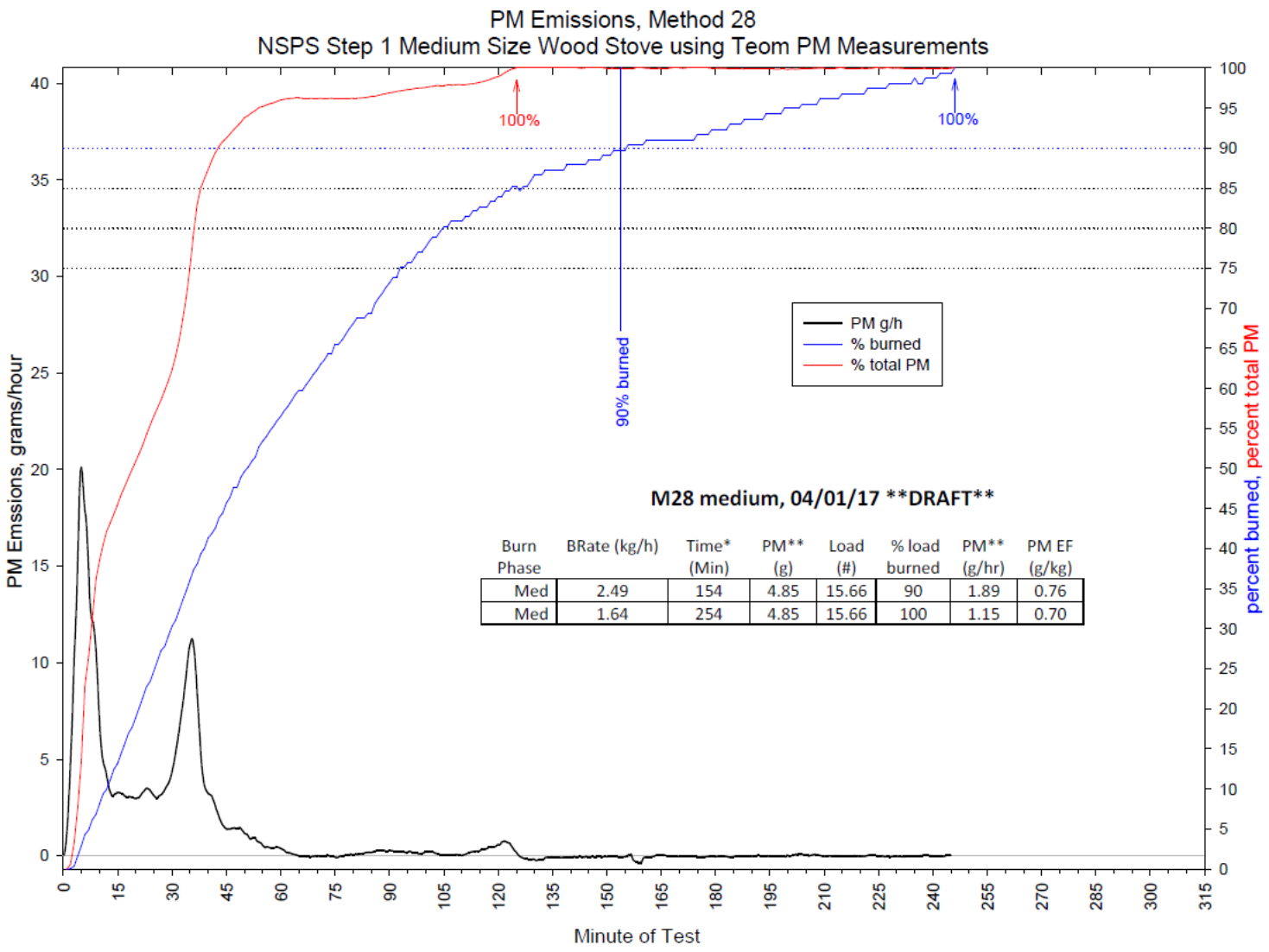


M28 high, 03/31/17 **DRAFT**

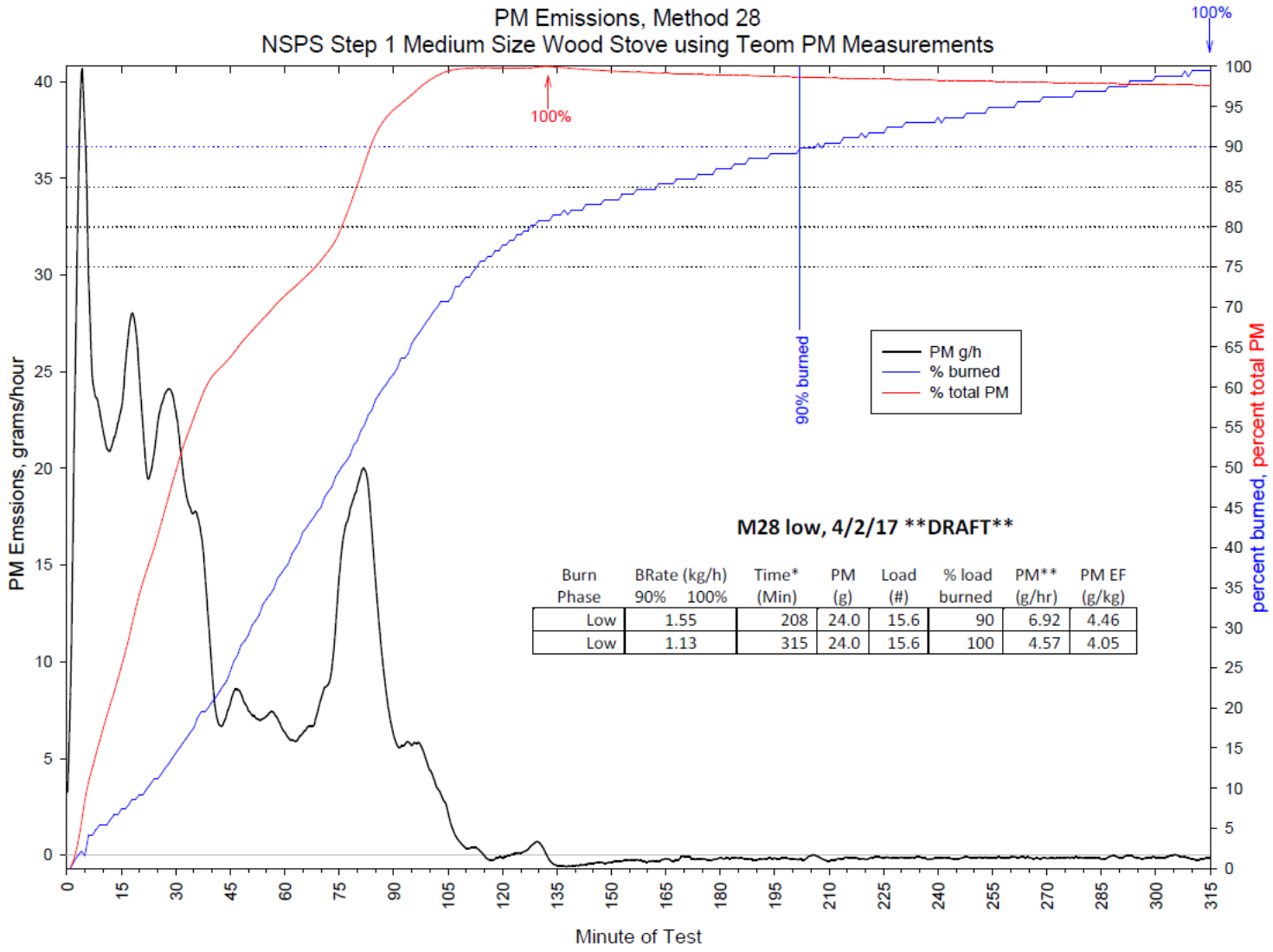
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62



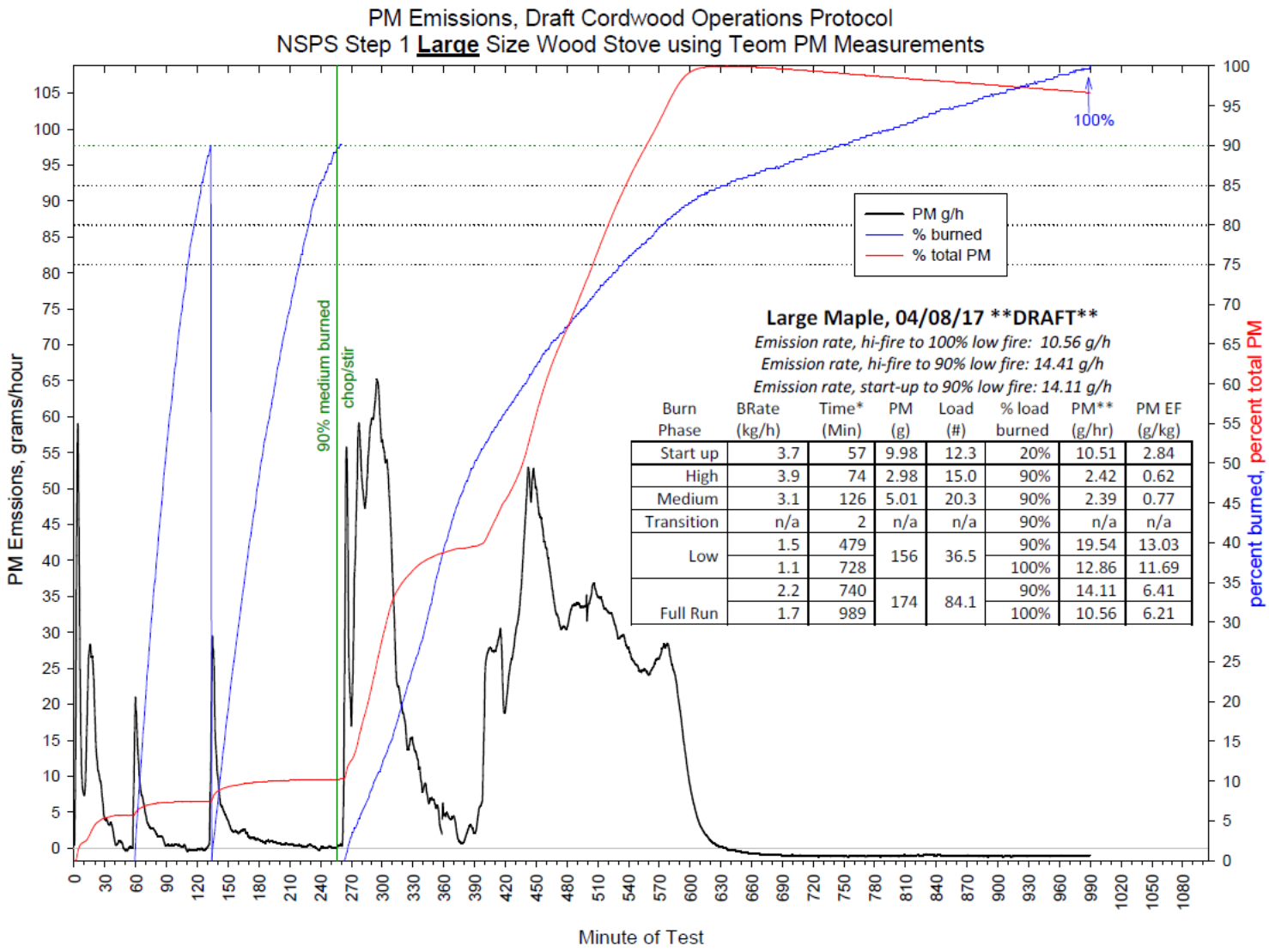
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70



Burn Phase	BRate (kg/h) 90%	BRate (kg/h) 100%	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Low	1.55		208	24.0	15.6	90	6.92	4.46
Low	1.13		315	24.0	15.6	100	4.57	4.05



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
	1.7	989			100%	10.56	6.21

Fuel charge

FUEL CHARGES WITH DIFFERENT SPECIES

Birch – start-up, high and medium fuel charge

Maple – start-up, high and medium fuel charge

Oak – start-up, high and medium fuel charge

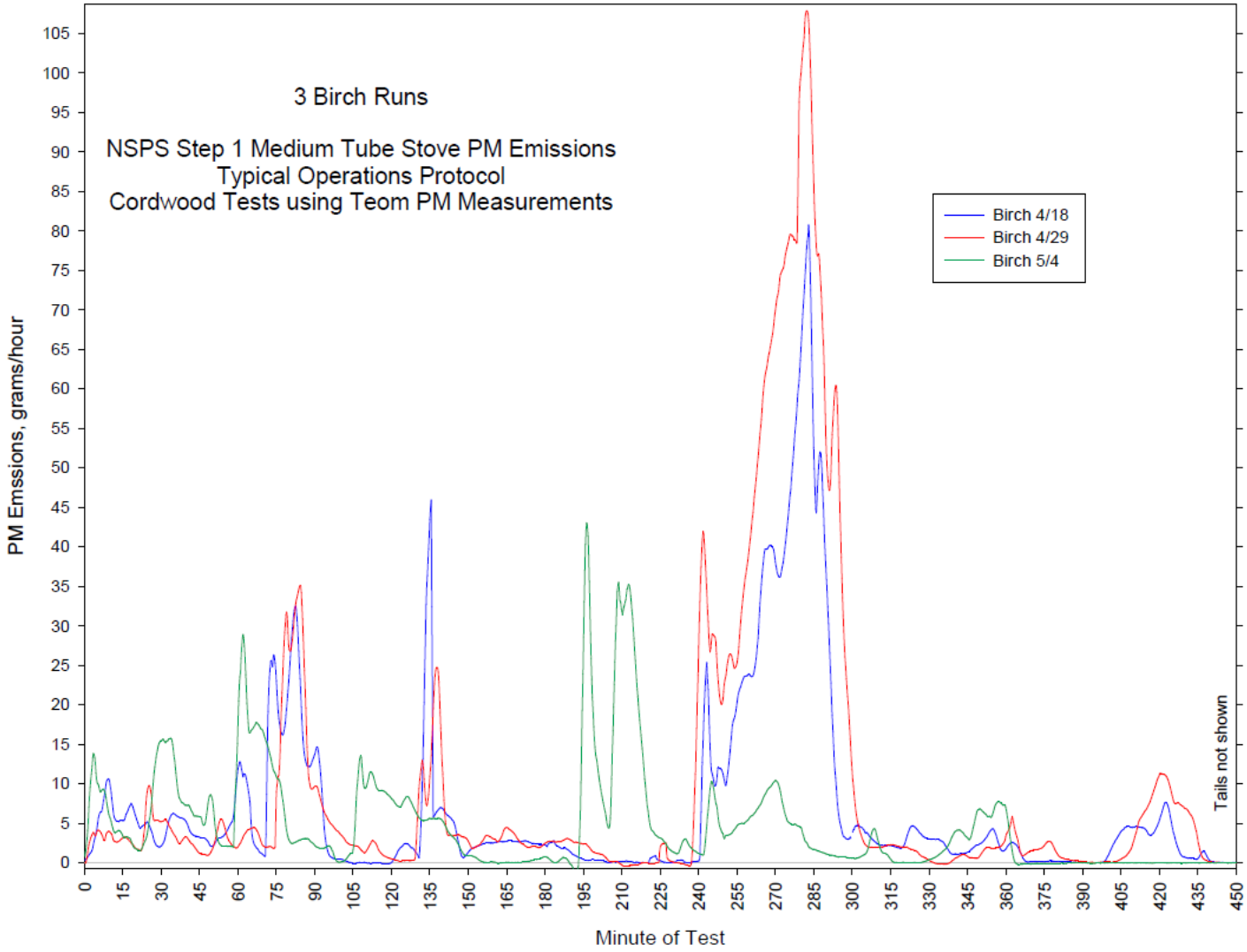
Birch – low load pile, all but two small pieces were loaded

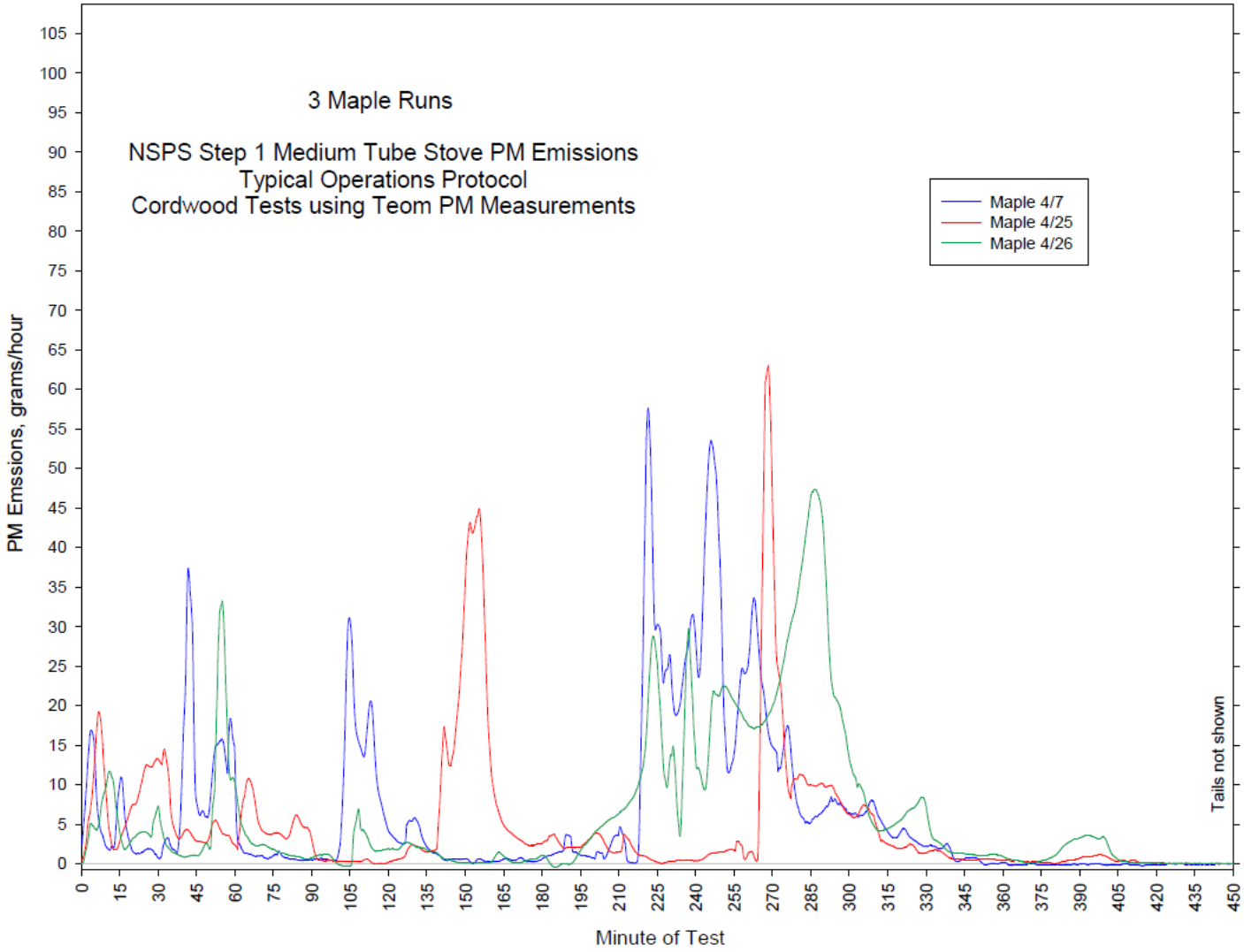
Kindling – 2 lb/ft^3

Start-up load, medium firebox – Washington State Protocol

Start-up load, large firebox – Washington State Protocol

Coal bed before load low added


3 Birch Runs
NSPS Step 1 Medium Tube Stove PM Emissions
Typical Operations Protocol
Cordwood Tests using Teom PM Measurements
Birch 4/18
Birch 4/29
Birch 5/4
PM Emssions, grams/hour
Minute of Test
Tails not shown
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360
375
390
405
420
435
450


3 Maple Runs
NSPS Step 1 Medium Tube Stove PM Emissions
Typical Operations Protocol
Cordwood Tests using Teom PM Measurements
Maple 4/7
Maple 4/25
Maple 4/26
PM Emssions, grams/hour
Minute of Test
Tails not shown
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360
375
390
405
420
435
450

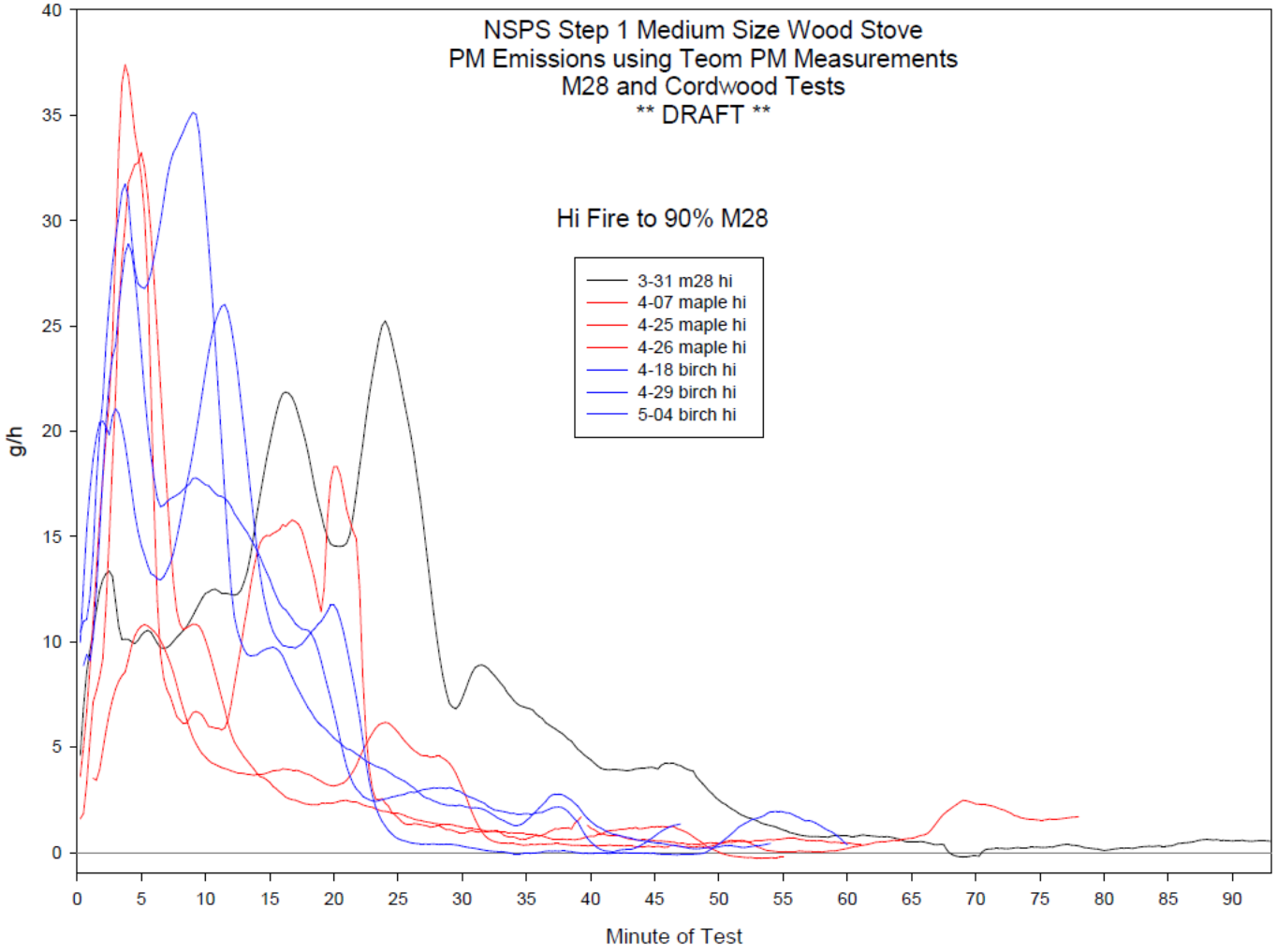
Analysis Full Runs

Birch

Run	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
4/18	2.2	460	51.7	50.9	6.74	3.07
4/29	2.3	430	76.6	51.8	11.38	4.95
5/4	2.5	392	35.3	49.3	5.40	2.16

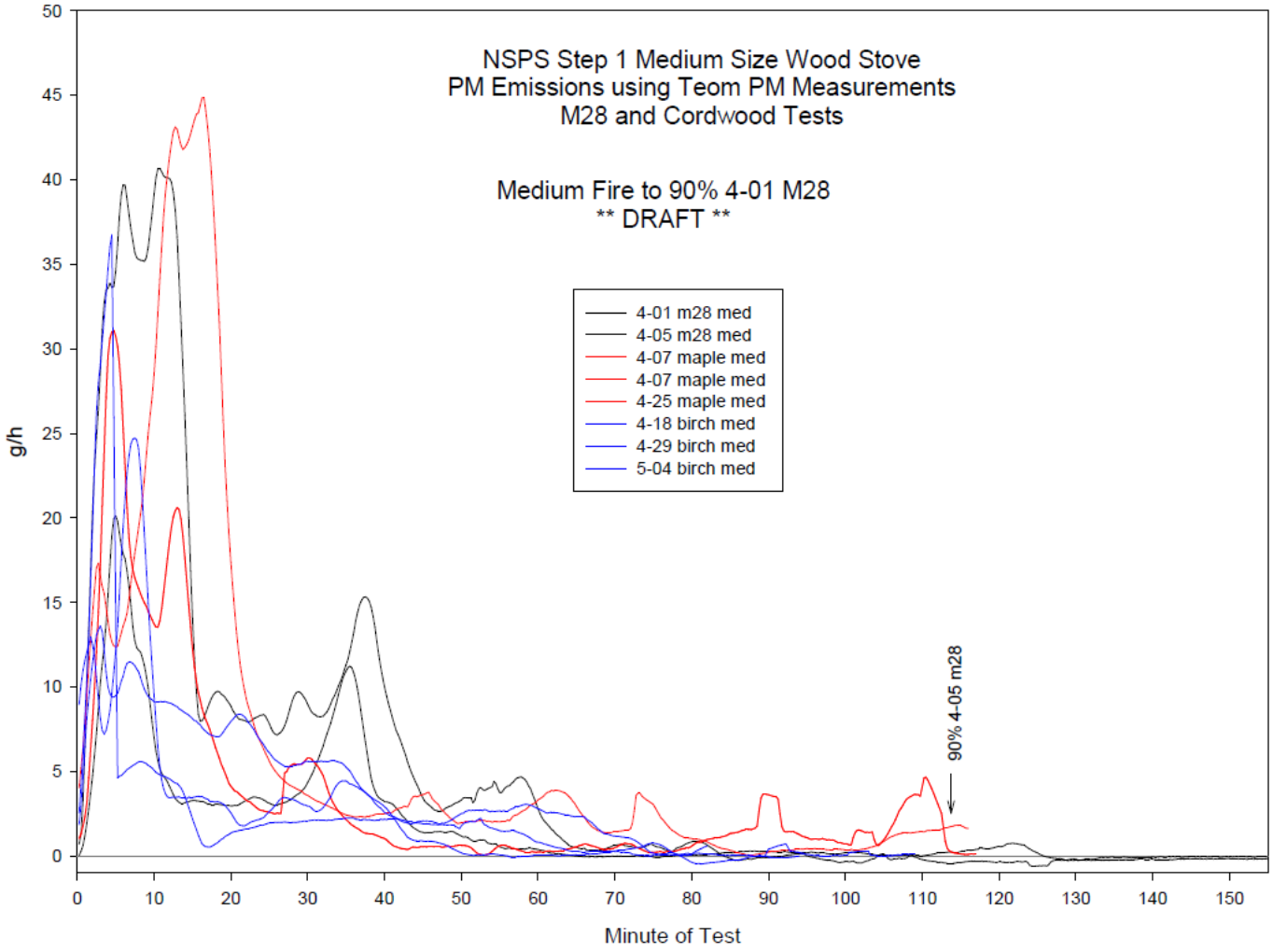
Maple

Run	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
4/7	2.3	436	47.6	50.5	6.55	2.85
4/25	2.2	432	35.6	47.9	4.94	2.25
5/4	2.0	440	47.6	49.3	6.49	3.25


NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
** DRAFT **
Hi Fire to 90% M28
3-31 m28 hi
4-07 maple hi
4-25 maple hi
4-26 maple hi
4-18 birch hi
4-29 birch hi
5-04 birch hi
g/h
Minute of Test
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

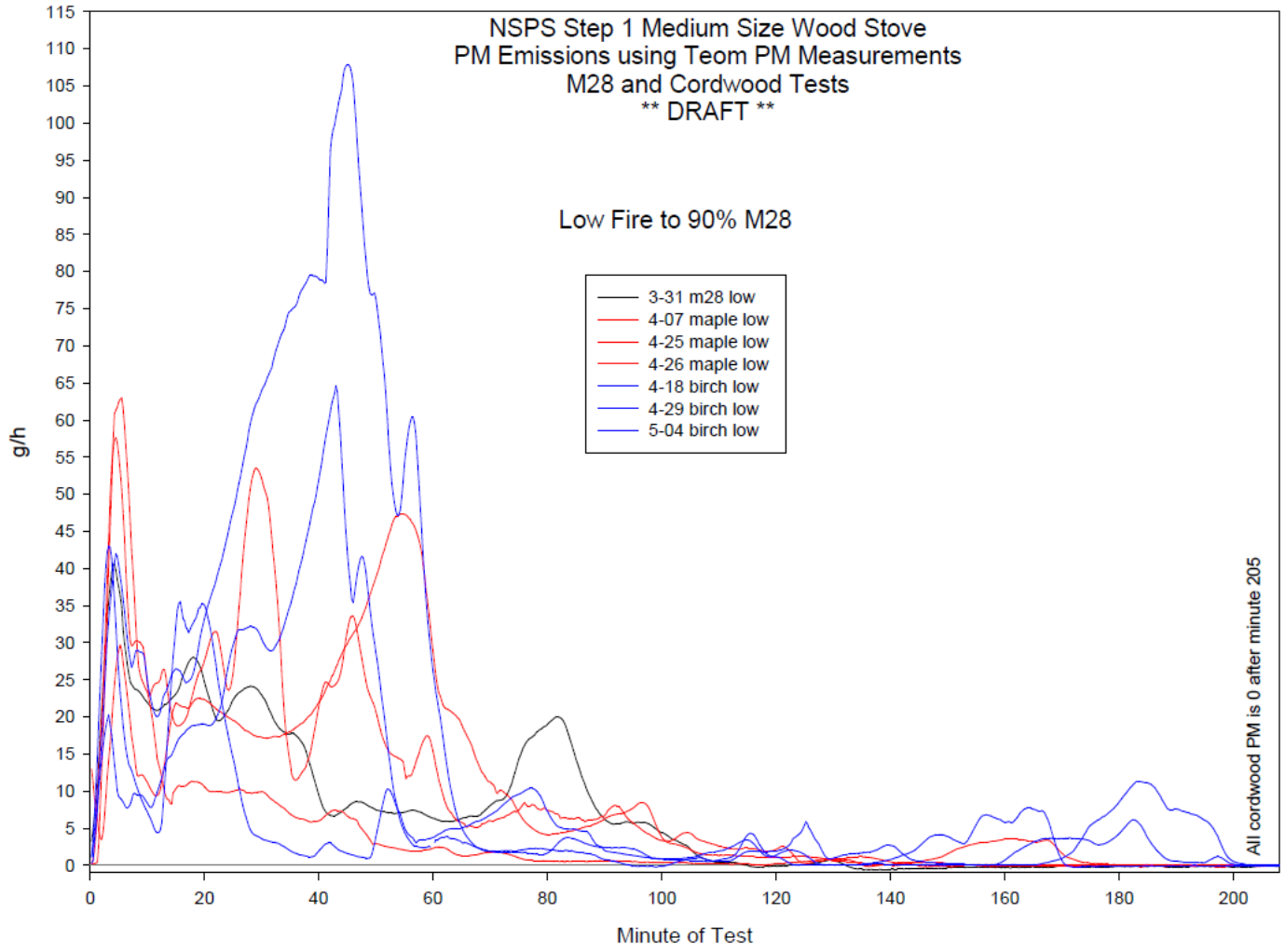
Comparison of High Fire Phase Data

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
M28 Doug Fir	3.48	93	9.58	15.68	6.18	1.78
4/7 Maple	3.0	61	6.0	9.3	5.90	1.97
4/25 Maple	2.4	78	3.17	9.5	2.44	1.02
4/26 Maple	3.3	55	4.17	9.8	4.55	1.38
4/18 Birch	3.3	59	6.08	9.8	6.18	1.87
4/29 Birch	3.6	54	7.15	9.9	3.33	1.85
5/4 Birch	4.1	47	5.96	9.8	7.61	1.86


NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
Medium Fire to 90% 4-01 M28
** DRAFT **
4-01 m28 med
4-05 m28 med
4-07 maple med
4-07 maple med
4-25 maple med
4-18 birch med
4-29 birch med
5-04 birch med
90% 4-05 m28
g/h
Minute of Test
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Comparison of Medium-Fire Phase

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
M28 Doug Fir	2.49	154	4.85	15.66	1.89	0.76
	2.08	155	4.79	15.64	1.86	0.89
4/7 Maple	2.9	88	6.2	13.3	4.23	1.46
4/25 Maple	2.3	117	12.7	13.6	6.51	2.83
4/26 Maple	2.1	125	7.77	14.0	3.73	1.78
4/18 Birch	2.9	90	4.45	13.0	2.97	1.02
4/29 Birch	2.8	95	5.34	13.6	3.38	1.2
5/4 Birch	3.4	82	5.18	14.0	3.79	1.11


NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
** DRAFT **
Low Fire to 90% M28
3-31 m28 low
4-07 maple low
4-25 maple low
4-26 maple low
4-18 birch low
4-29 birch low
5-04 birch low
g/h
Minute of Test
All cordwood PM is 0 after minute 205

Comparison of Low-Fire Phase

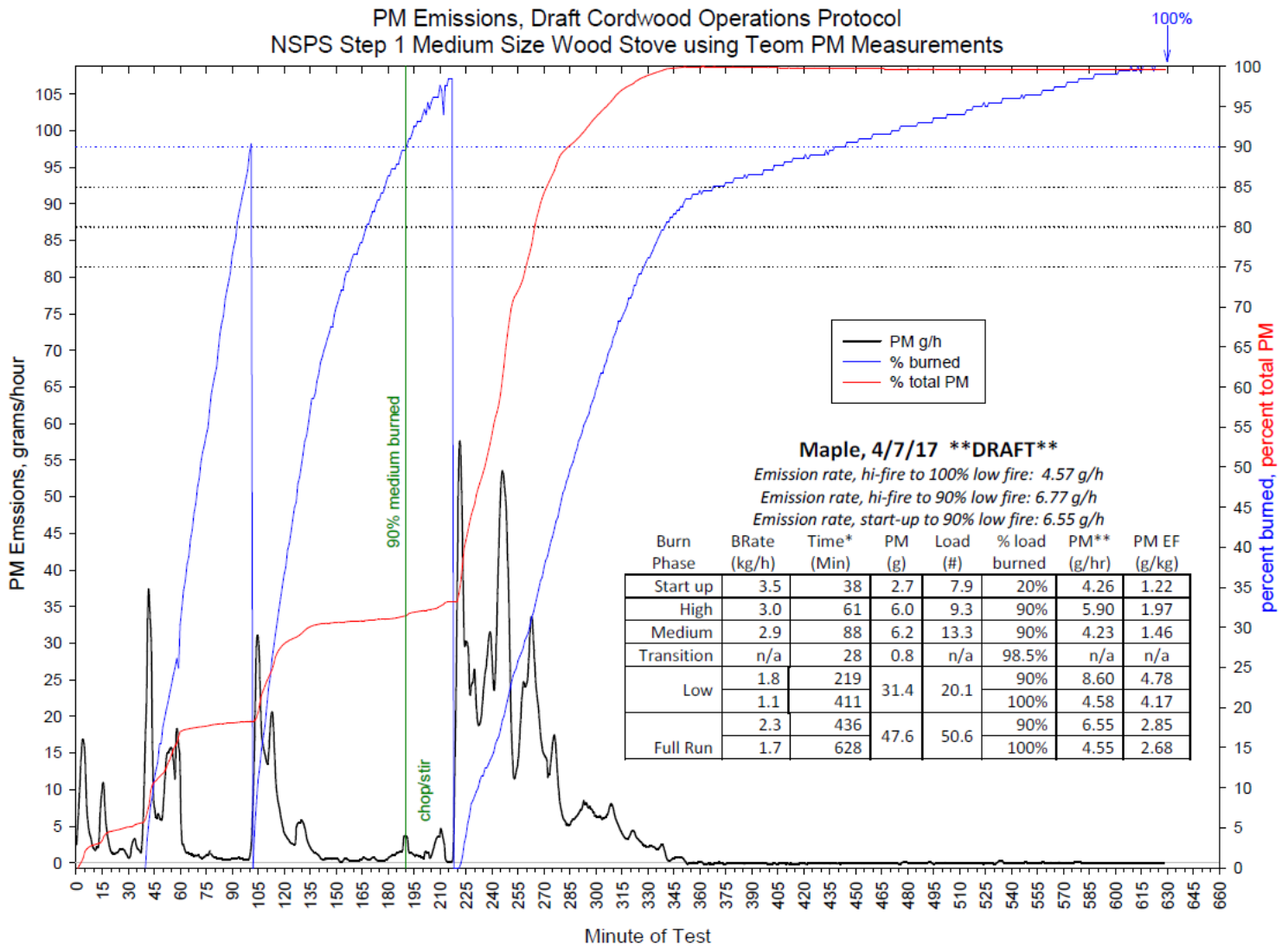
Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
M28 Doug Fir	1.55	208	24	15.6	6.92	4.46
	1.33	*315*	*24*	*15.6*	*4.57*	*4.05*
4/7 Maple	1.8	219	31.4	20.1	8.60	4.78
	1.1	*411*	*31.4*	*20.1*	*4.58*	*4.17*
4/25 Maple	2.0	168	12.8	17.0	4.57	2.29
	1.1	*340*	*12.8*	*17.0*	*2.26*	*2.05*
4/26 Maple	1.5	208	32.3	17.7	9.32	6.21
	1.1	*321*	*32.3*	*17.7*	*6.04*	*5.49*
4/18 Birch	1.8	223	35.6	20.4	9.58	5.32
	1.1	*420*	*35.6*	*20.4*	*5.09*	*4.62*
4/29 Birch	2.0	193	59.8	20.6	18.57	9.30
	1.1	*404*	*59.8*	*20.6*	*8.89*	*8.07*
5/4 Birch	1.7	200	17.6	17.7	5.28	3.11
	1.1	*342*	*17.6*	*17.7*	*3.09*	*2.57*

Washington State Stove Protocol

QUESTIONS/DISCUSSION

Washington State Cordwood Stove Protocol

TEOM CHARTS



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Medium	2.9	88	6.2	13.3	90%	4.23	1.46
Transition	n/a	28	0.8	n/a	98.5%	n/a	n/a
Low	1.8	219	31.4	20.1	90%	8.60	4.78
	1.1	411			100%	4.58	4.17
Full Run	2.3	436	47.6	50.6	90%	6.55	2.85
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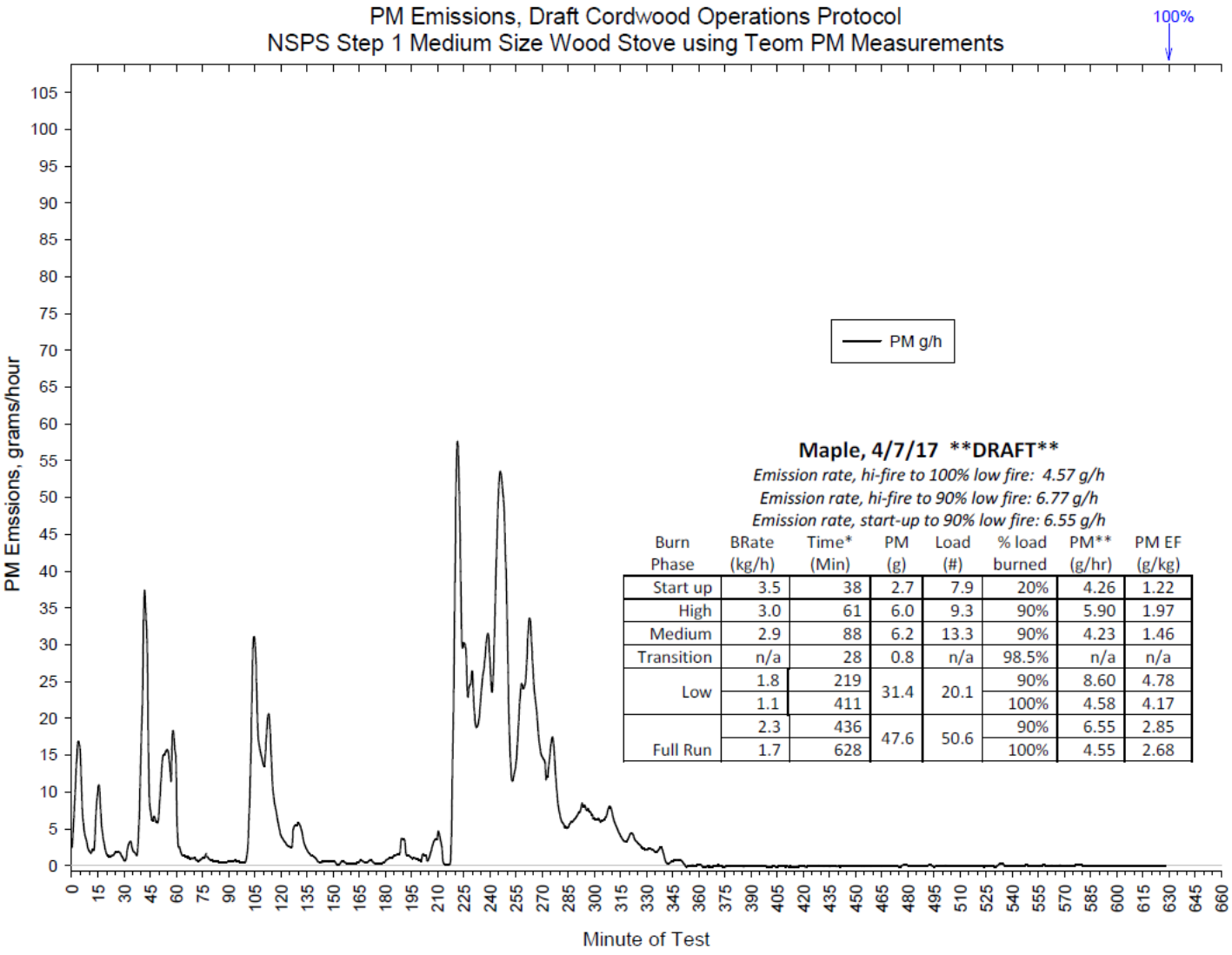

Maple, 4/7/17 **DRAFT**

Emission rate, hi-fire to 100% low fire: 4.57 g/h
Emission rate, hi-fire to 90% low fire: 6.77 g/h
Emission rate, start-up to 90% low fire: 6.55 g/h

Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.5	38	2.7	7.9	20%	4.26	1.22
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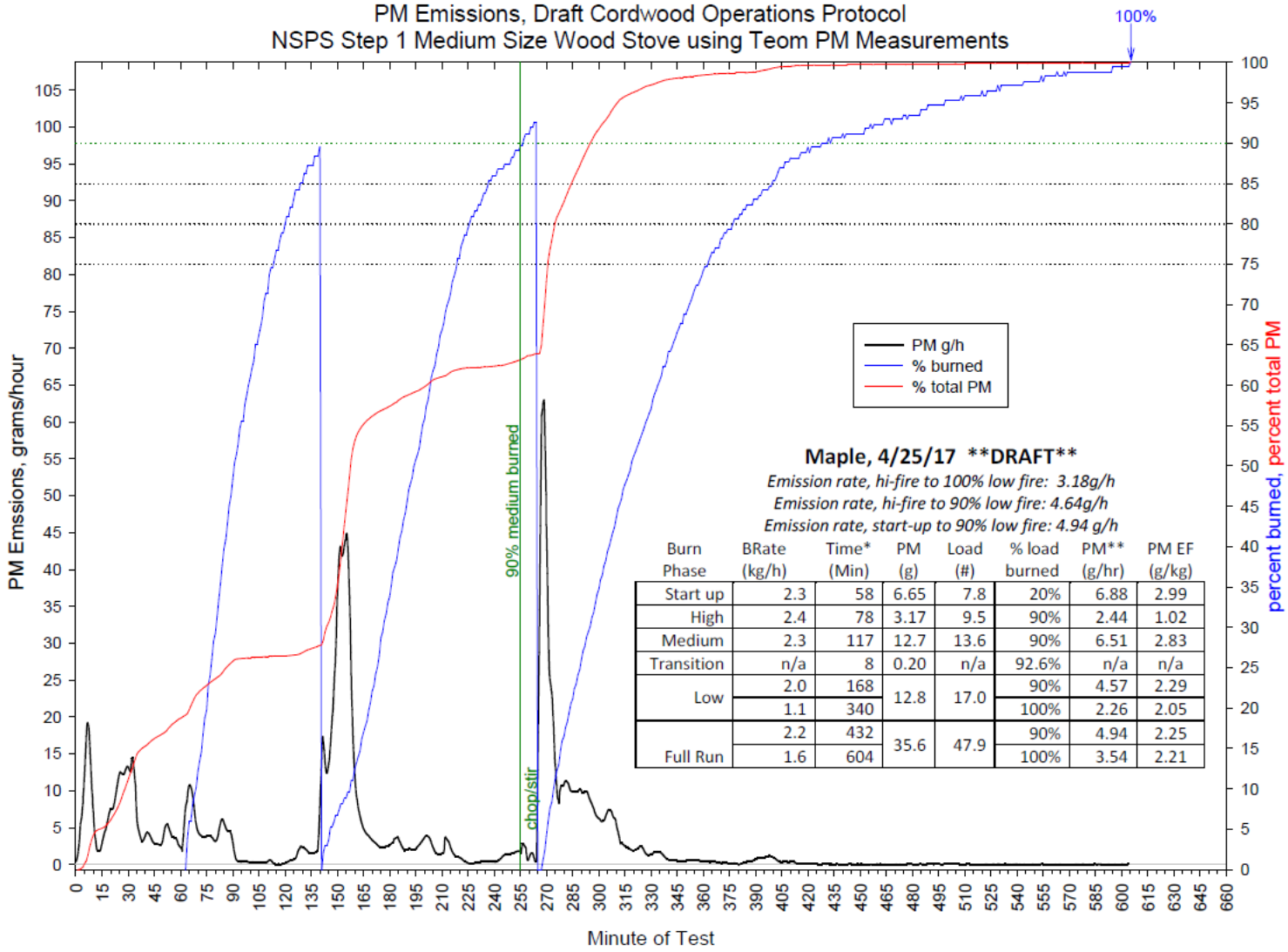

Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.3	58	6.65	7.8	20%	6.88	2.99
High	2.4	78	3.17	9.5	90%	2.44	1.02
Medium	2.3	117	12.7	13.6	90%	6.51	2.83
Transition	n/a	8	0.20	n/a	92.6%	n/a	n/a
Low	2.0	168	12.8	17.0	90%	4.57	2.29
	1.1	340			100%	2.26	2.05
Full Run	2.2	432	35.6	47.9	90%	4.94	2.25
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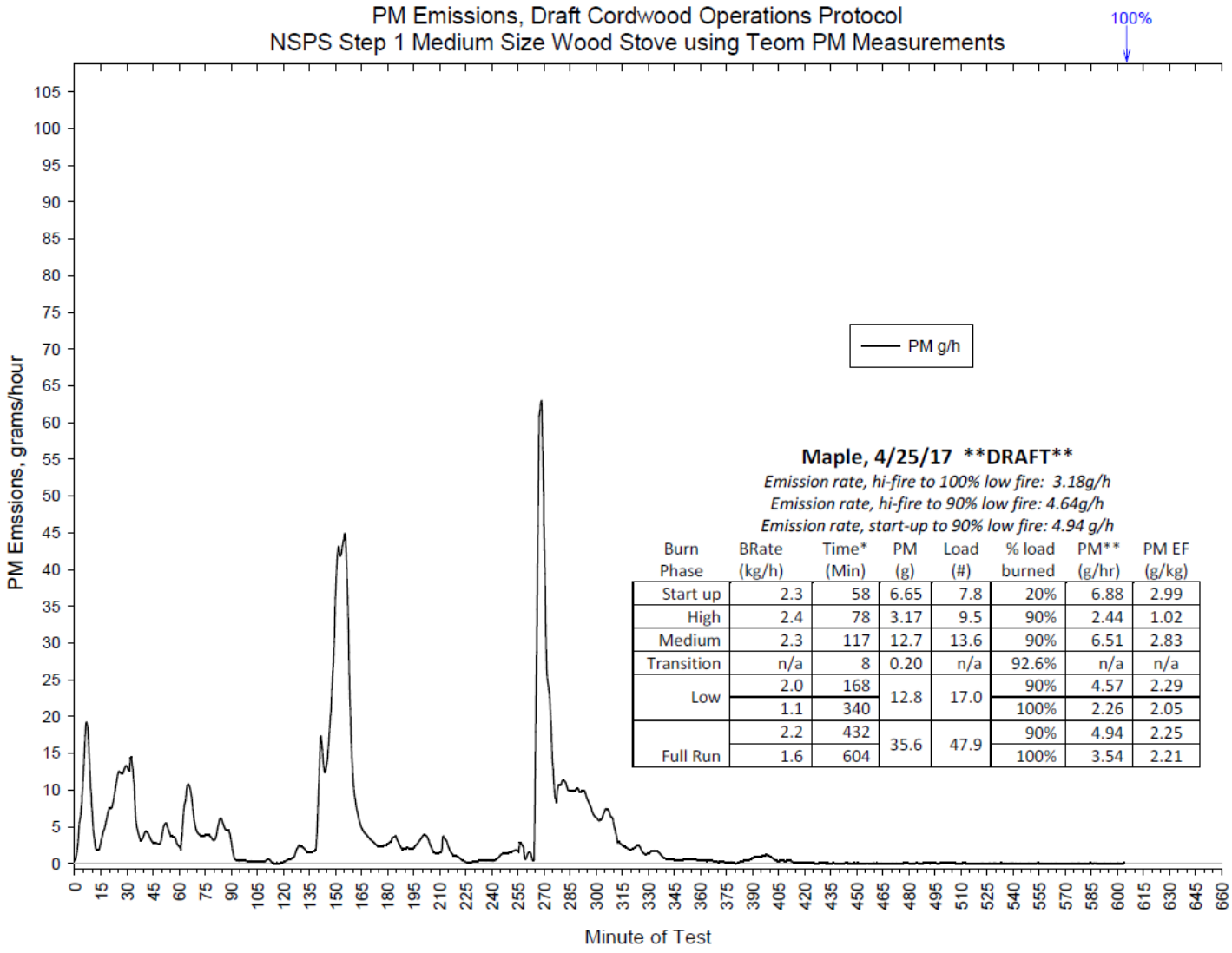

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High	2.4	78	3.17	9.5	90%	2.44	1.02
Medium	2.3	117	12.7	13.6	90%	6.51	2.83
Transition	n/a	8	0.20	n/a	92.6%	n/a	n/a
Low	2.0	168	12.8	17.0	90%	4.57	2.29
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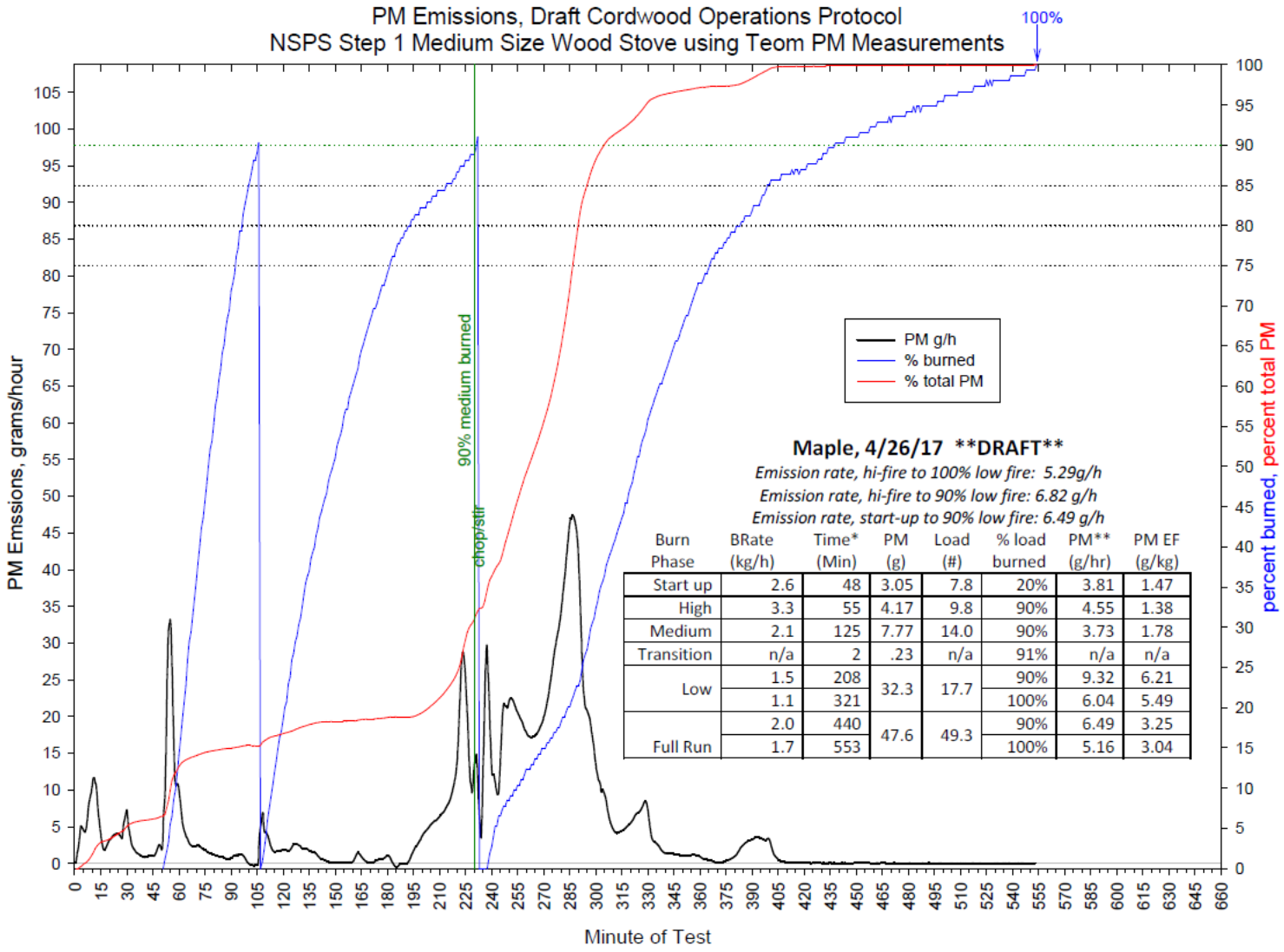

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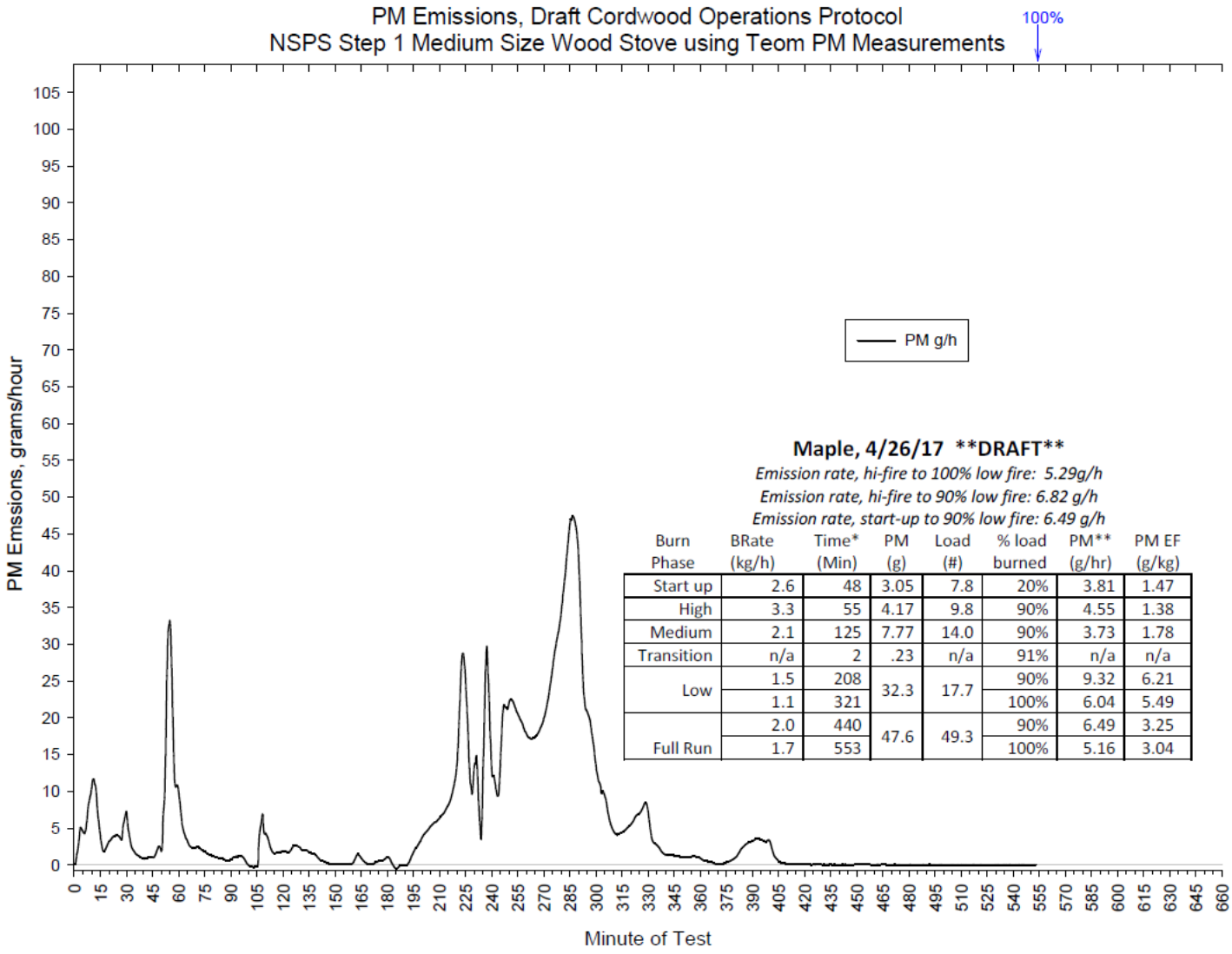

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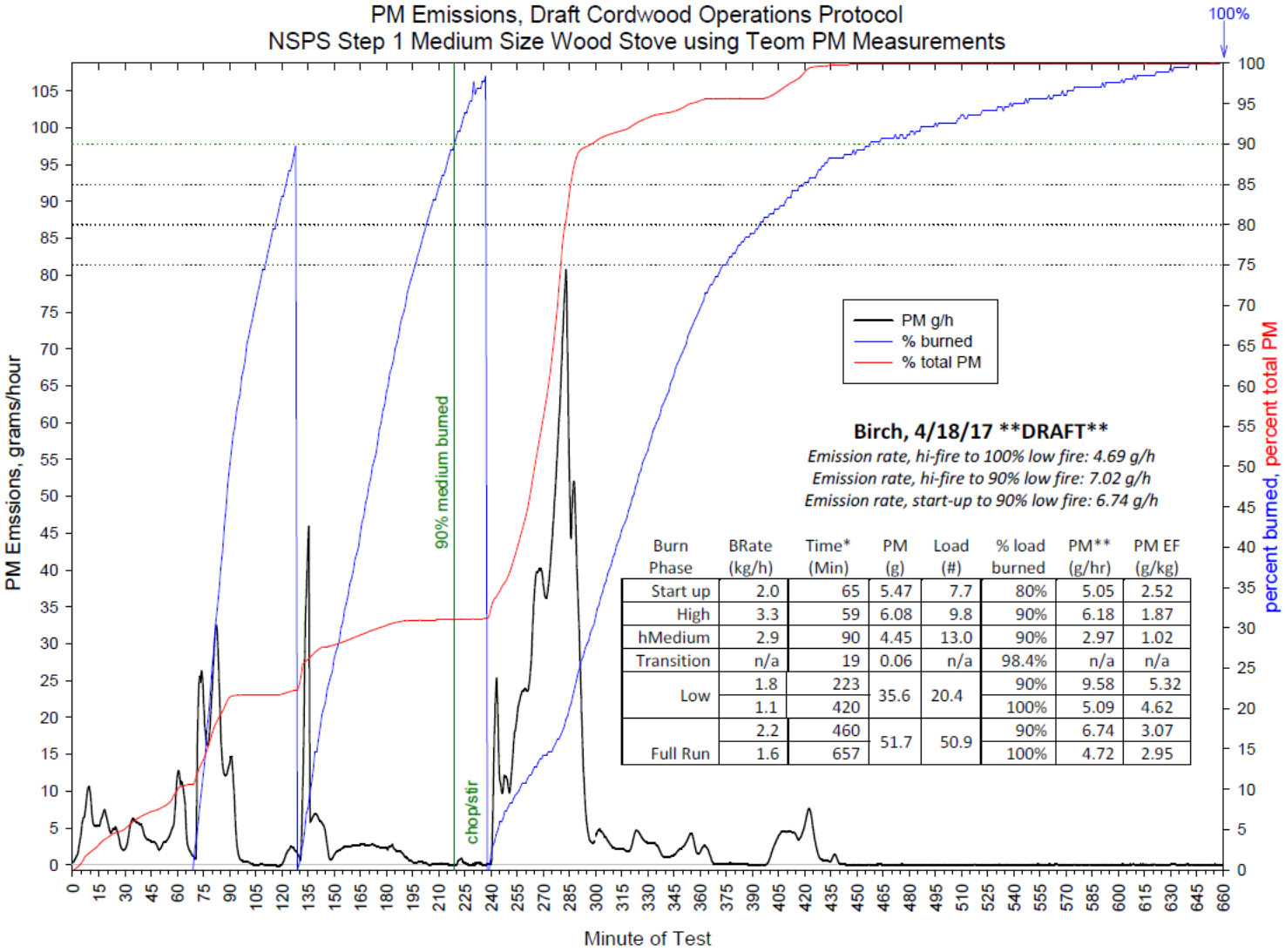
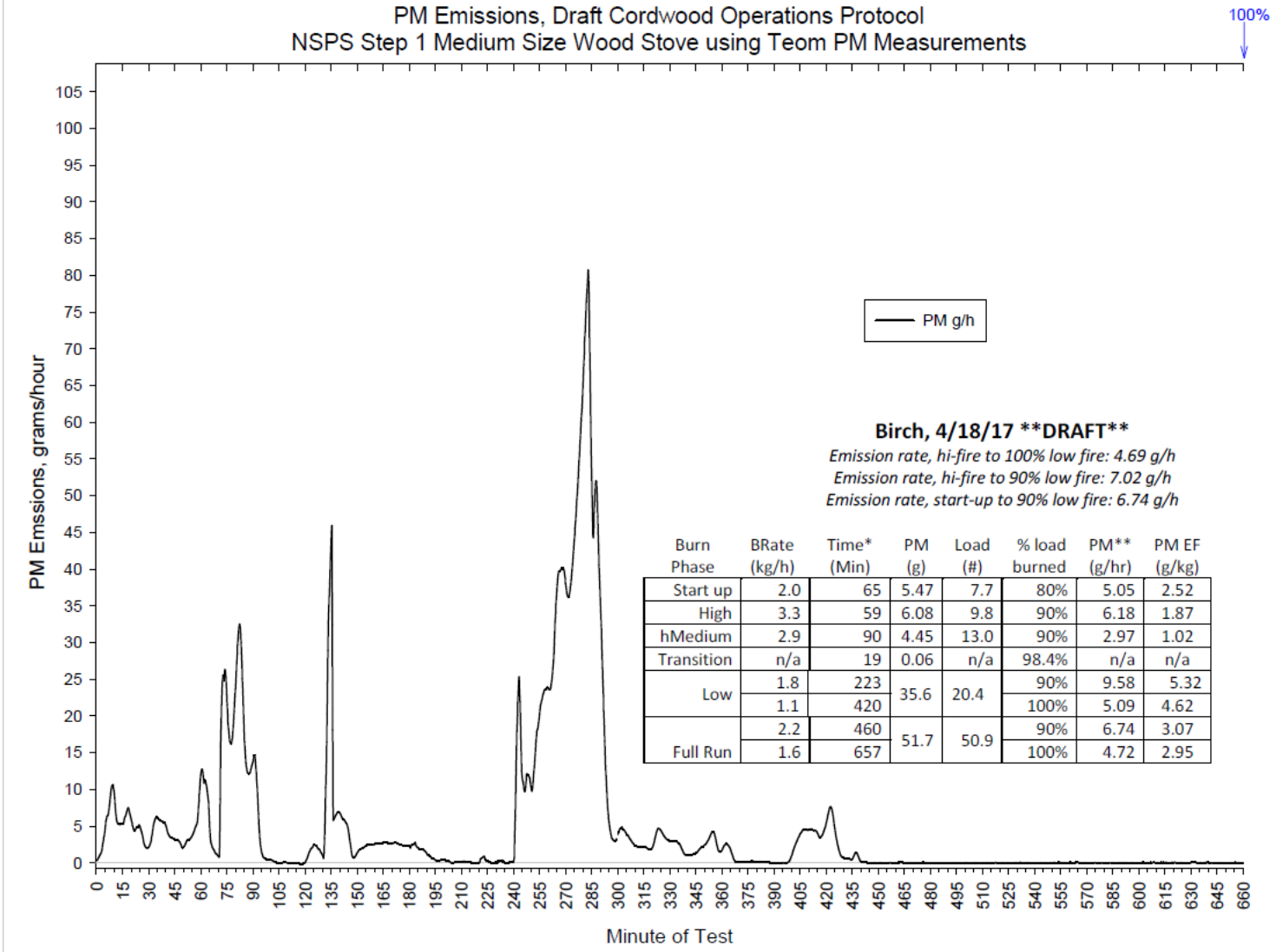
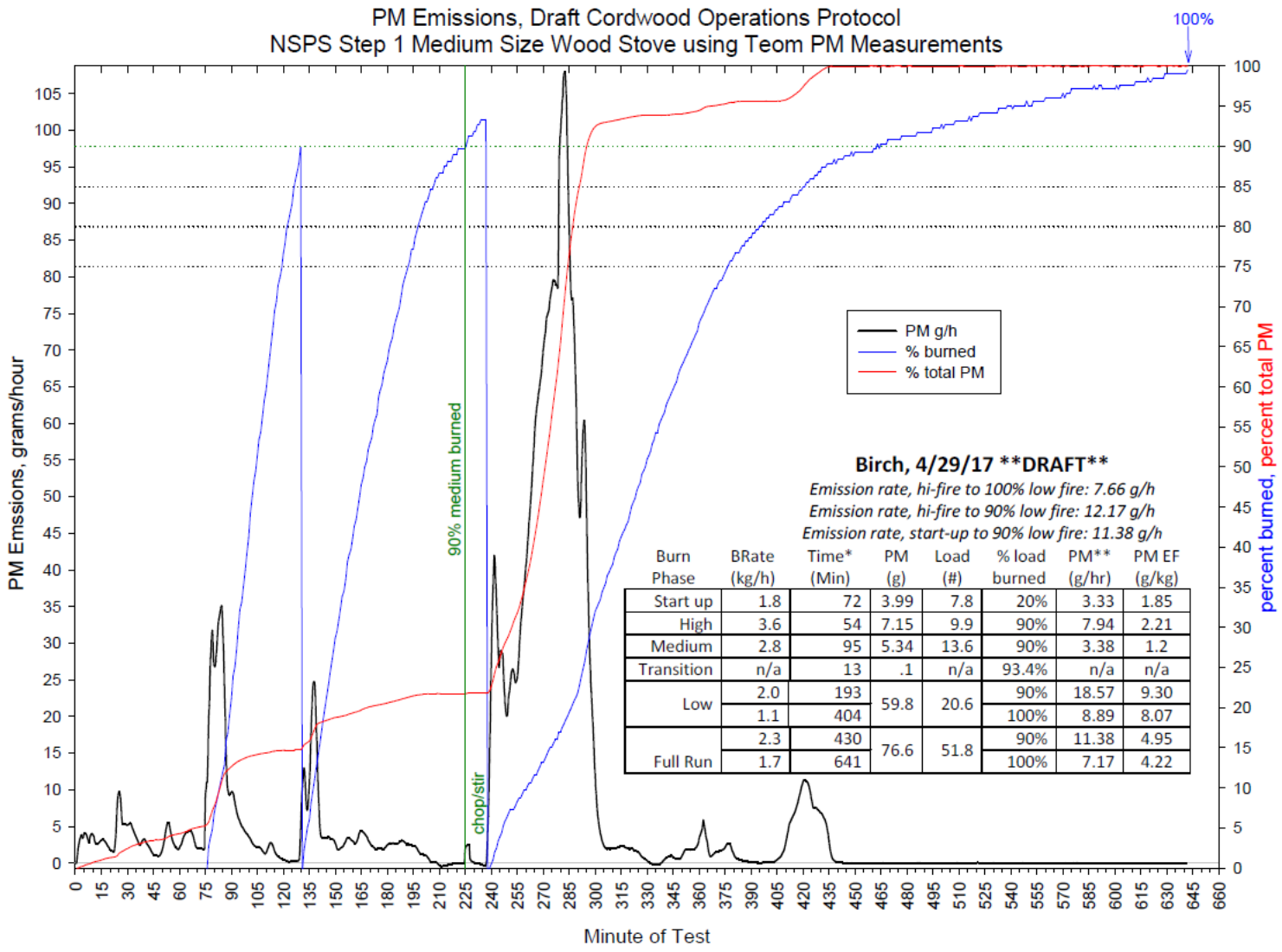


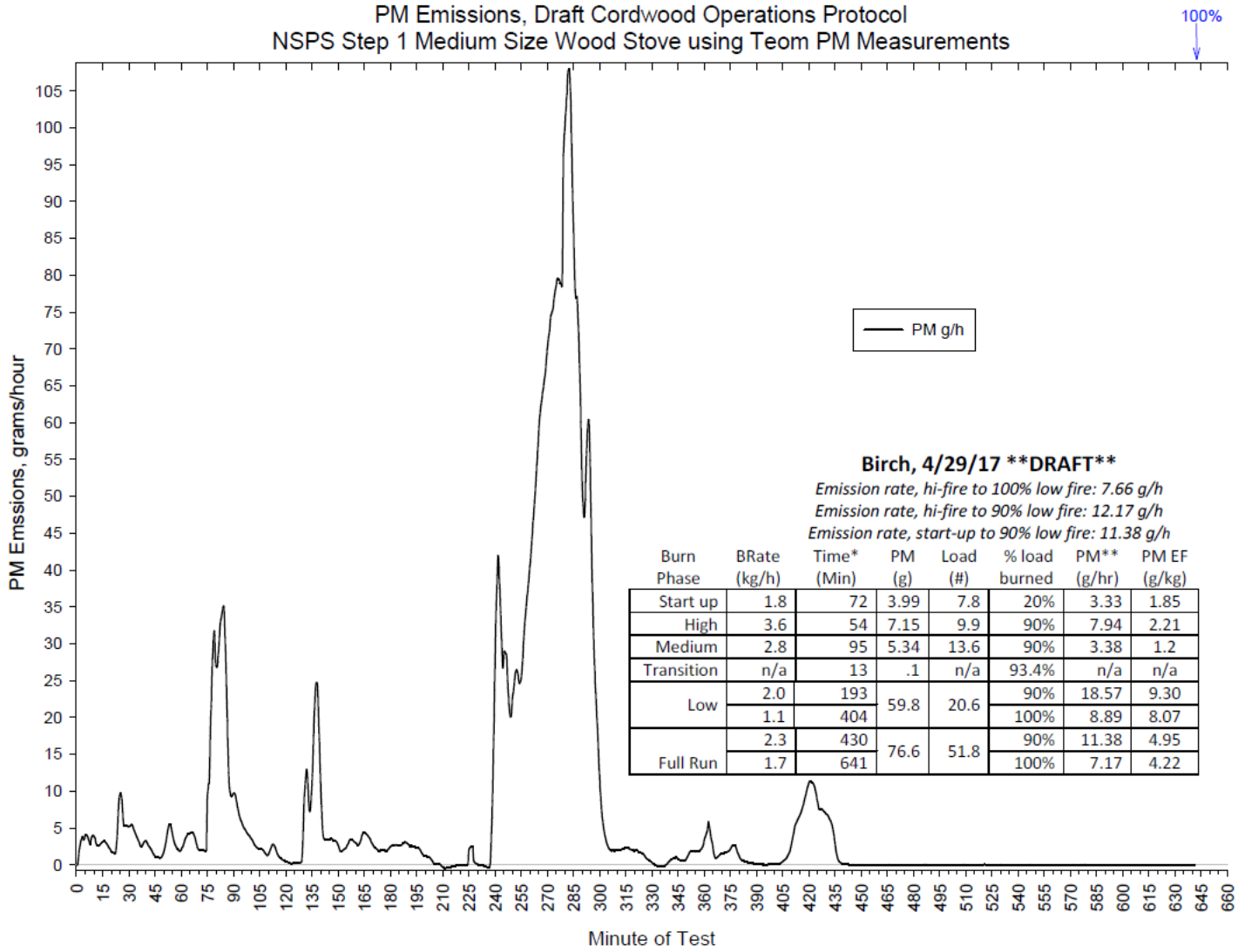
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.0	65	5.47	7.7	80%	5.05	2.52
High	3.3	59	6.08	9.8	90%	6.18	1.87
hMedium	2.9	90	4.45	13.0	90%	2.97	1.02
Transition	n/a	19	0.06	n/a	98.4%	n/a	n/a
Low	1.8	223	35.6	20.4	90%	9.58	5.32
	1.1	420			100%	5.09	4.62
Full Run	2.2	460	51.7	50.9	90%	6.74	3.07
	1.6	657			100%	4.72	2.95



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.0	65	5.47	7.7	80%	5.05	2.52
High	3.3	59	6.08	9.8	90%	6.18	1.87
hMedium	2.9	90	4.45	13.0	90%	2.97	1.02
Transition	n/a	19	0.06	n/a	98.4%	n/a	n/a
Low	1.8	223	35.6	20.4	90%	9.58	5.32
	1.1	420			100%	5.09	4.62
Full Run	2.2	460	51.7	50.9	90%	6.74	3.07
	1.6	657			100%	4.72	2.95



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	1.8	72	3.99	7.8	20%	3.33	1.85
High	3.6	54	7.15	9.9	90%	7.94	2.21
Medium	2.8	95	5.34	13.6	90%	3.38	1.2
Transition	n/a	13	.1	n/a	93.4%	n/a	n/a
Low	2.0	193	59.8	20.6	90%	18.57	9.30
	1.1	404			100%	8.89	8.07
Full Run	2.3	430	76.6	51.8	90%	11.38	4.95
	1.7	641			100%	7.17	4.22



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
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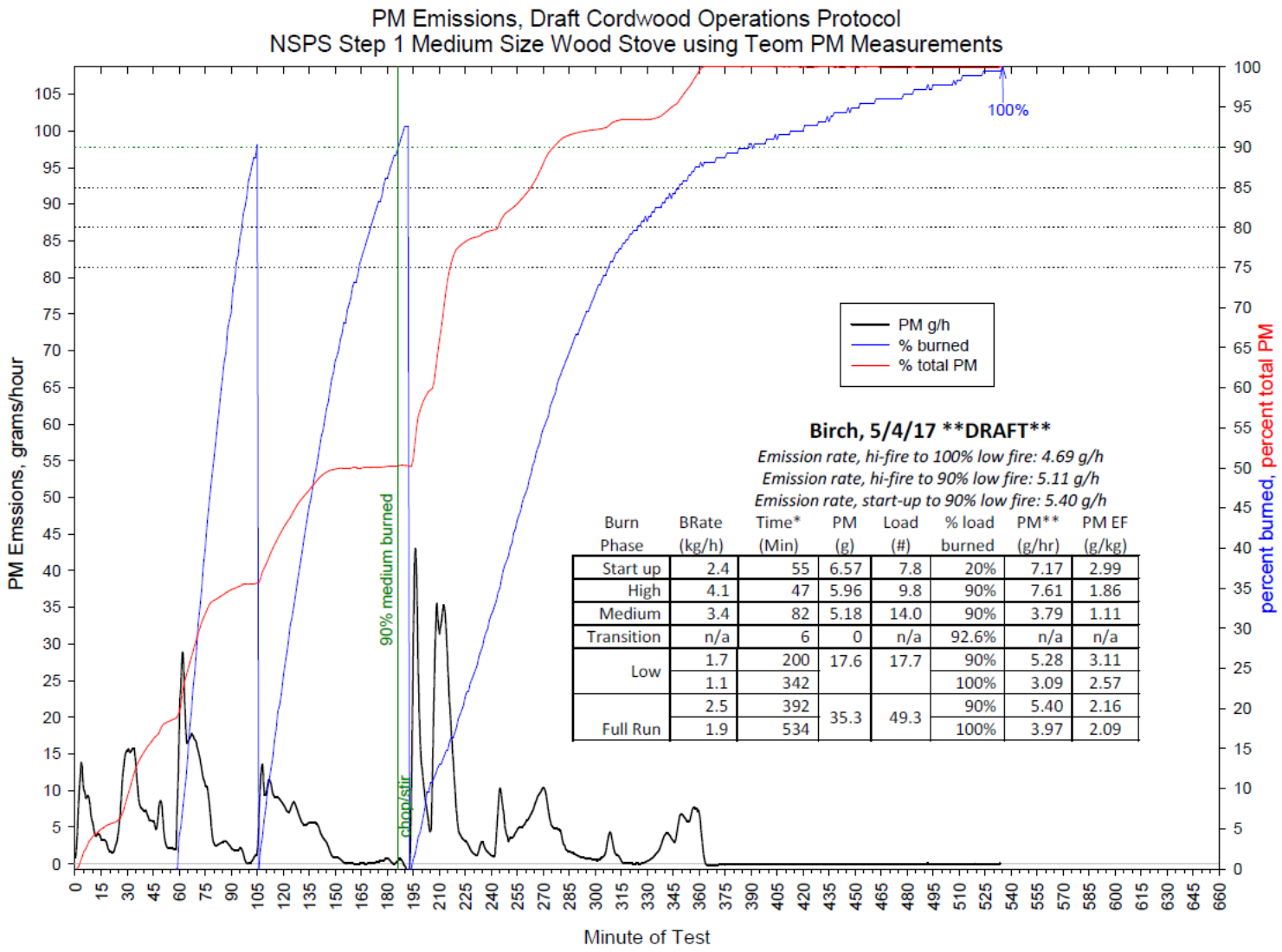
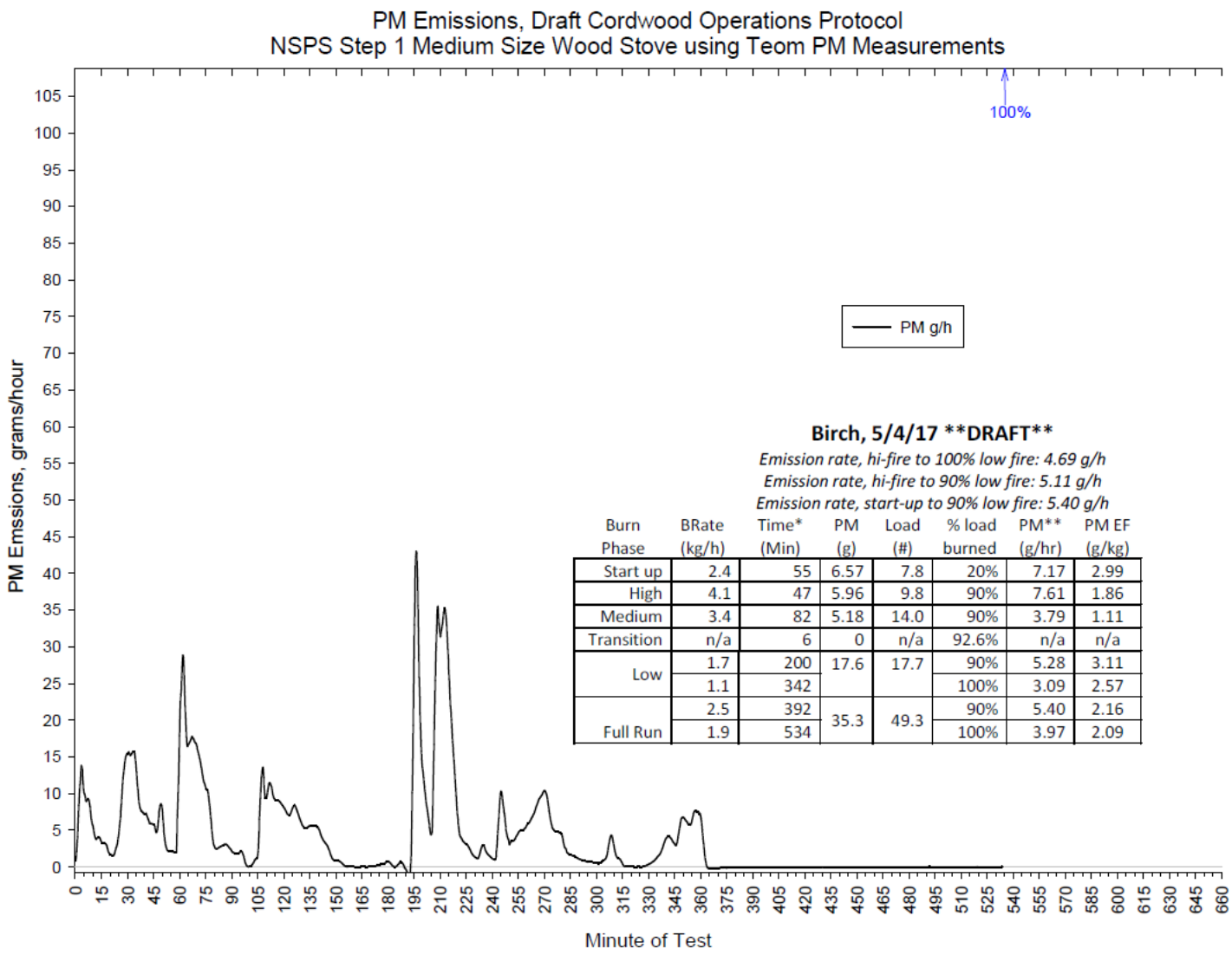


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.4	55	6.57	7.8	20%	7.17	2.99
High	4.1	47	5.96	9.8	90%	7.61	1.86
Medium	3.4	82	5.18	14.0	90%	3.79	1.11
Transition	n/a	6	0	n/a	92.6%	n/a	n/a
Low	1.7	200	17.6	17.7	90%	5.28	3.11
	1.1	342			100%	3.09	2.57
Full Run	2.5	392	35.3	49.3	90%	5.40	2.16
	1.9	534			100%	3.97	2.09



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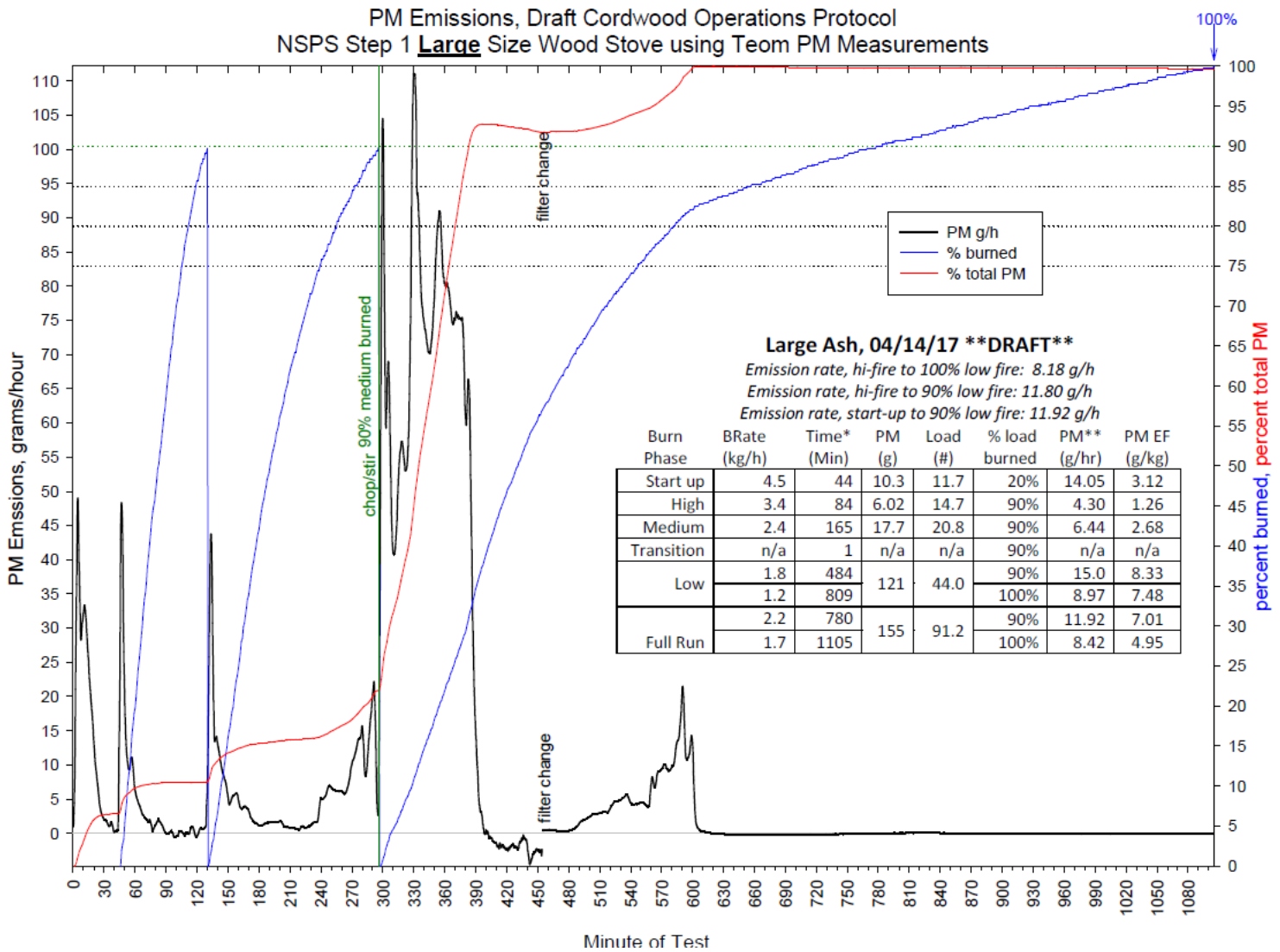
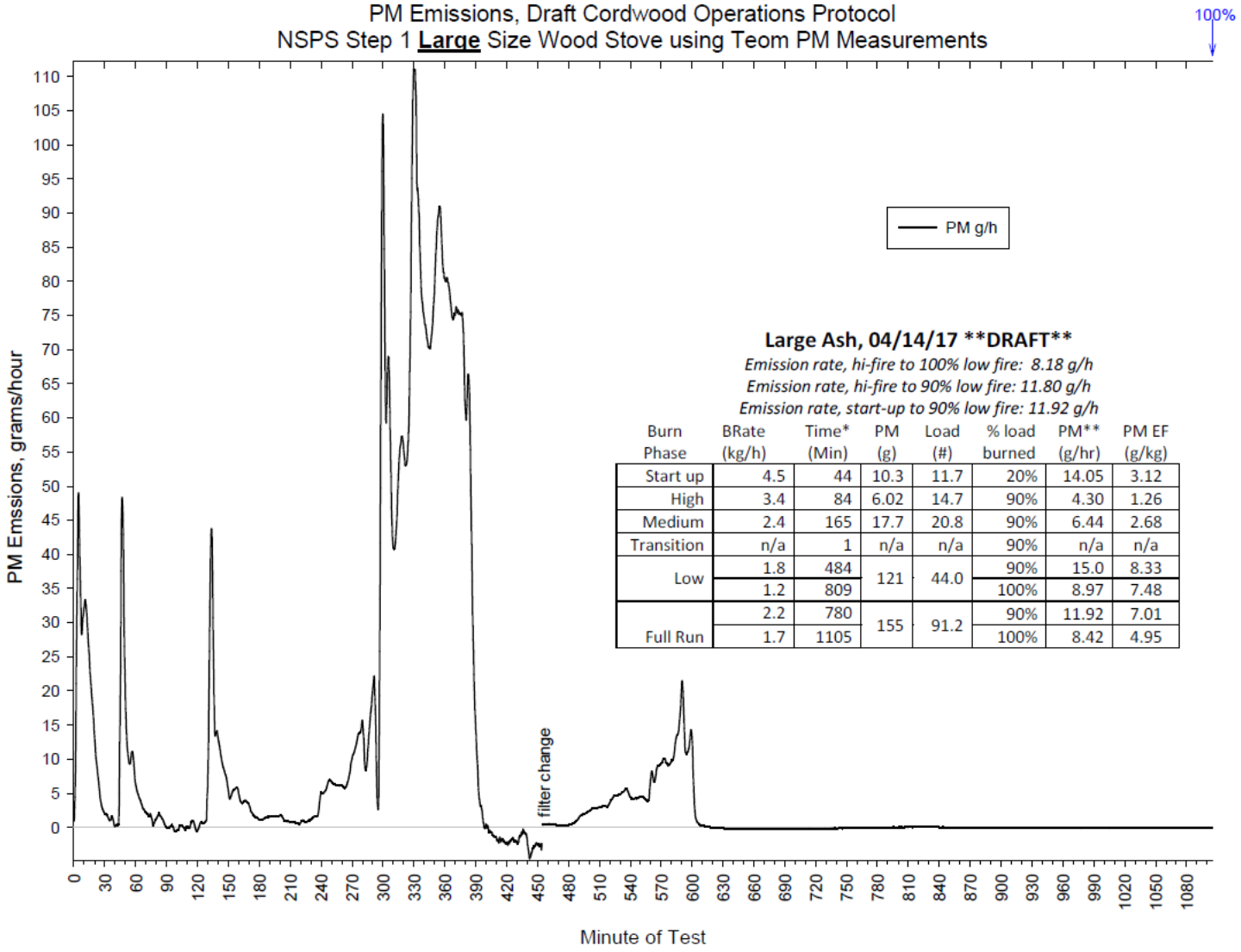


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	4.5	44	10.3	11.7	20%	14.05	3.12
High	3.4	84	6.02	14.7	90%	4.30	1.26
Medium	2.4	165	17.7	20.8	90%	6.44	2.68
Transition	n/a	1	n/a	n/a	90%	n/a	n/a
Low	1.8	484	121	44.0	90%	15.0	8.33
	1.2	809			100%	8.97	7.48
Full Run	2.2	780	155	91.2	90%	11.92	7.01
	1.7	1105			100%	8.42	4.95



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	4.5	44	10.3	11.7	20%	14.05	3.12
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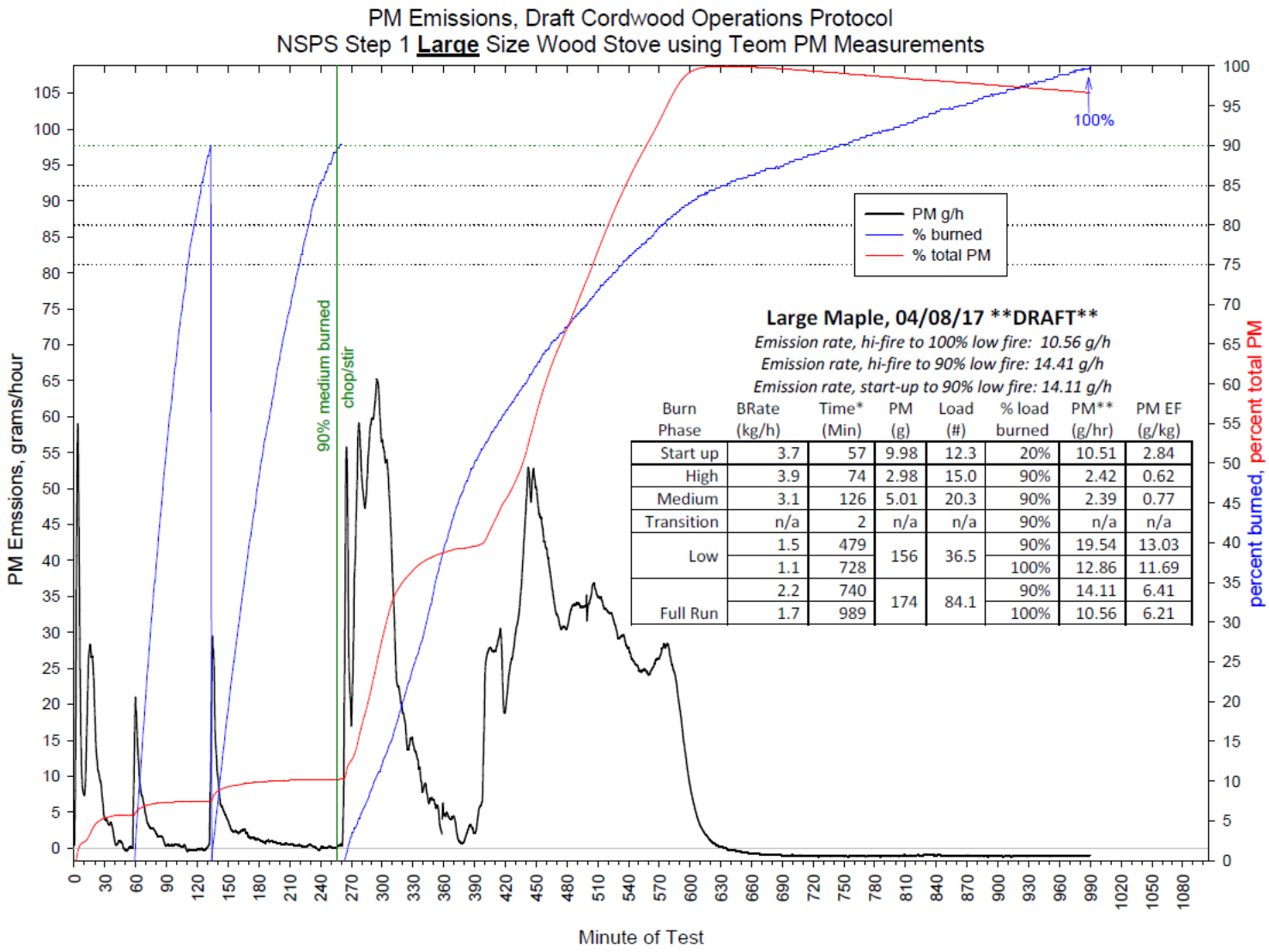
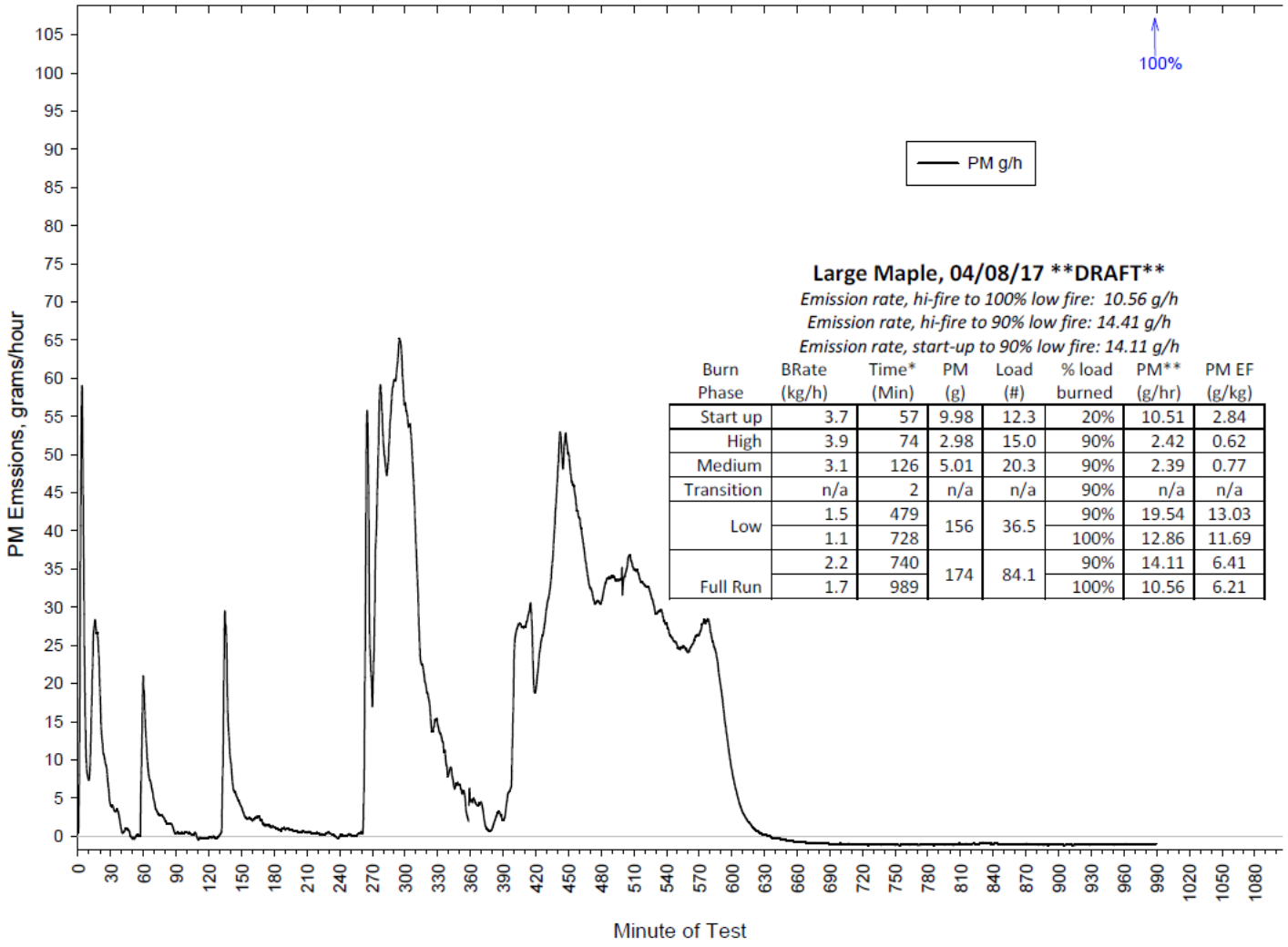


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
	1.7	989			100%	10.56	6.21

PM Emissions, Draft Cordwood Operations Protocol
NSPS Step 1 **Large** Size Wood Stove using Teom PM Measurements



Large Maple, 04/08/17 **DRAFT**

Emission rate, hi-fire to 100% low fire: 10.56 g/h
Emission rate, hi-fire to 90% low fire: 14.41 g/h
Emission rate, start-up to 90% low fire: 14.11 g/h

Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
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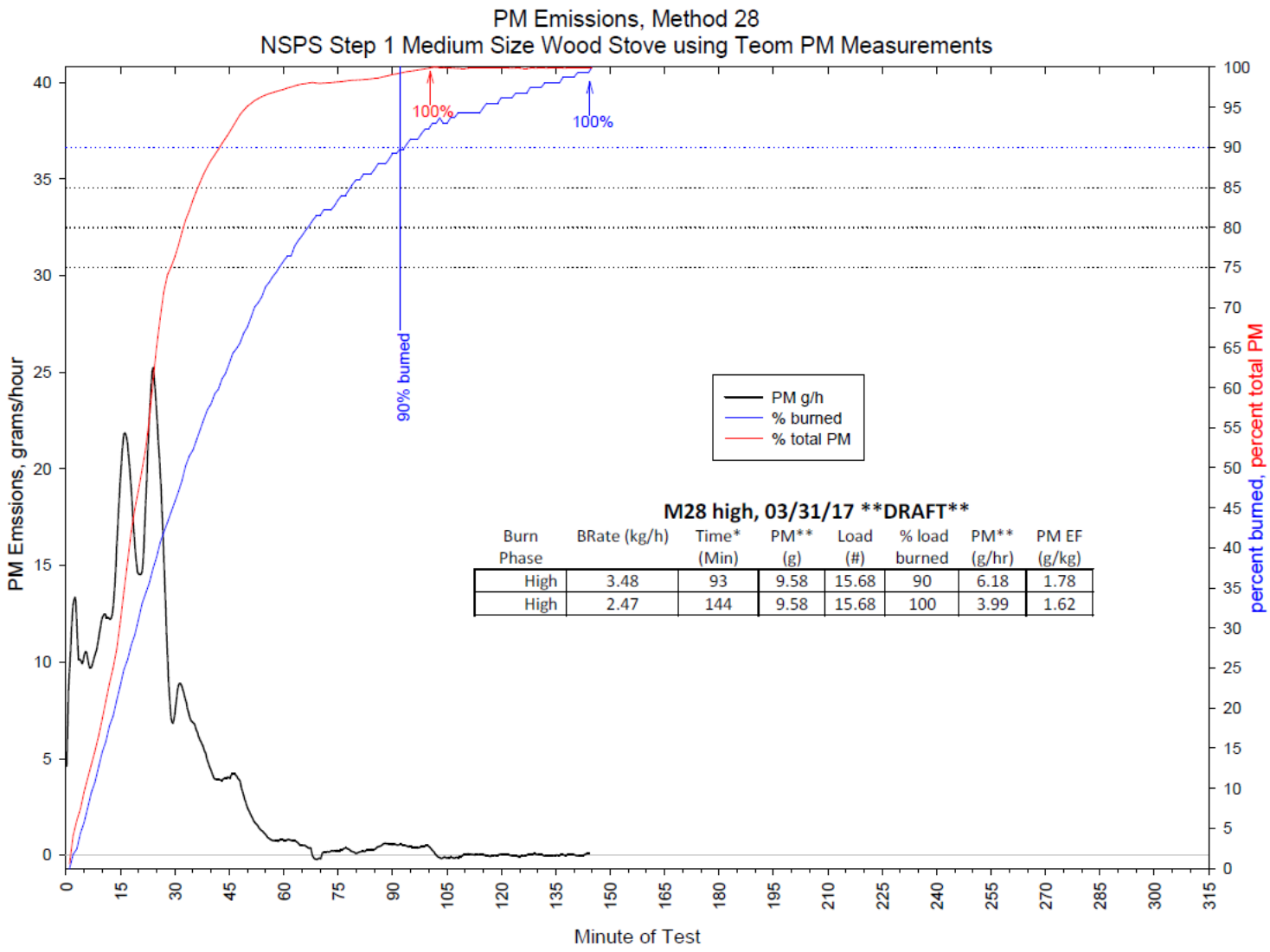
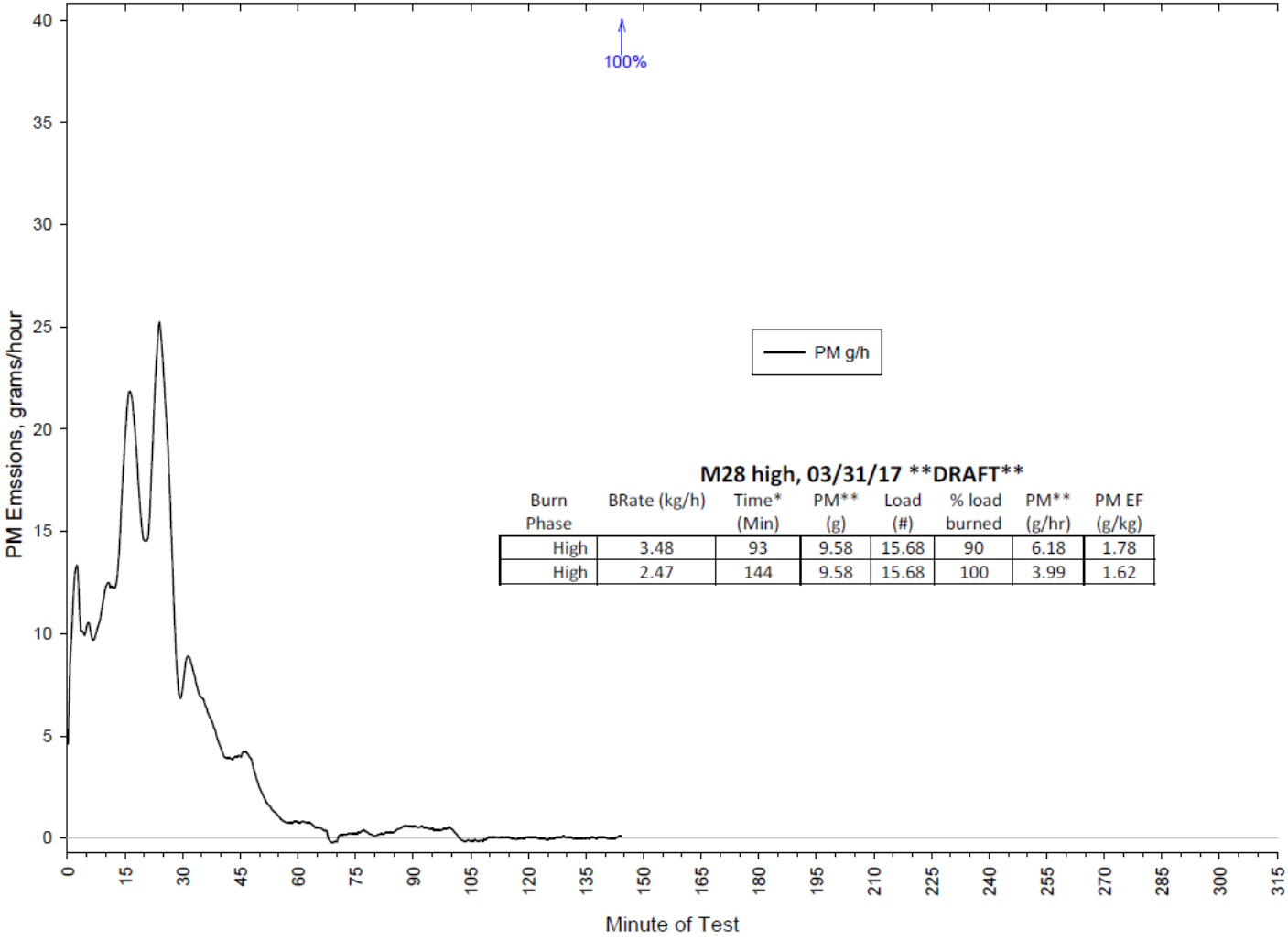


M28 high, 03/31/17 **DRAFT**

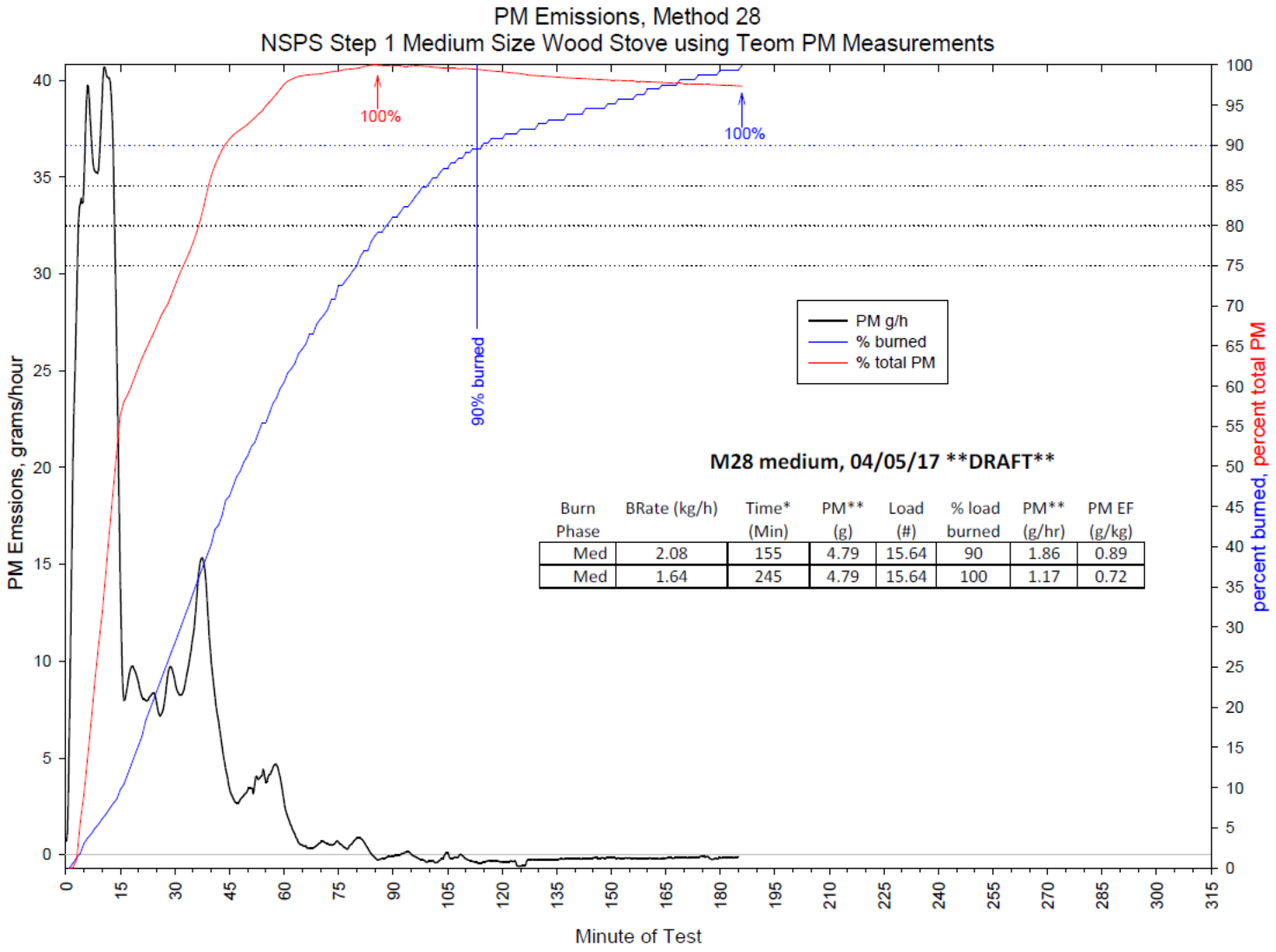
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62

PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements

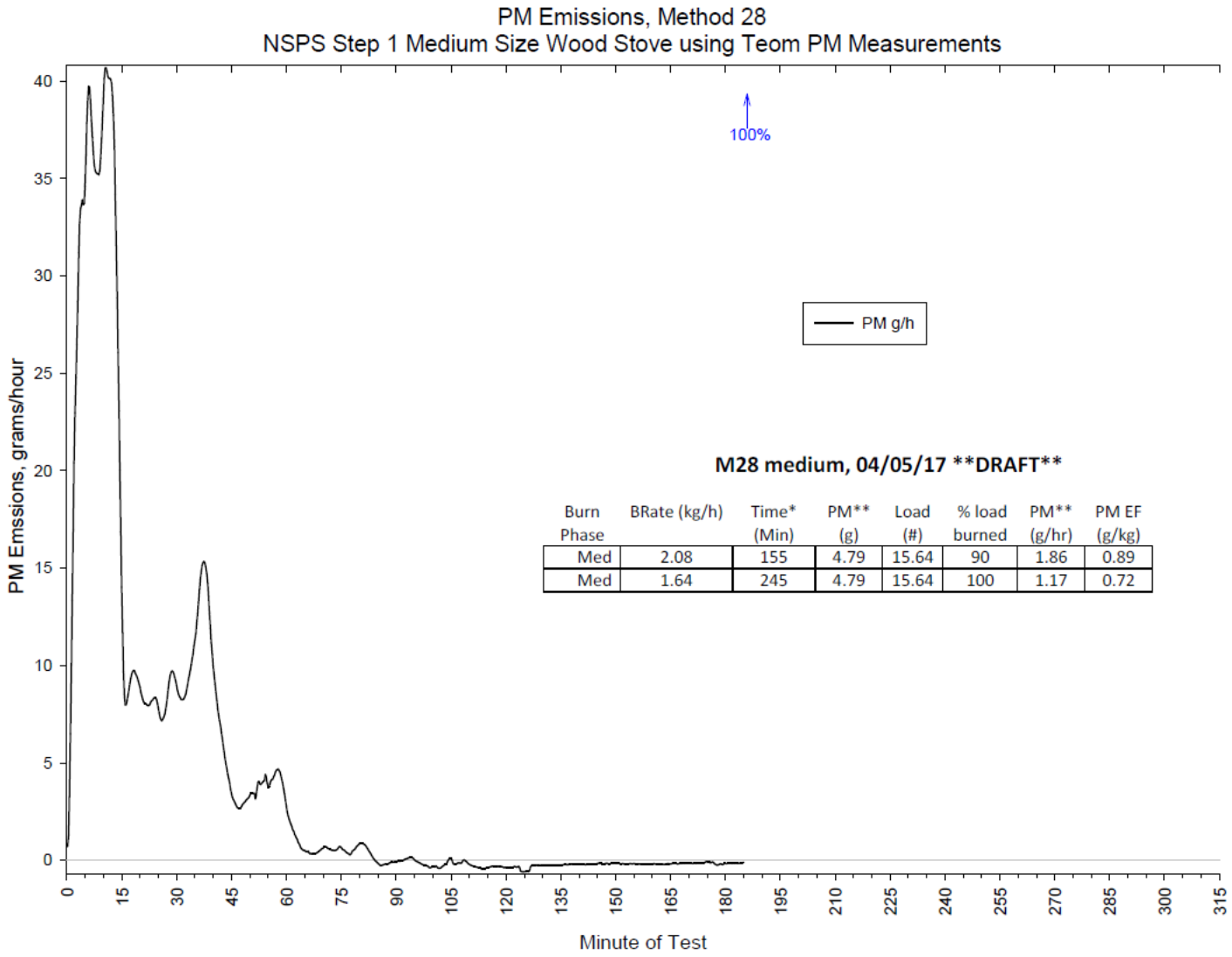


M28 high, 03/31/17 **DRAFT**

Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62

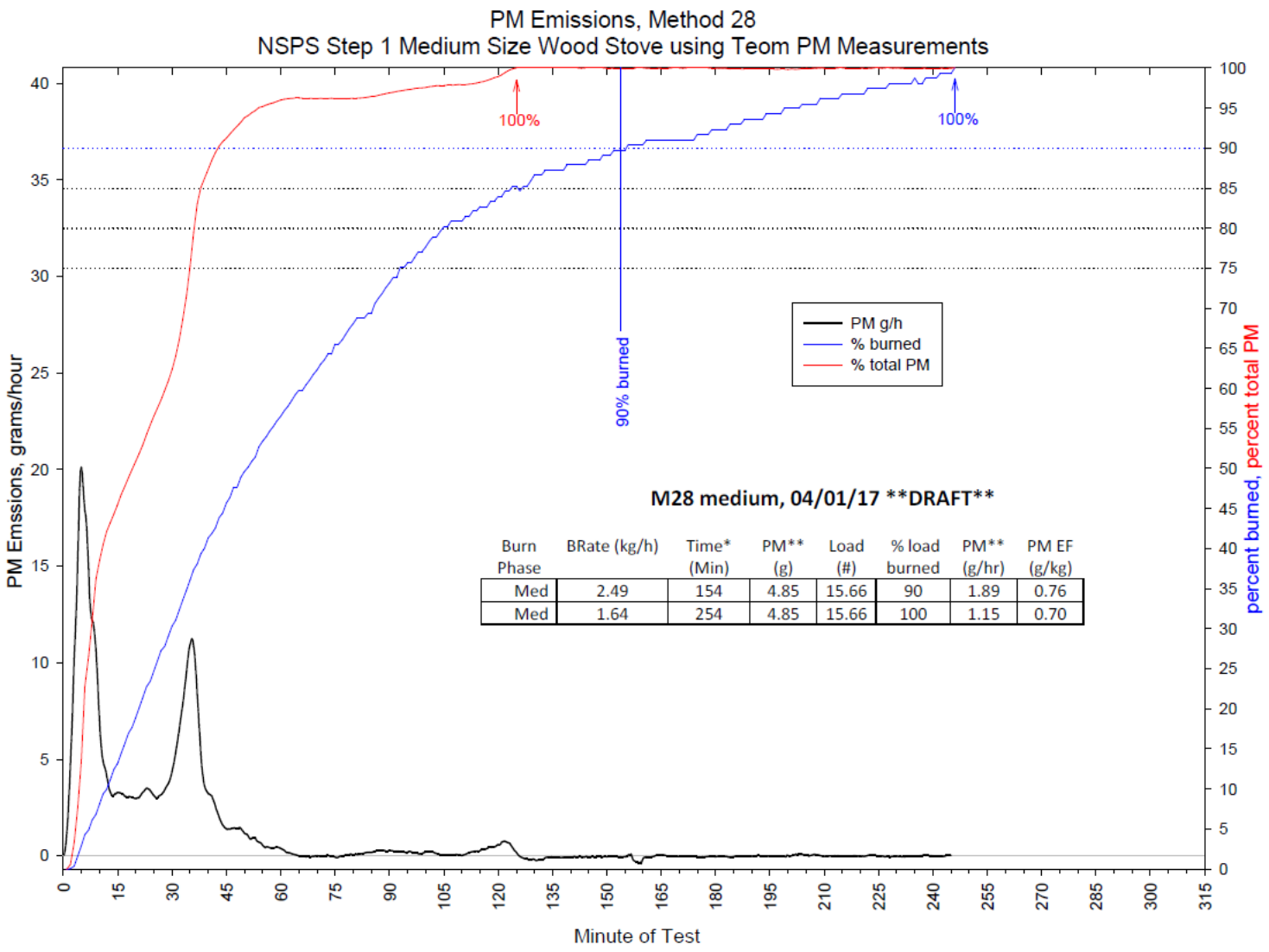


Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



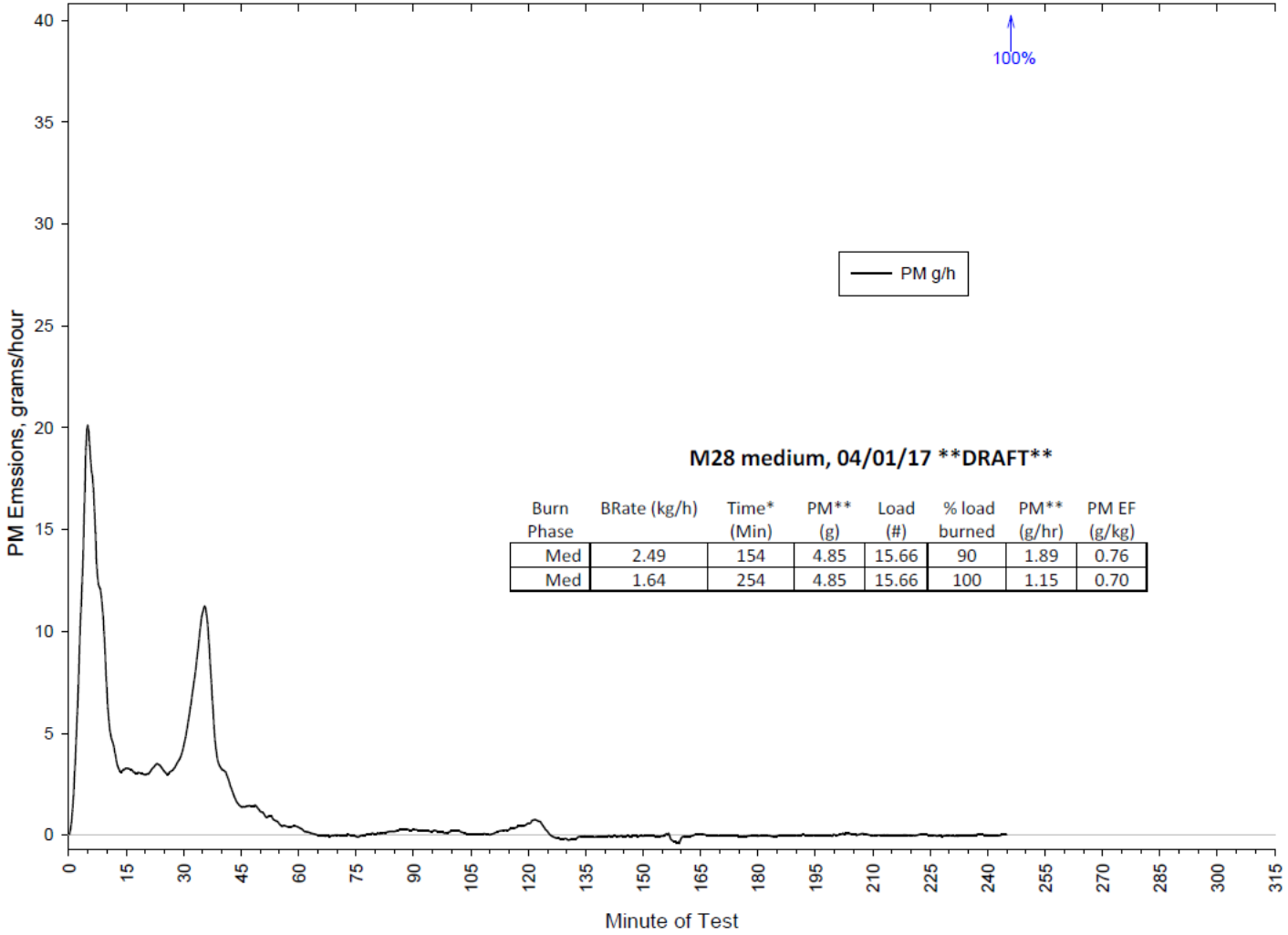
M28 medium, 04/05/17 **DRAFT**

Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



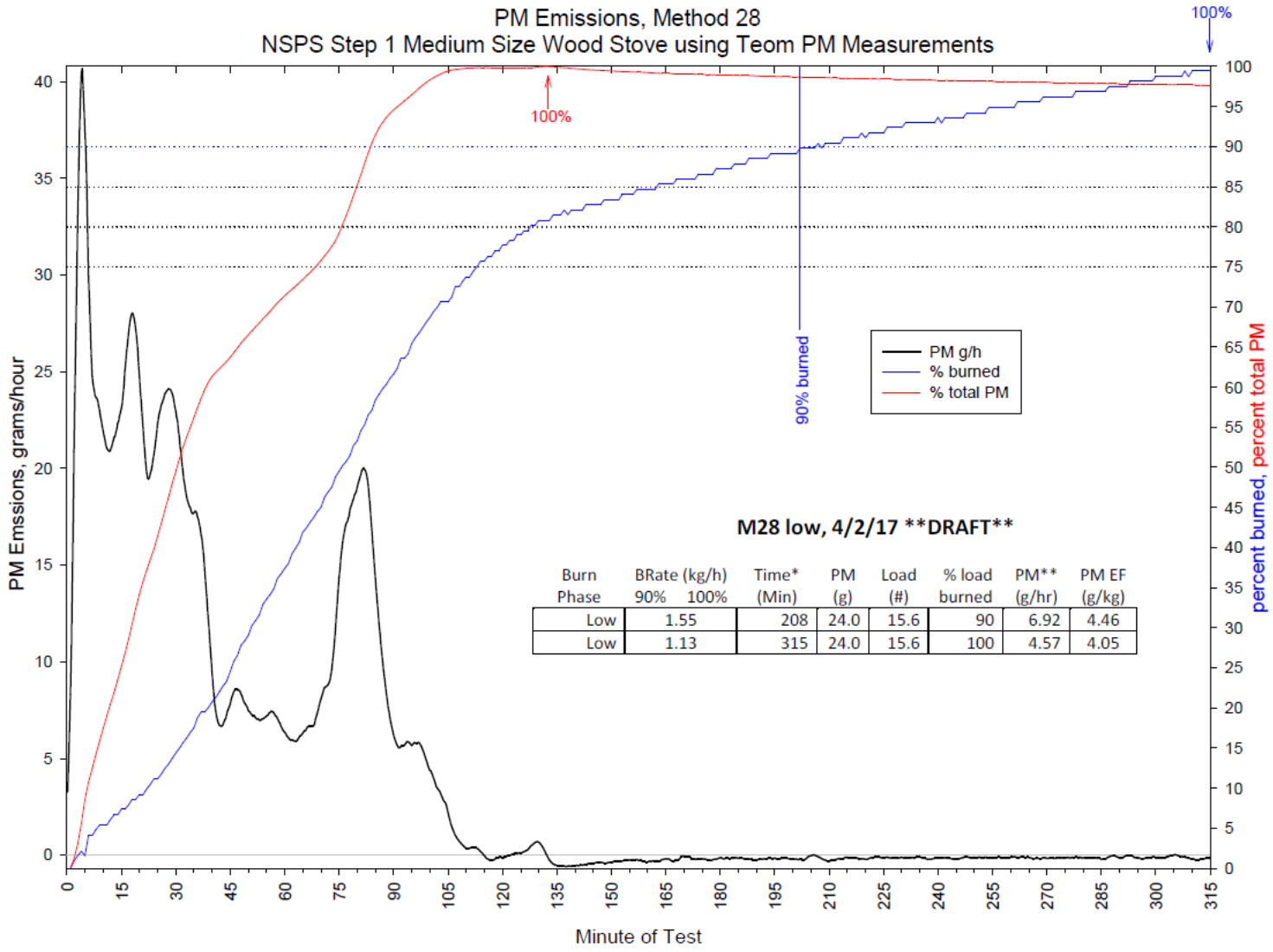
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70

PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements

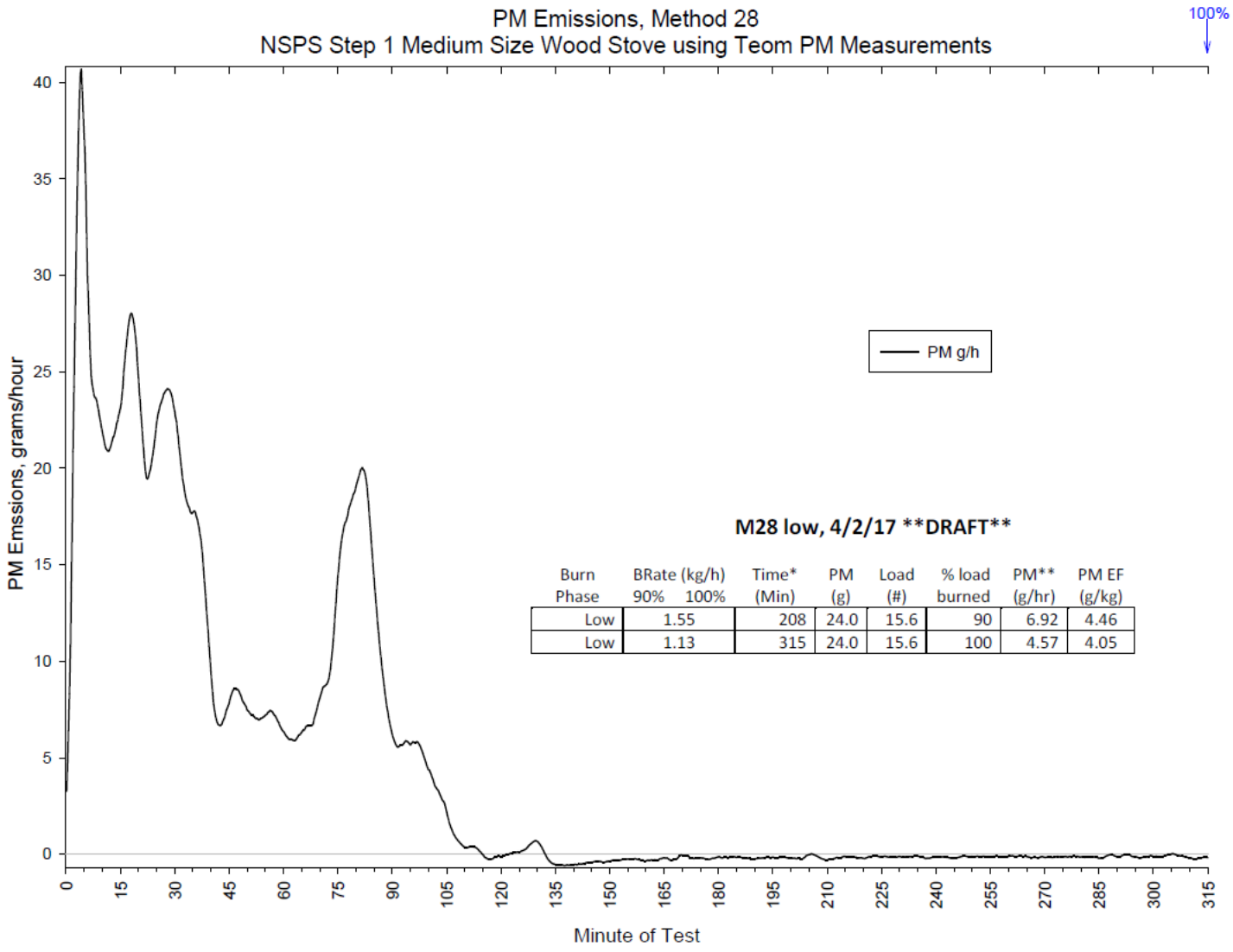


M28 medium, 04/01/17 **DRAFT**

Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70



Burn Phase	BRate (kg/h) 90%	BRate (kg/h) 100%	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Low	1.55		208	24.0	15.6	90	6.92	4.46
Low	1.13		315	24.0	15.6	100	4.57	4.05


PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements
100%
PM Emssions, grams/hour
Minute of Test
PM g/h
M28 low, 4/2/17 **DRAFT**
Burn Phase
BRate (kg/h) 90% 100%
Time* (Min)
PM (g)
Load (#)
% load burned
PM** (g/hr)
PM EF (g/kg)
Low 1.55 208 24.0 15.6 90 6.92 4.46
Low 1.13 315 24.0 15.6 100 4.57 4.05

Integrated Duty Cycle Protocol

12/11/2017

Overarching Goals

- Protocol Goals
  - Reflect typical loading patterns
  - Reflect typical operating patterns
  - Address variability by completing multiple runs of the same protocol
- Meeting Goals
  - Timeline development
  - Identify areas that need data from research runs
  - Identify areas of consensus

Protocol Overview

- Compress entire protocol into a single day test
  - Burn phases: startup, high, medium, medium-low transition, and low
    - Phases attempt to reflect common daily user practices such as start-up and reloads.
    - Phases end when 90% of fuel charge is burned.
    - Three reloads during the protocol, with different coal bed weights.
  - Piece sizes vary with phase:
    - Start-up kindling and starter – 4 lb/ft^3
    - High-fire: small pieces – 5 lb/ft^3
    - Medium-fire: large pieces – 7 lb/ft^3
    - Low-fire: mix of small and medium pieces – based on firebox capacity – min of 9 lb/ft^3

Changes from last iteration

- Operational protocol limited changes
  - Provide a range for coal bed weights for reload. Need to discuss what a reasonable range is and how to apply.
- Fueling protocol – major changes
  - Addressed typos that changed meaning in last iteration
  - Created draft fueling calculator
    - De minimus kindling for small stoves of 1 lb. Thoughts on maximum amount?
    - Changed target load piece sizes based on density of fuel used.

Testing/Research at HLS

Six stoves

1. High mass construction, large firebox, tube/non-cat emission controls
2. High mass construction, small firebox, catalytic emission controls
3. Steel construction, large firebox, catalytic emission controls
4. Cast iron construction, small firebox, tube/non-cat emission controls
5. Cast iron construction, medium firebox, non-cat/non-tube emission controls (this is likely a top loading unit)
6. Steel construction, medium firebox, tube/non-cat emission controls

Birch – start-up, high and medium fuel charge

Maple – start-up, high and medium fuel charge

Oak – start-up, high and medium fuel charge

Issues Raised on IDC test method

- Fuel loading parameters
  - Configuration laid out in test method or manufacturers instructions?
- Is it really one day, does it save time? Need to consider time for pre-burns that are used in M28
  - Timing analysis for medium stove
    - M28 ~1780 minutes of burning – one preburn
    - 3 runs of IDC ~1300 minutes of burning
- What is the passing grade?
  - Ending test at 90% cuts test run at each phase by 30-50%
- How do measure efficiency?
  - Move in the direction of ASHRAE standards or use TCC methods

Start Up Phase

Start-up load, large firebox – Washington State Protocol

Start-up load, medium firebox – Washington State Protocol

Kindling – 2 lb/ft^3

Comparison of Start Up Phase Data

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
4/7 –Maple	3.5	*38*	*2.7*	7.9	4.26	*1.22*
4/25 – Maple	2.3	58	6.65	7.8	6.88	2.99
4/26 – Maple	2.6	48	*3.05*	7.8	*3.81*	1.47
4/18 – Birch	2.0	65	5.47	7.7	5.05	2.52
4/29 – Birch	*1.8*	72	3.99	7.8	*3.33*	1.85
5/4 – Birch	2.4	55	6.57	7.8	7.17	2.99
Oak	3.4	*40*	11.6	7.9	16.9	3.7
Ash	2.9	*44*	4.4	7.6	6.2	2.1
Range	1.8 - 3.5	38 - 72	2.7 - 11.6	7.6 - 7.9	3.33 - 16.9	1.22 - 3.7
3 ft maple	3.7	57	9.98	12.3	10.51	2.84
3 ft ash	4.5	44	10.3	11.7	14.05	3.12

Start Up Phase Discussion Items

- Loading density
  - Amount of kindling
  - Starter fuel
  - Capacity to use in a wide variety of stoves sizes and configurations
- Load configuration
  - Manufacturers instructions
  - Prescribed conditions
- End of Phase
  - Questions about size of coal bed to light off high fire

Integrated Duty Cycle Test Method

HIGH FIRE PHASE

High Fire Discussion Items

- Timing of placing the high fire load
  - It appears that wood could loaded earlier
- Amount of wood loaded
  - 5lbs per ft^3 - is it enough? What happens to timing?

Comparison of High Fire Phase Data

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
M28/10 Doug Fir	2.47	144	9.58	15.68	3.99	1.62
M28/90 Doug Fir	3.48	93	9.58	15.68	6.18	1.78
4/7 –Maple	3.0	61	6.0	*9.3*	5.90	1.97
4/25 – Maple	*2.4*	78	*3.17*	9.5	*2.44*	*1.02*
4/26 – Maple	3.3	55	4.17	9.8	4.55	1.38
4/18 – Birch	3.3	59	6.08	9.8	6.18	1.87
4/29 – Birch	3.6	54	7.15	9.9	3.33	1.85
5/4 – Birch	4.1	*47*	5.96	9.8	7.61	1.86
Oak	3.6	52	5.7	9.4	6.2	1.7
Ash	3.0	69	8.0	10.2	6.9	2.3
Range med stove	2.4 - 4.1	47 - 78	3.17 – 8.0	9.3 – 10.2	2.44 – 7.61	1.02 – 2.3
3 ft maple	3.9	74	2.98	15.0	2.42	0.62
3 ft ash	3.4	84	6.02	14.7	4.30	1.26

Integrated Duty Cycle Protocol

MEDIUM FIRE PHASE

Medium Fire Phase

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
M28 Doug Fir	2.49	154	4.85	15.66	1.89	0.76
	2.08	155	4.79	15.64	1.86	0.89
4/7 Maple	2.9	88	6.2	13.3	4.23	1.46
4/25 Maple	2.3	117	12.7	13.6	6.51	2.83
4/26 Maple	*2.1*	125	7.77	14.0	3.73	1.78
4/18 Birch	2.9	90	*4.45*	13.0	*2.97*	*1.02*
4/29 Birch	2.8	95	5.34	13.6	3.38	1.2
5/4 Birch	3.4	82	5.18	14.0	3.79	1.11
Oak	3.6	*52*	5.7		6.2	1.7
Ash	3.0	69	8.0		6.9	2.3
Range	2.1 – 3.6	52-125			2.97 – 6.9	1.02 – 2.83
3 ft maple	3.9	74	2.98	15.0	2.42	0.62
3 ft ash	3.4	84	6.02	14.7	4.30	1.26

Medium Fire Discussion Items

- Transition to low burn
- Fuel adjustments

Integrated Duty Cycle Protocol

LOW FIRE PHASE

Coal bed before load low added

Birch – low load pile, all but two small pieces were loaded

Low Fire Phase Data

Stove size	Species	Rate (kg/h)	Time (Min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
2 ft^3	M28 doug fir – 100%	1.13	315	24.0	15.6	4.57	4.05
2 ft^3	M28 doug fir – 90%	1.55	208	24.0	15.6	6.92	4.46
2 ft^3	Oak	1.9	209	NA	20.5	13.7	6.4
2 ft^3	Ash	1.5	364	NA	28.0	7.1	4.6
2 ft^3	Birch	1.8	223	35.6	20.4	9.58	5.32
2 ft^3	Birch	2.0	193	59.8	20.6	18.57	9.30
2 ft^3	Birch	1.7	200	17.6	17.7	5.28	3.11
2 ft^3	Maple	1.8	219	31.4	20.1	8.60	4.78
2 ft^3	Maple	2.0	168	12.8	17.0	4.57	2.29
2 ft^3	Maple	1.5	208	32.3	17.7	9.32	6.21
2ft	Range	1.5 – 2.0	168 – 364		17.0 – 28.0	4.57 – 18.57	2.29 – 9.30
3ft^3	Maple	1.5	479	156	36.5	19.54	13.03
3 ft^3	Ash	1.8	484	121	44.0	15.0	8.33

Comparison of Low-Fire Phase 90 vs 100

Run Species	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr) @90%	PM EF (g/kg) @90%
M28 Doug Fir	1.55	208	24	15.6	6.92	4.46
	1.33	*315*	*24*	*15.6*	*4.57*	*4.05*
4/7 Maple	1.8	219	31.4	20.1	8.60	4.78
	1.1	*411*	*31.4*	*20.1*	*4.58*	*4.17*
4/25 Maple	2.0	168	12.8	17.0	4.57	2.29
	1.1	*340*	*12.8*	*17.0*	*2.26*	*2.05*
4/26 Maple	1.5	208	32.3	17.7	9.32	6.21
	1.1	*321*	*32.3*	*17.7*	*6.04*	*5.49*
4/18 Birch	1.8	223	35.6	20.4	9.58	5.32
	1.1	*420*	*35.6*	*20.4*	*5.09*	*4.62*
4/29 Birch	2.0	193	59.8	20.6	18.57	9.30
	1.1	*404*	*59.8*	*20.6*	*8.89*	*8.07*
5/4 Birch	1.7	200	17.6	17.7	5.28	3.11
	1.1	*342*	*17.6*	*17.7*	*3.09*	*2.57*

FULL RUN ANALYSIS

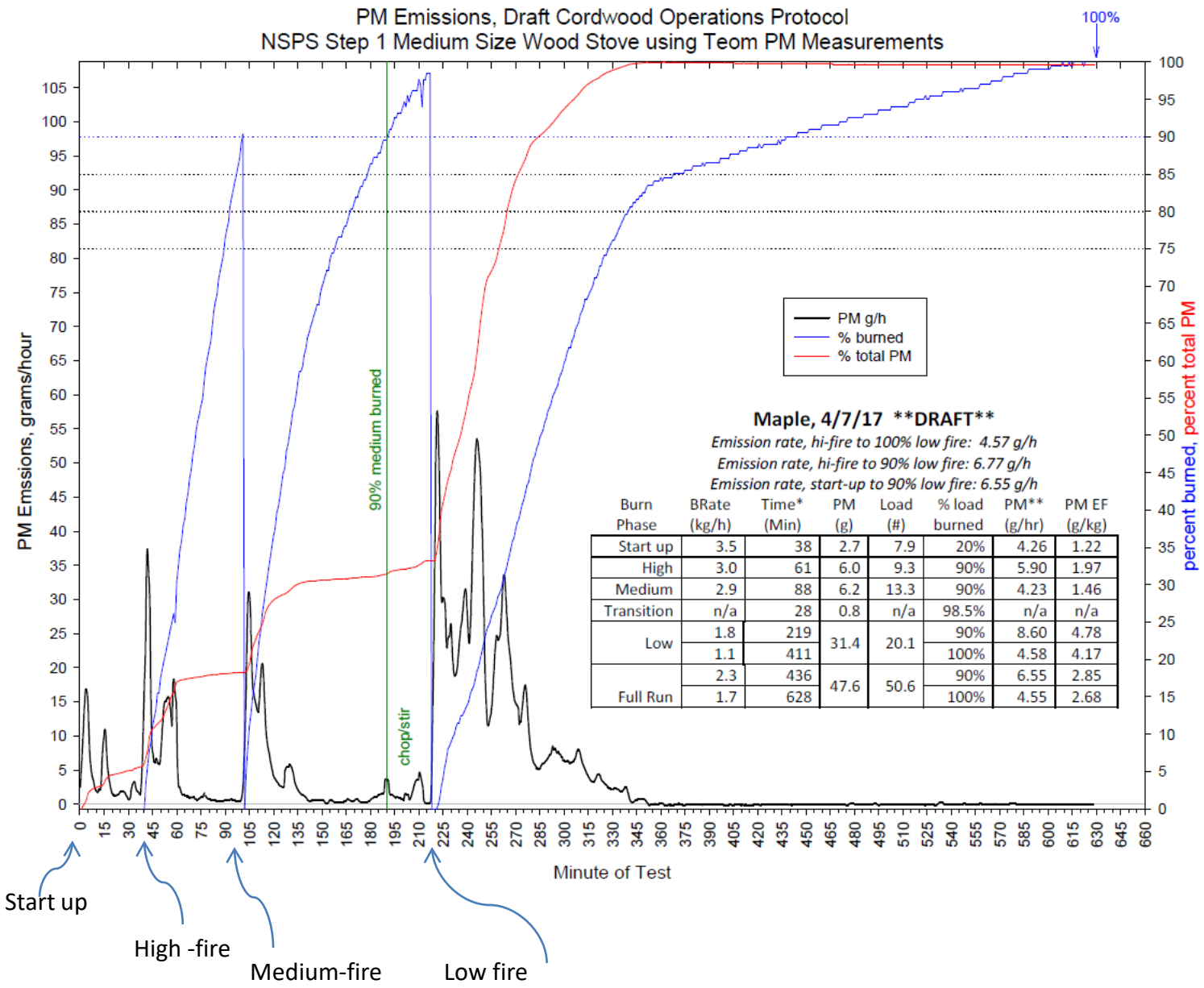
Analysis Full Runs

Birch

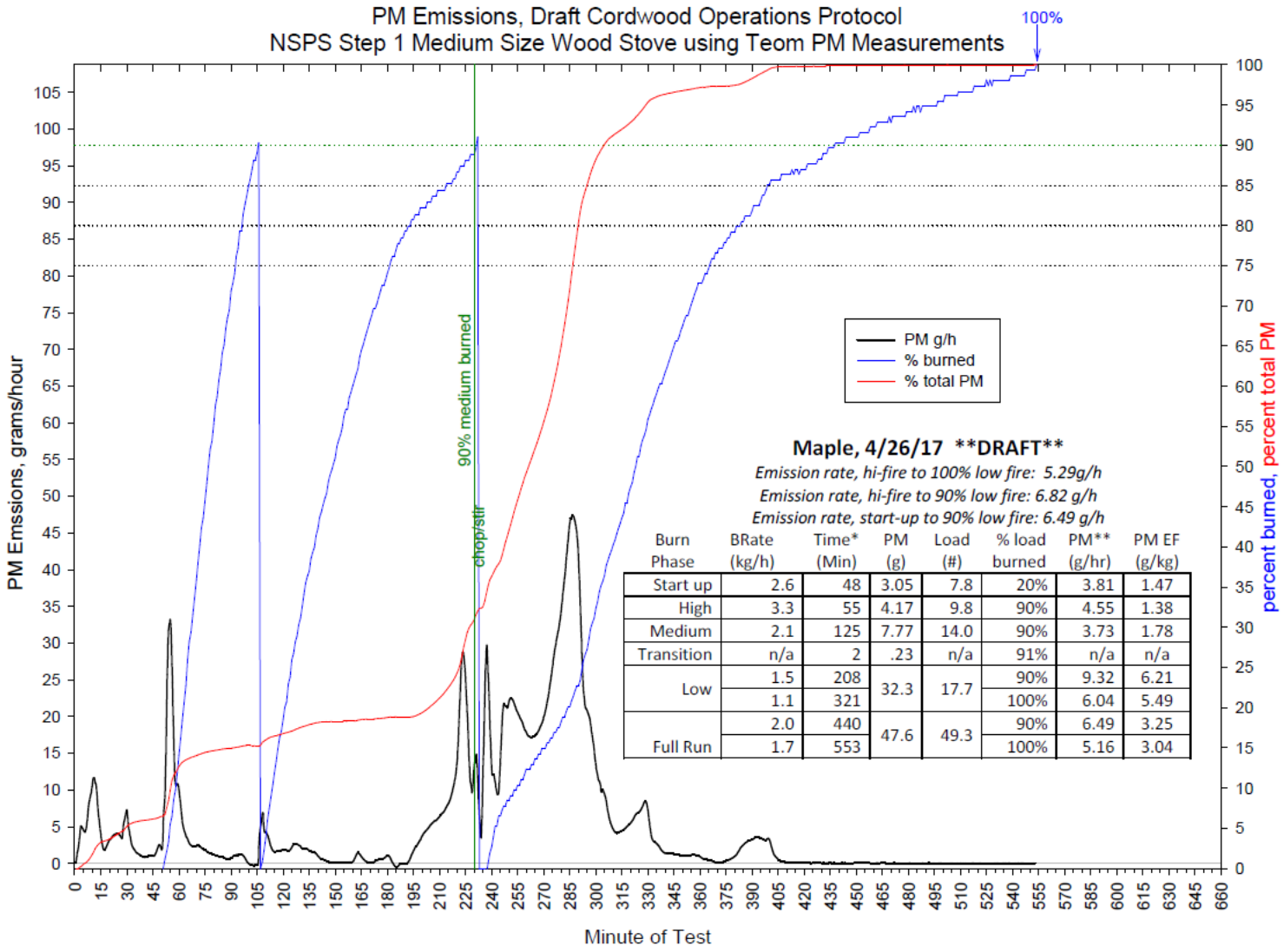
Run	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
4/18	2.2	460	51.7	50.9	6.74	3.07
4/29	2.3	430	76.6	51.8	11.38	4.95
5/4	2.5	392	35.3	49.3	5.40	2.16

Maple

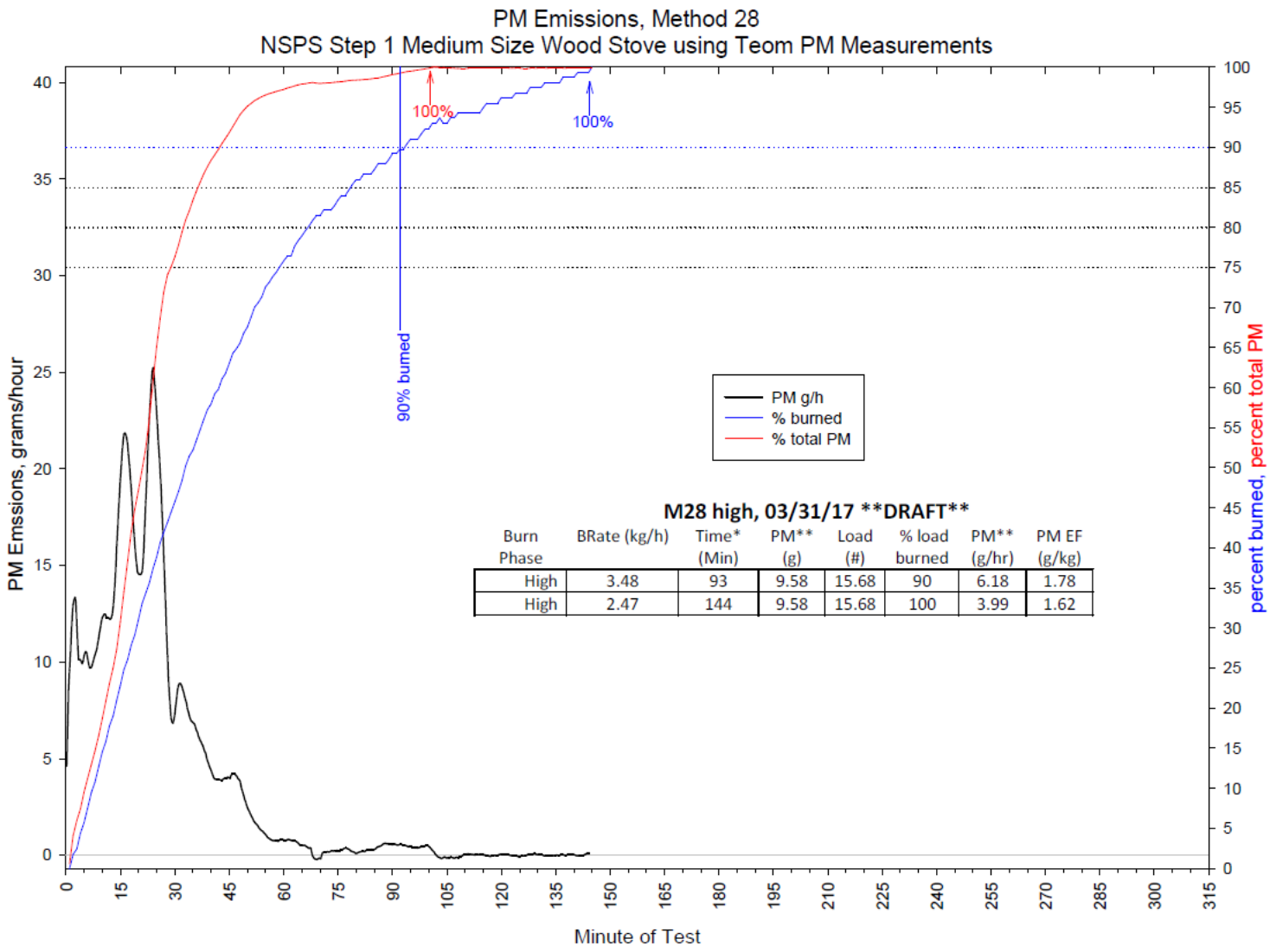
Run	Burn Rate (g/kg)	Time (min)	PM (g)	Load (#)	PM (g/hr)	PM EF (g/kg)
4/7	2.3	436	47.6	50.5	6.55	2.85
4/25	2.2	432	35.6	47.9	4.94	2.25
5/4	2.0	440	47.6	49.3	6.49	3.25



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.5	38	2.7	7.9	20%	4.26	1.22
High	3.0	61	6.0	9.3	90%	5.90	1.97
Medium	2.9	88	6.2	13.3	90%	4.23	1.46
Transition	n/a	28	0.8	n/a	98.5%	n/a	n/a
Low	1.8	219	31.4	20.1	90%	8.60	4.78
	1.1	411			100%	4.58	4.17
Full Run	2.3	436	47.6	50.6	90%	6.55	2.85
	1.7	628			100%	4.55	2.68

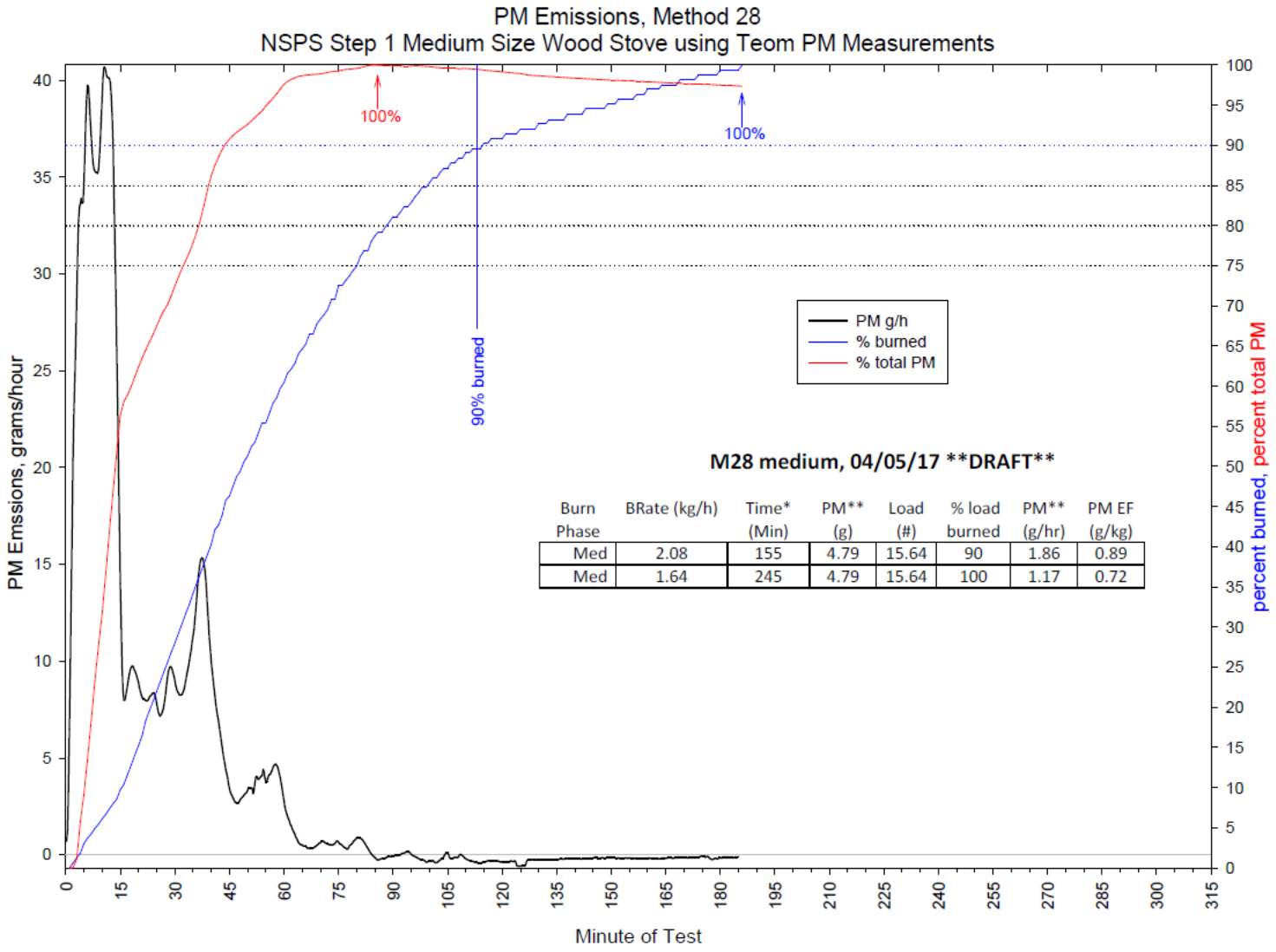


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.6	48	3.05	7.8	20%	3.81	1.47
High	3.3	55	4.17	9.8	90%	4.55	1.38
Medium	2.1	125	7.77	14.0	90%	3.73	1.78
Transition	n/a	2	.23	n/a	91%	n/a	n/a
Low	1.5	208	32.3	17.7	90%	9.32	6.21
	1.1	321			100%	6.04	5.49
Full Run	2.0	440	47.6	49.3	90%	6.49	3.25
	1.7	553			100%	5.16	3.04

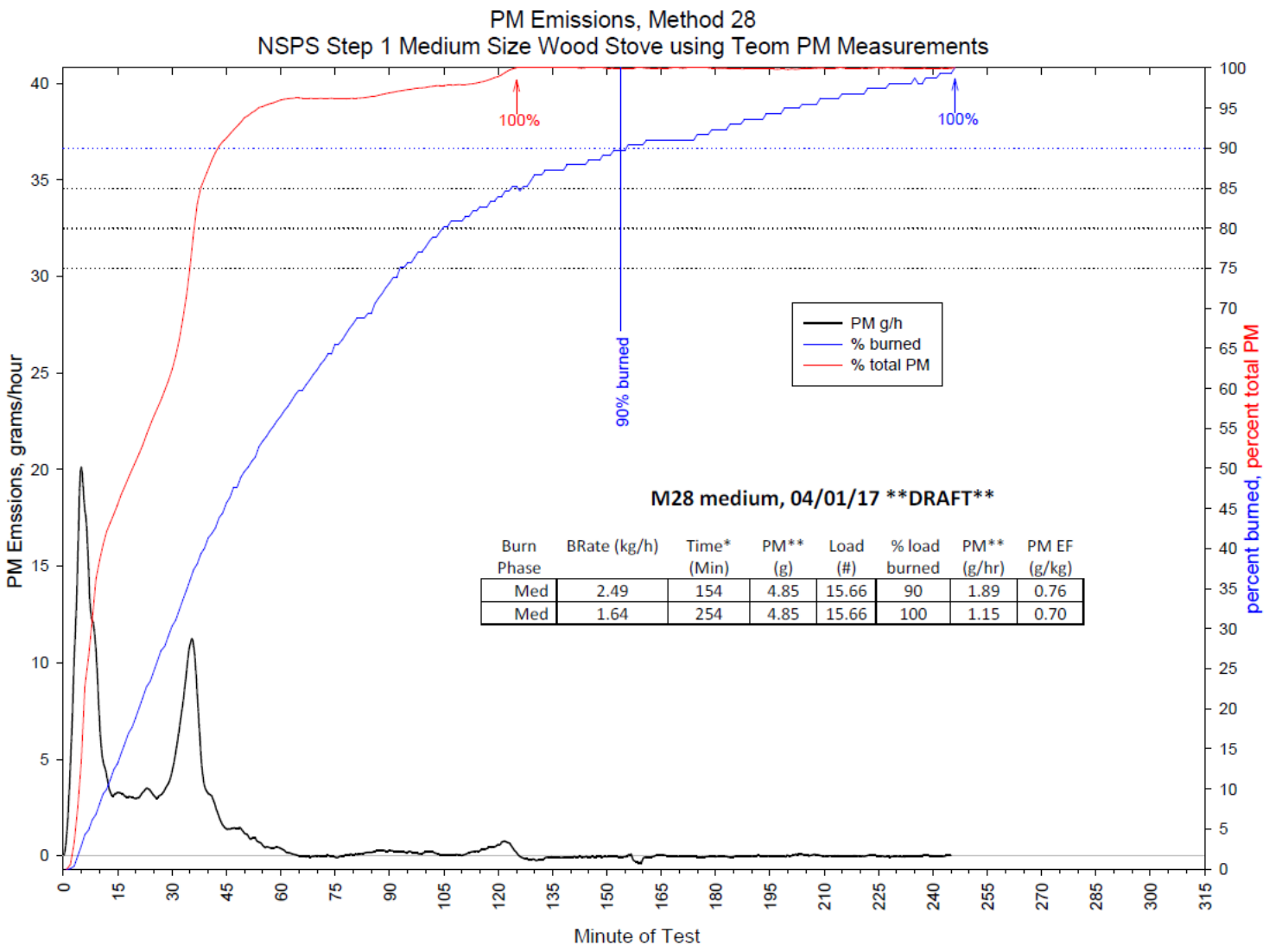


M28 high, 03/31/17 **DRAFT**

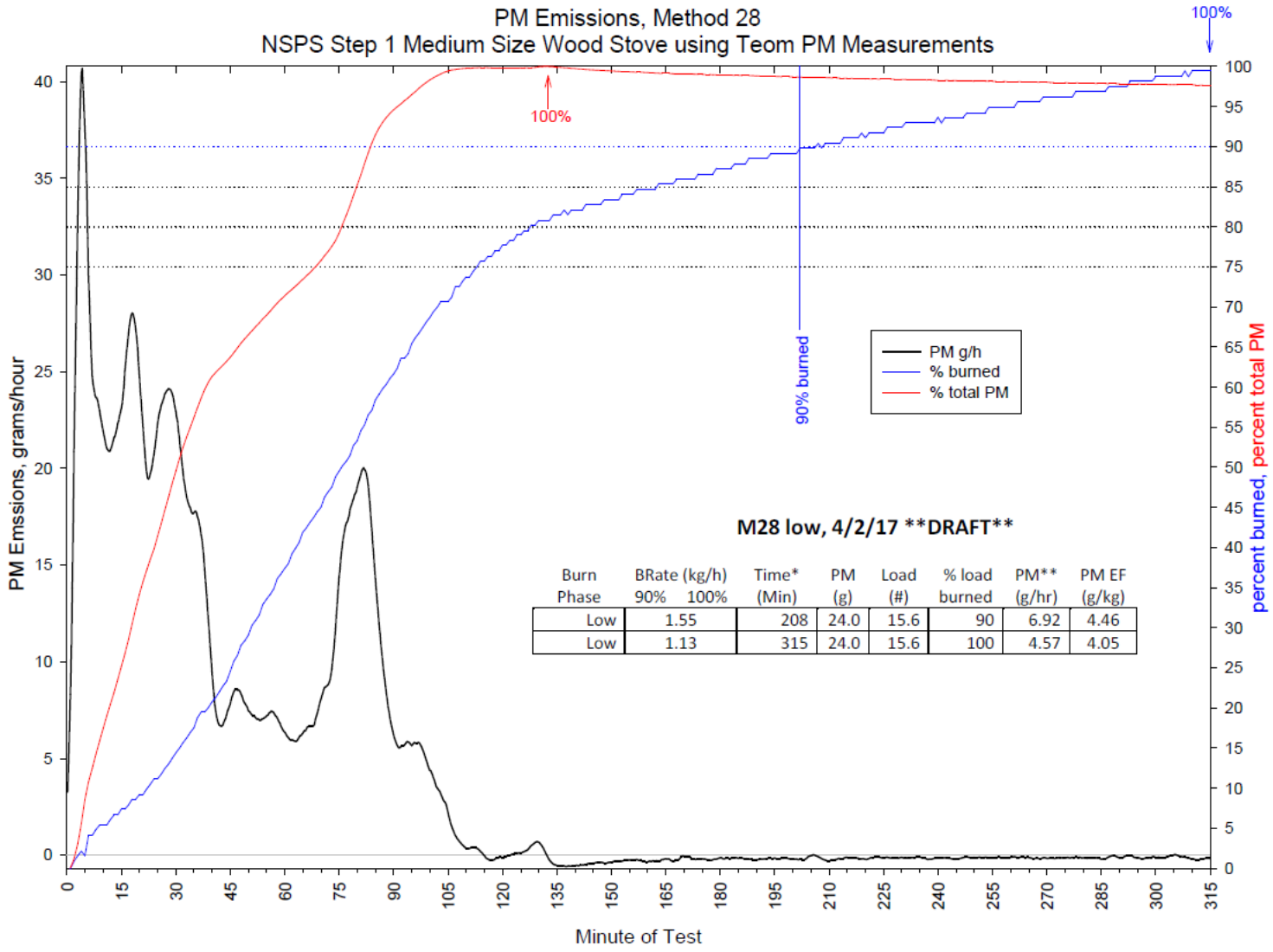
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62



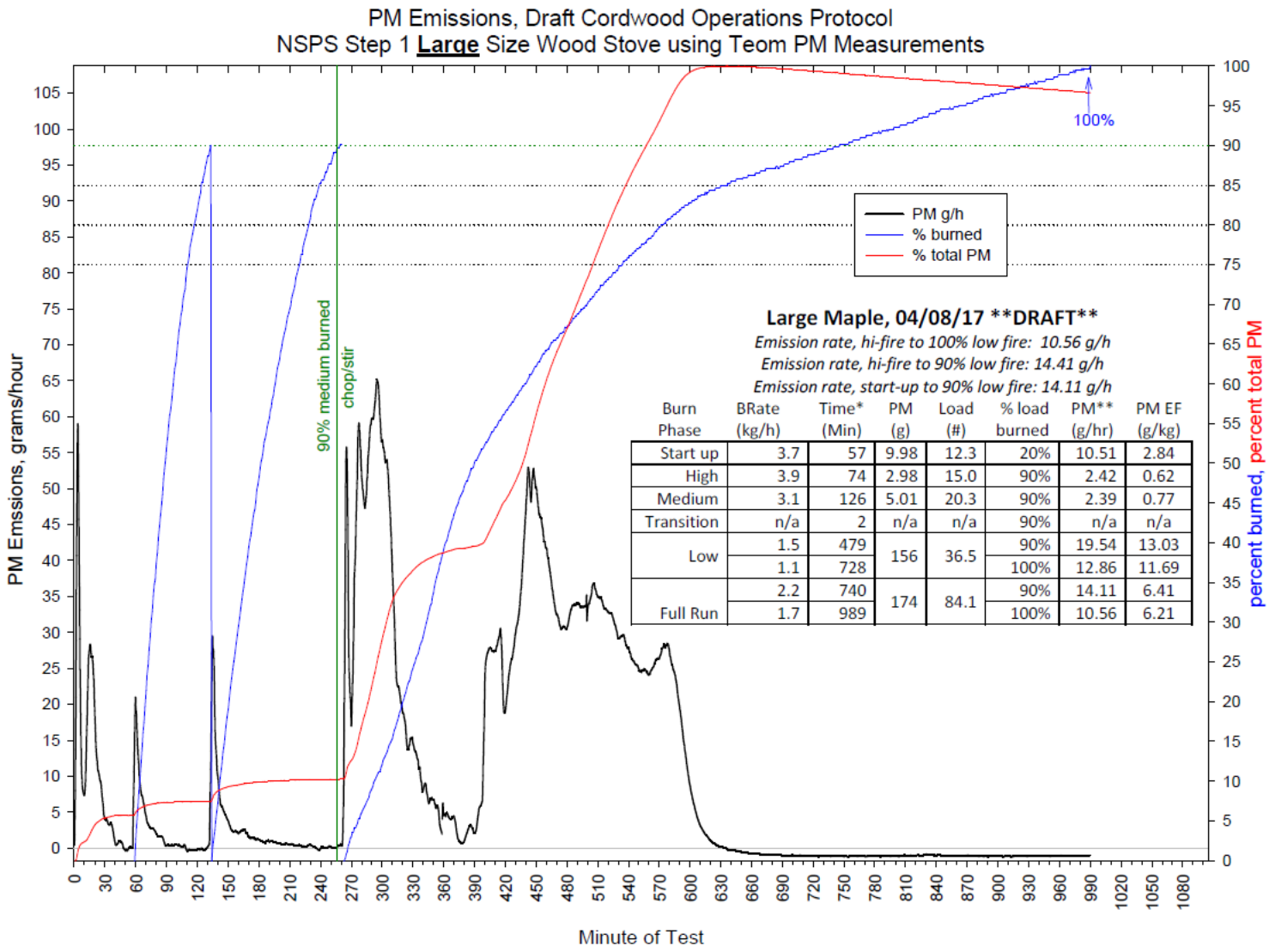
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



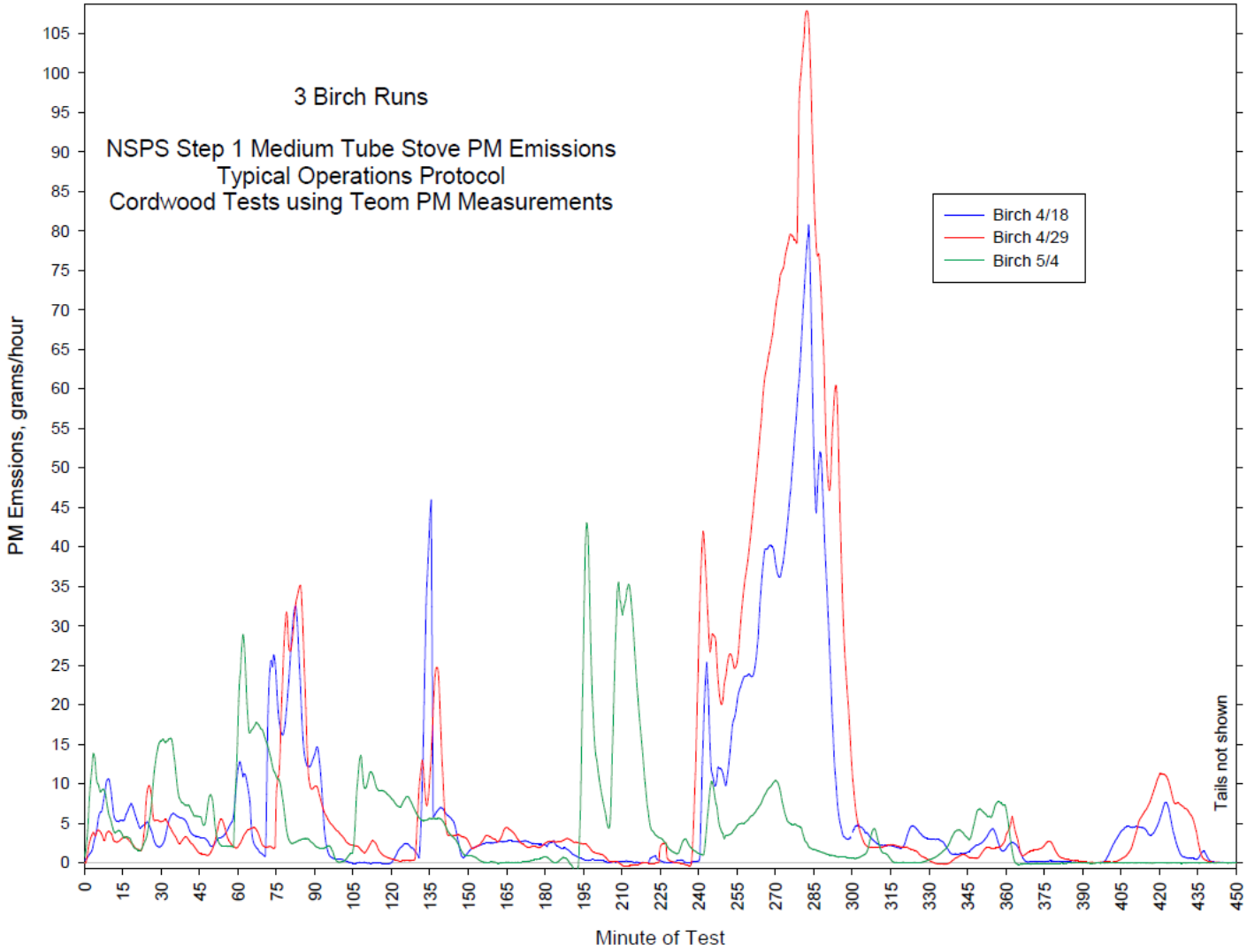
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70

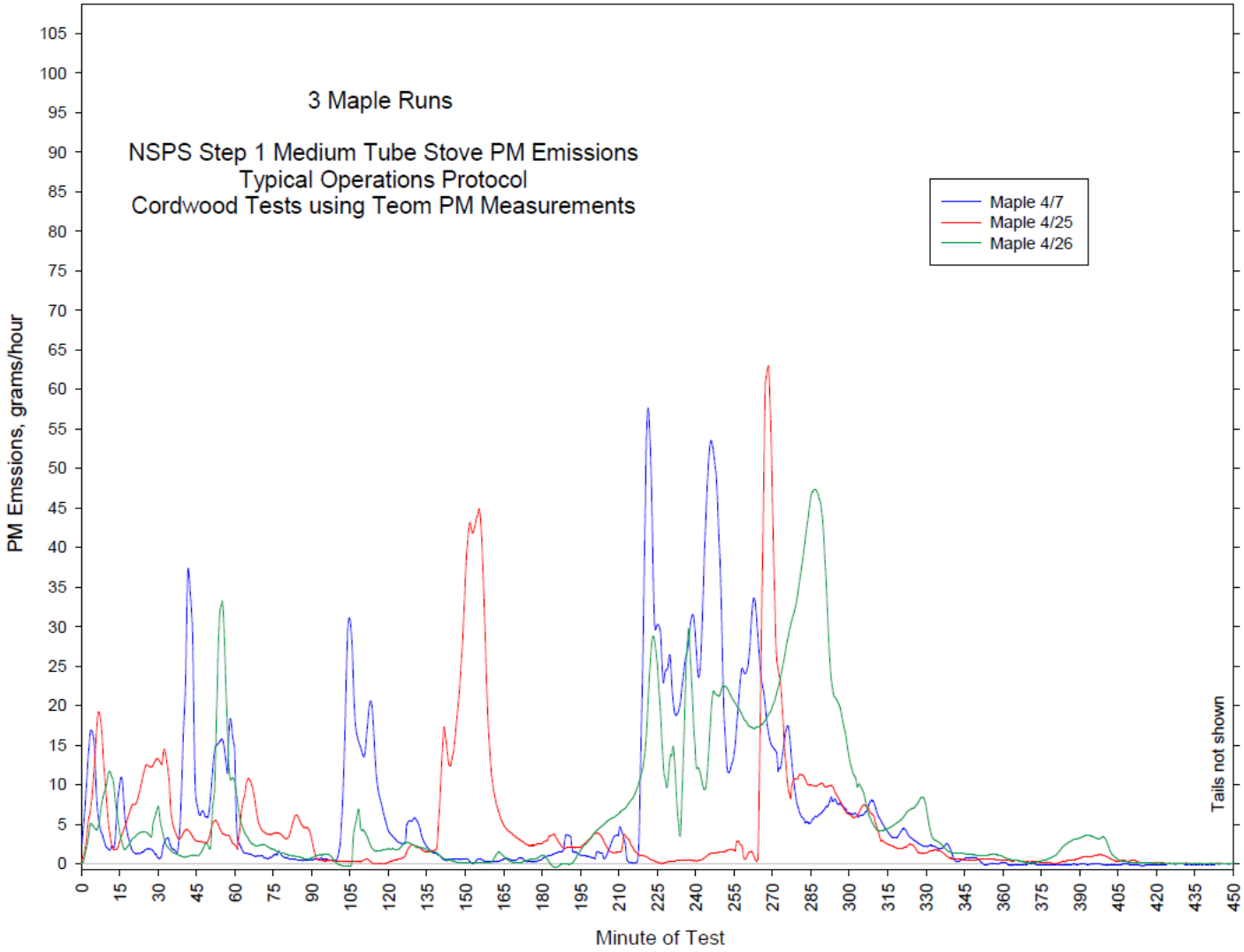


Burn Phase	BRate (kg/h) 90%	BRate (kg/h) 100%	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Low	1.55		208	24.0	15.6	90	6.92	4.46
Low	1.13		315	24.0	15.6	100	4.57	4.05



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
	1.7	989			100%	10.56	6.21


3 Birch Runs
NSPS Step 1 Medium Tube Stove PM Emissions
Typical Operations Protocol
Cordwood Tests using Teom PM Measurements
Birch 4/18
Birch 4/29
Birch 5/4
PM Emssions, grams/hour
Minute of Test
Tails not shown
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
255
270
285
300
315
330
345
360
375
390
405
420
435
450


3 Maple Runs
NSPS Step 1 Medium Tube Stove PM Emissions
Typical Operations Protocol
Cordwood Tests using Teom PM Measurements
Maple 4/7
Maple 4/25
Maple 4/26
PM Emssions, grams/hour
Minute of Test
Tails not shown
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
0
15
30
45
60
75
90
105
120
135
150
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330
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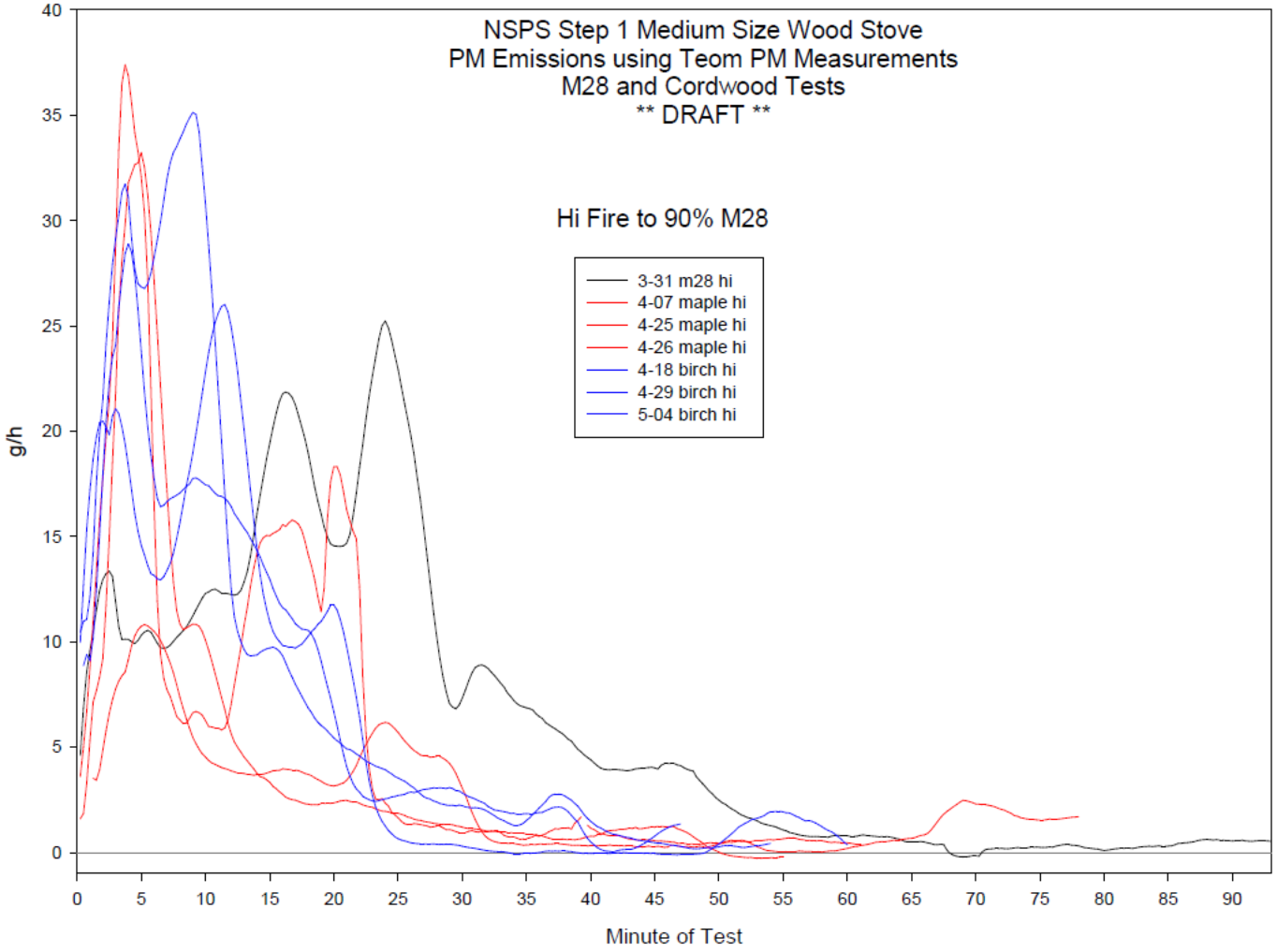
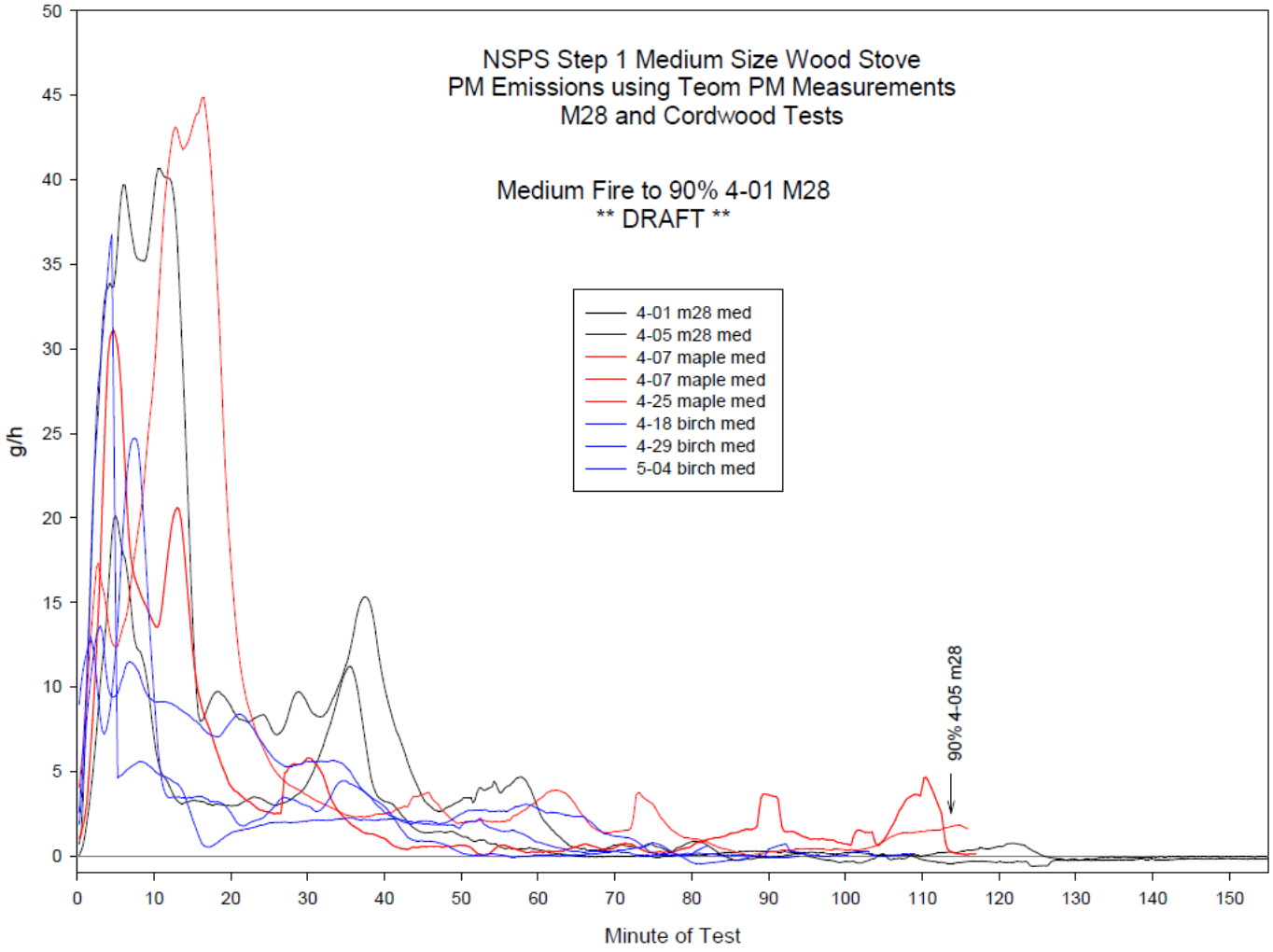
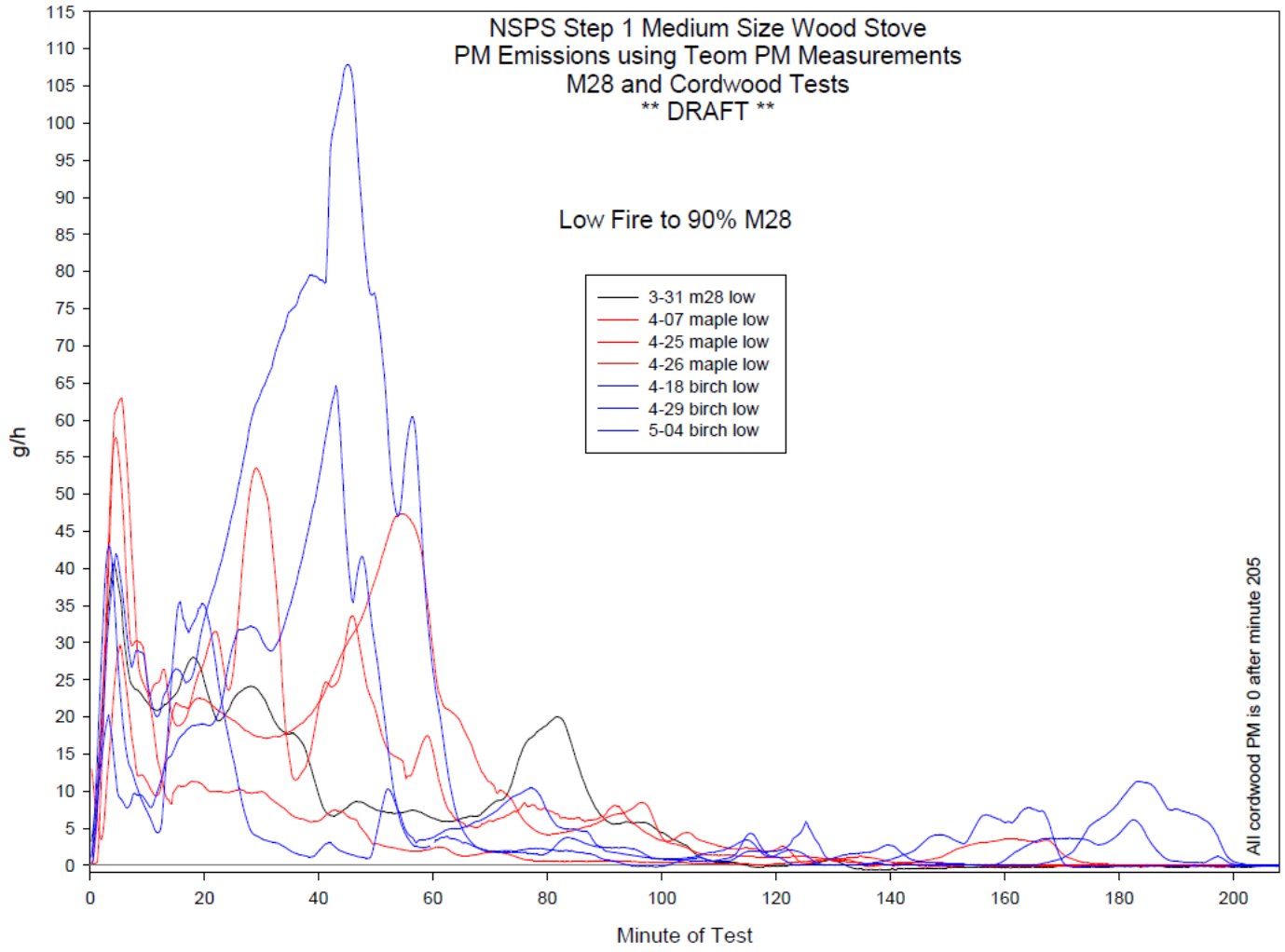
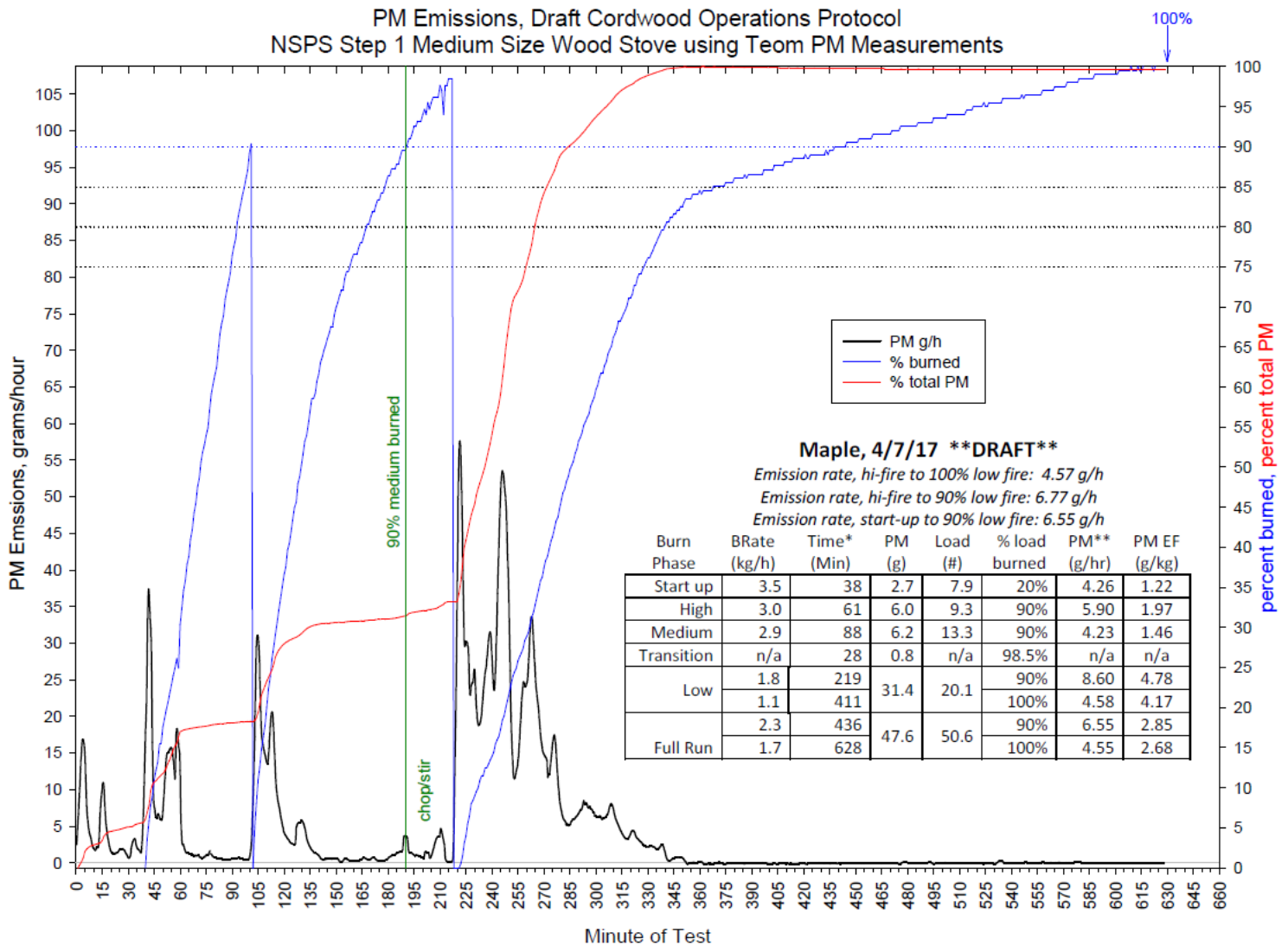
420
435
450

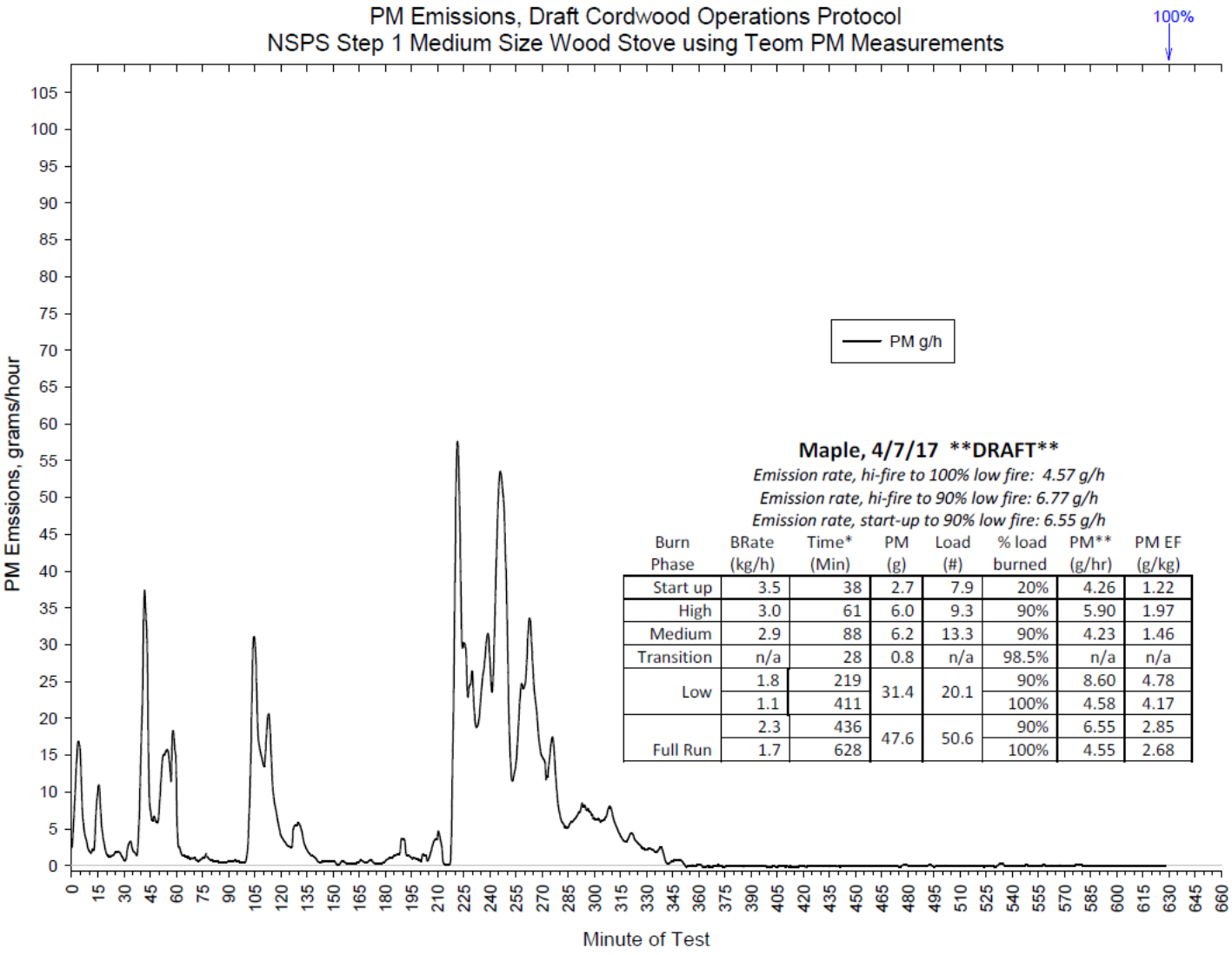

NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
** DRAFT **
Hi Fire to 90% M28
3-31 m28 hi
4-07 maple hi
4-25 maple hi
4-26 maple hi
4-18 birch hi
4-29 birch hi
5-04 birch hi
g/h
Minute of Test
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90


NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
Medium Fire to 90% 4-01 M28
** DRAFT **
4-01 m28 med
4-05 m28 med
4-07 maple med
4-07 maple med
4-25 maple med
4-18 birch med
4-29 birch med
5-04 birch med
90% 4-05 m28
g/h
Minute of Test
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150


NSPS Step 1 Medium Size Wood Stove
PM Emissions using Teom PM Measurements
M28 and Cordwood Tests
** DRAFT **
Low Fire to 90% M28
3-31 m28 low
4-07 maple low
4-25 maple low
4-26 maple low
4-18 birch low
4-29 birch low
5-04 birch low
g/h
Minute of Test
All cordwood PM is 0 after minute 205



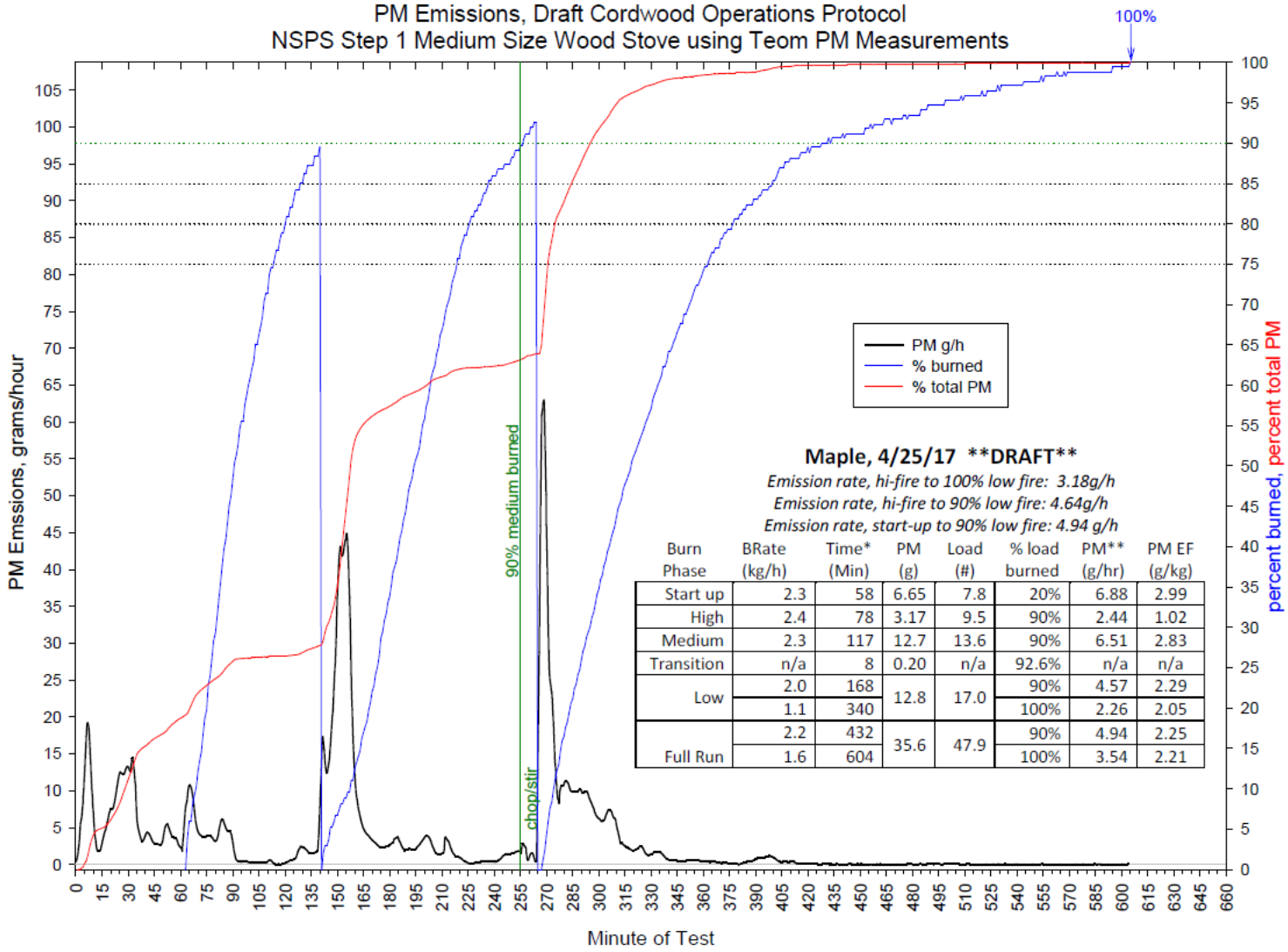
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.5	38	2.7	7.9	20%	4.26	1.22
High	3.0	61	6.0	9.3	90%	5.90	1.97
Medium	2.9	88	6.2	13.3	90%	4.23	1.46
Transition	n/a	28	0.8	n/a	98.5%	n/a	n/a
Low	1.8	219	31.4	20.1	90%	8.60	4.78
	1.1	411			100%	4.58	4.17
Full Run	2.3	436	47.6	50.6	90%	6.55	2.85
	1.7	628			100%	4.55	2.68



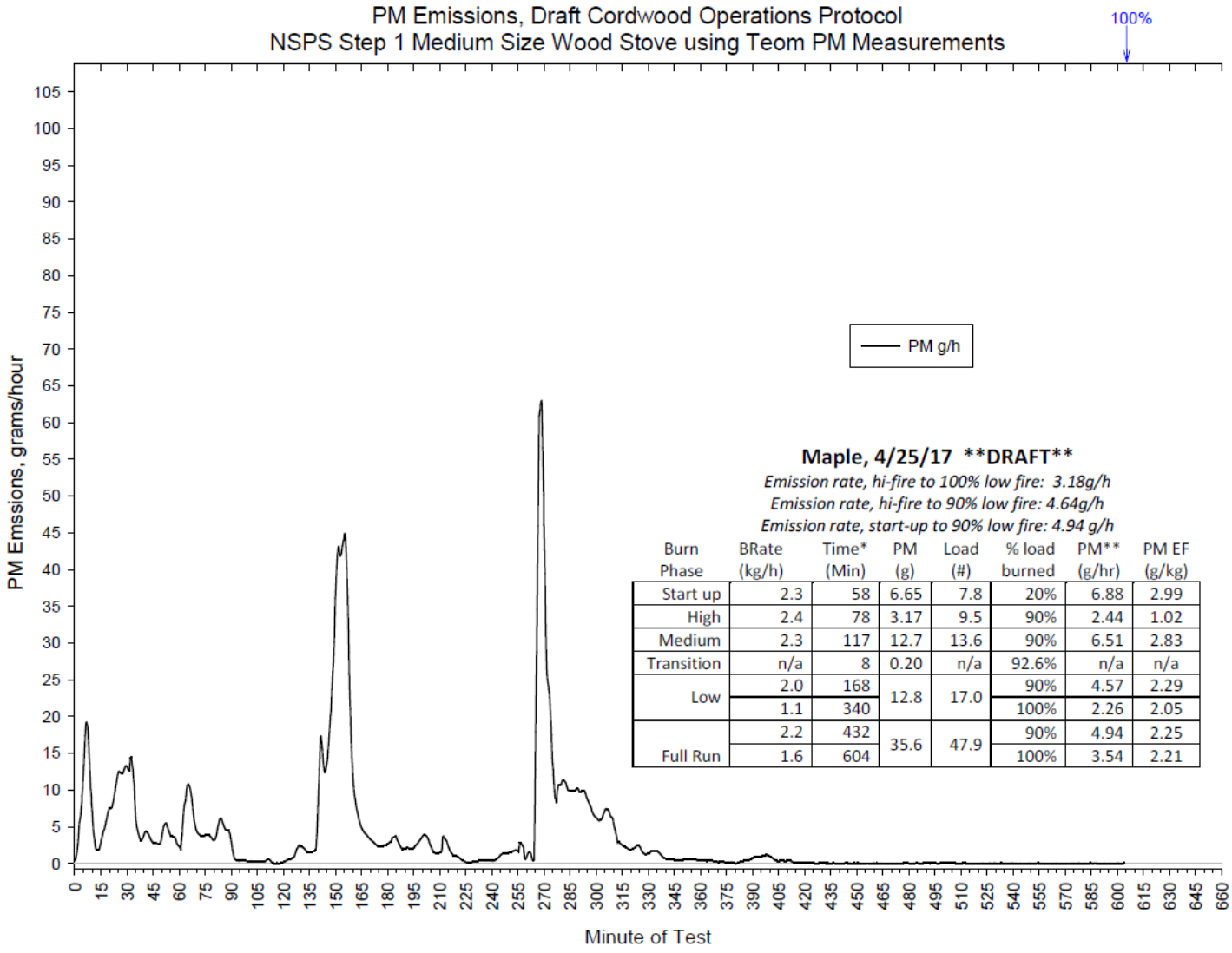
Maple, 4/7/17 **DRAFT**

Emission rate, hi-fire to 100% low fire: 4.57 g/h
Emission rate, hi-fire to 90% low fire: 6.77 g/h
Emission rate, start-up to 90% low fire: 6.55 g/h

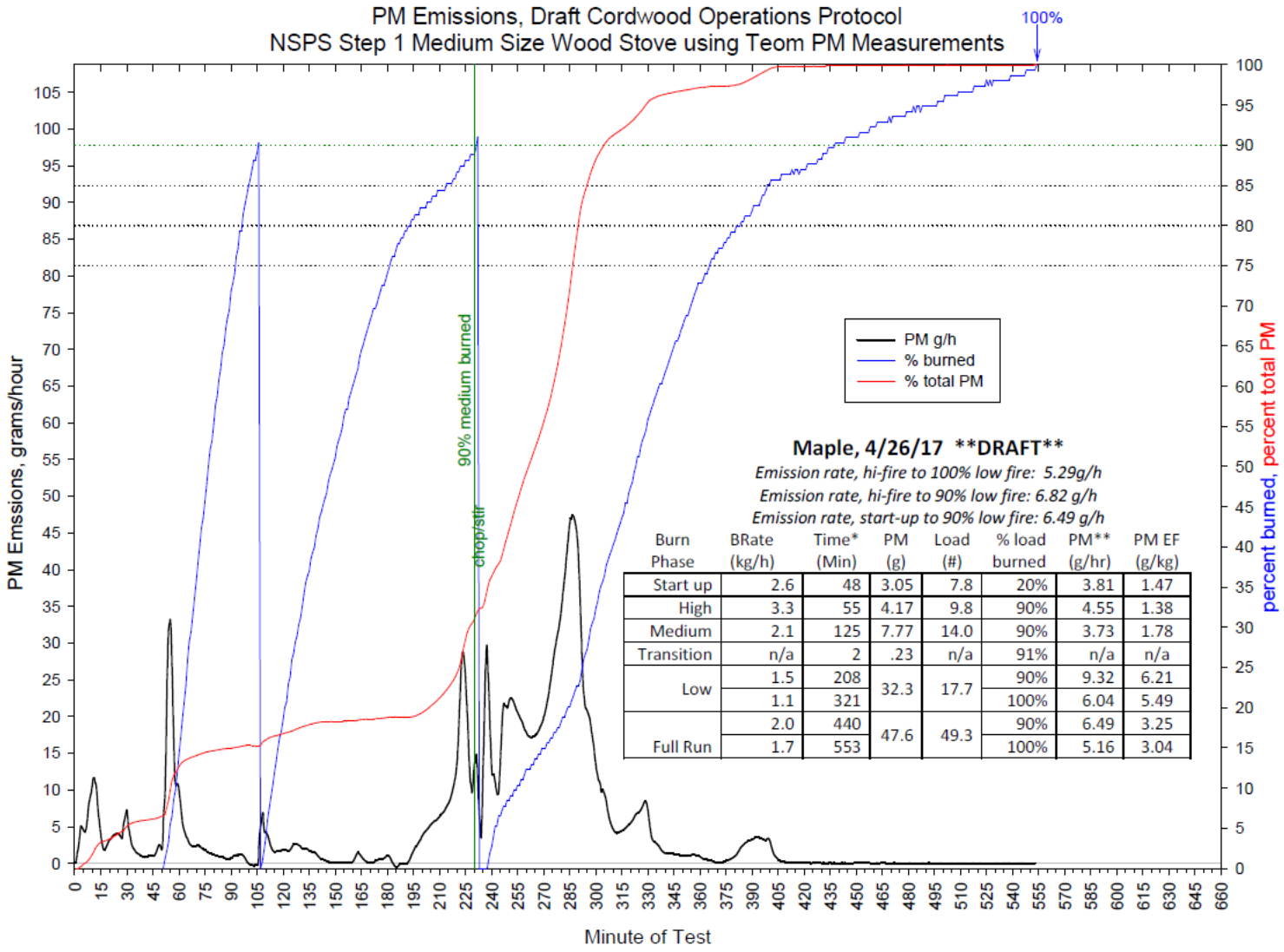
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.5	38	2.7	7.9	20%	4.26	1.22
High	3.0	61	6.0	9.3	90%	5.90	1.97
Medium	2.9	88	6.2	13.3	90%	4.23	1.46
Transition	n/a	28	0.8	n/a	98.5%	n/a	n/a
Low	1.8	219	31.4	20.1	90%	8.60	4.78
	1.1	411			100%	4.58	4.17
Full Run	2.3	436	47.6	50.6	90%	6.55	2.85
	1.7	628			100%	4.55	2.68



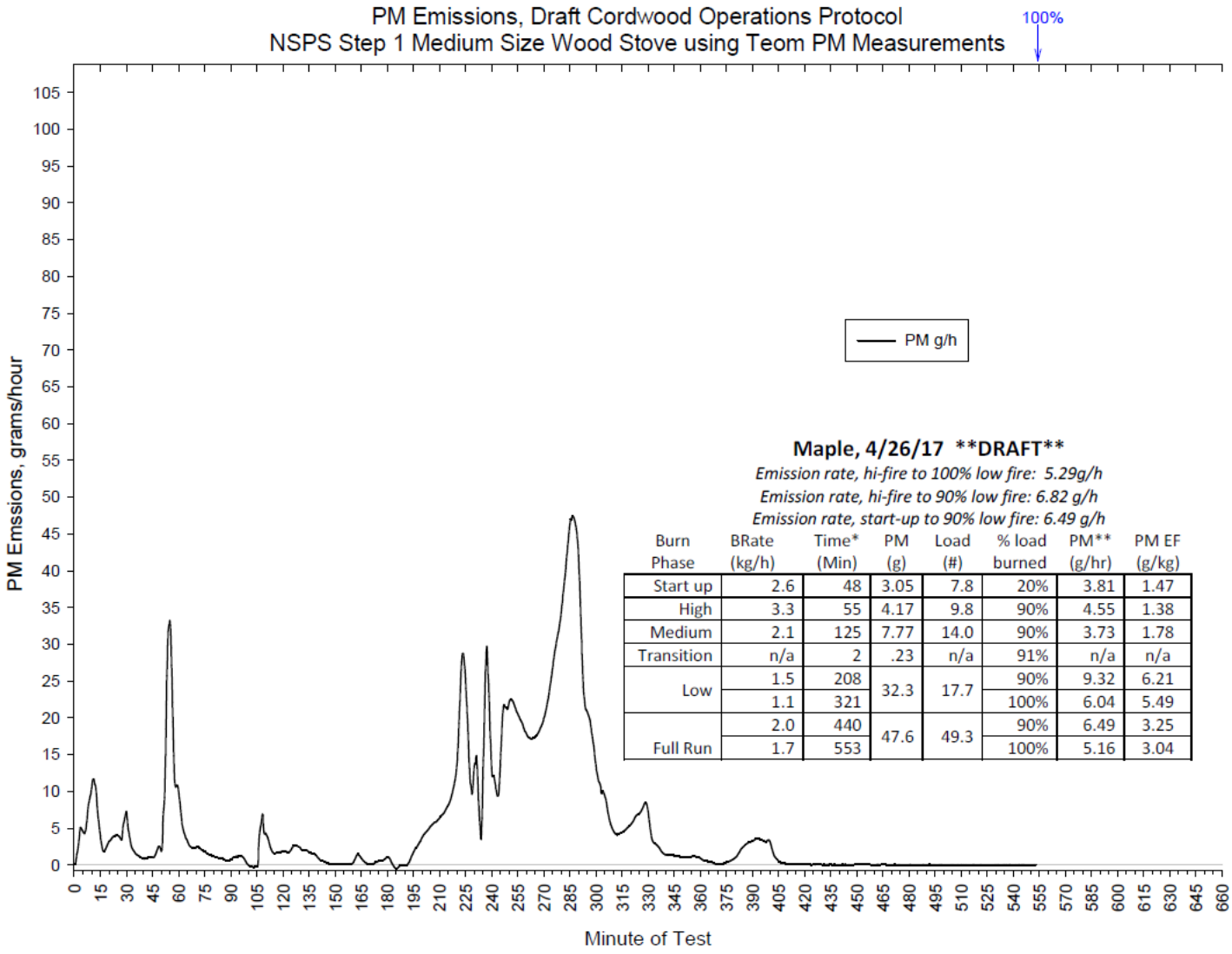
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.3	58	6.65	7.8	20%	6.88	2.99
High	2.4	78	3.17	9.5	90%	2.44	1.02
Medium	2.3	117	12.7	13.6	90%	6.51	2.83
Transition	n/a	8	0.20	n/a	92.6%	n/a	n/a
Low	2.0	168	12.8	17.0	90%	4.57	2.29
	1.1	340			100%	2.26	2.05
Full Run	2.2	432	35.6	47.9	90%	4.94	2.25
	1.6	604			100%	3.54	2.21



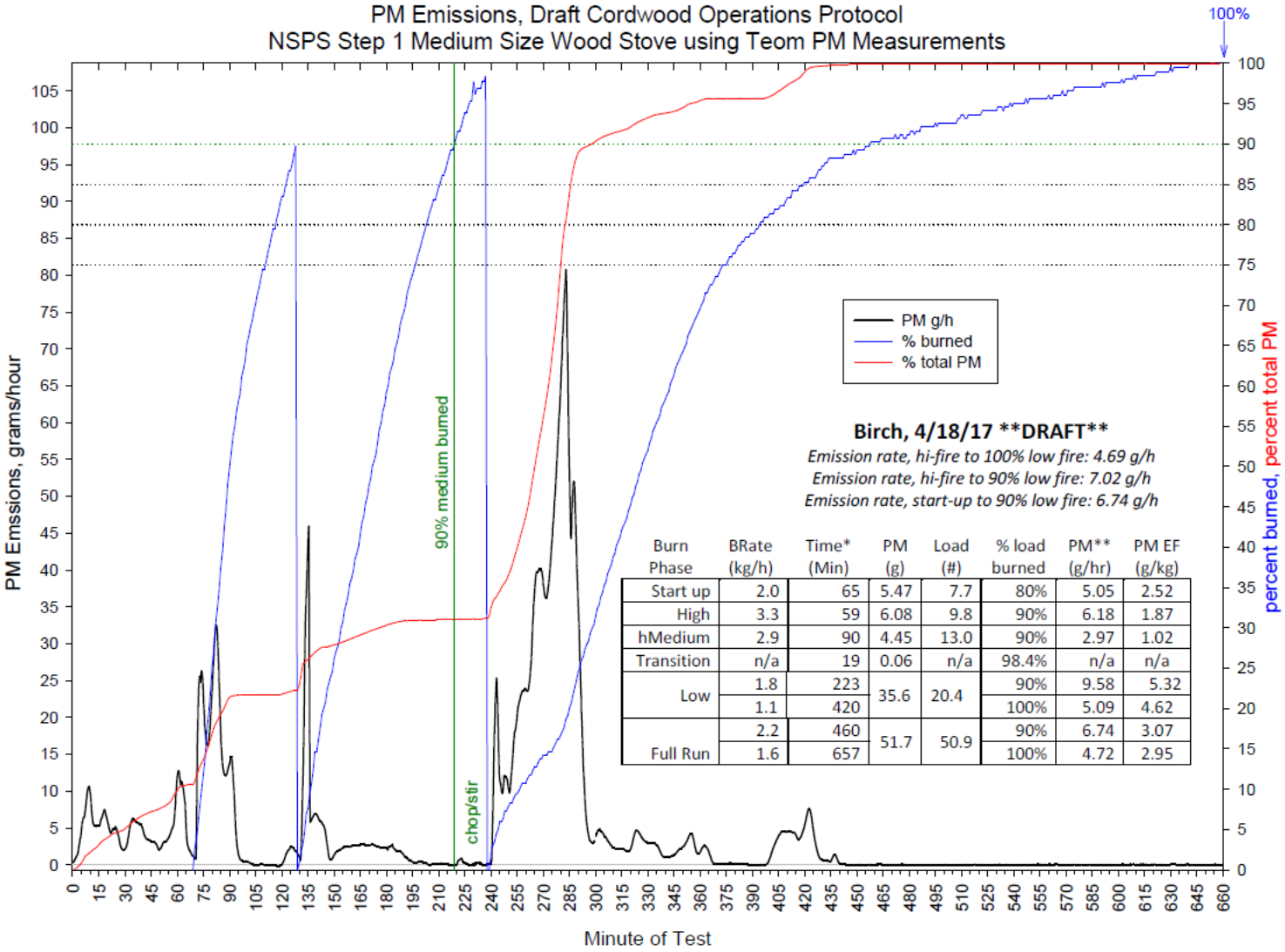
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.3	58	6.65	7.8	20%	6.88	2.99
High	2.4	78	3.17	9.5	90%	2.44	1.02
Medium	2.3	117	12.7	13.6	90%	6.51	2.83
Transition	n/a	8	0.20	n/a	92.6%	n/a	n/a
Low	2.0	168	12.8	17.0	90%	4.57	2.29
	1.1	340			100%	2.26	2.05
Full Run	2.2	432	35.6	47.9	90%	4.94	2.25
	1.6	604			100%	3.54	2.21



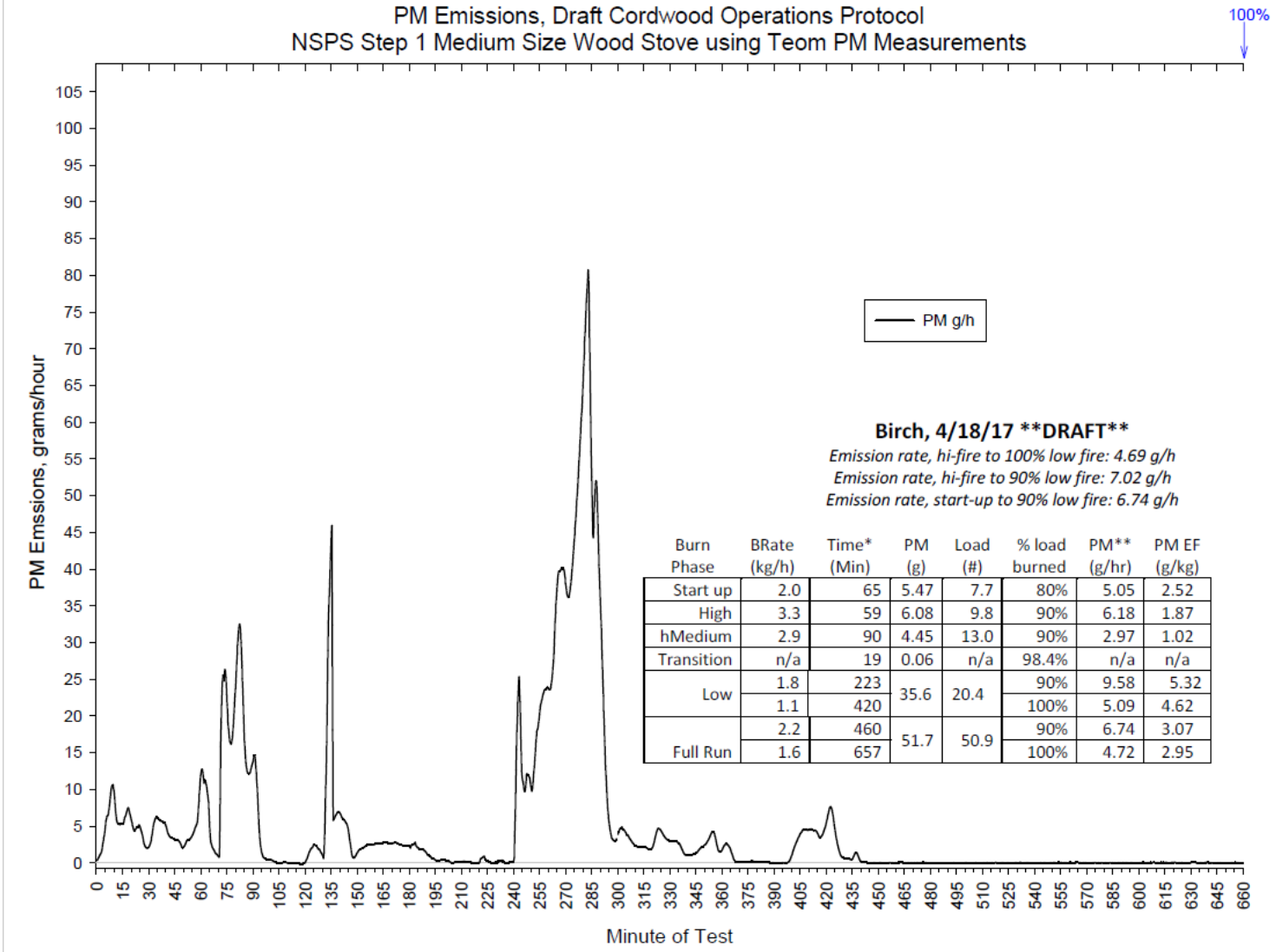
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.6	48	3.05	7.8	20%	3.81	1.47
High	3.3	55	4.17	9.8	90%	4.55	1.38
Medium	2.1	125	7.77	14.0	90%	3.73	1.78
Transition	n/a	2	.23	n/a	91%	n/a	n/a
Low	1.5	208	32.3	17.7	90%	9.32	6.21
	1.1	321			100%	6.04	5.49
Full Run	2.0	440	47.6	49.3	90%	6.49	3.25
	1.7	553			100%	5.16	3.04



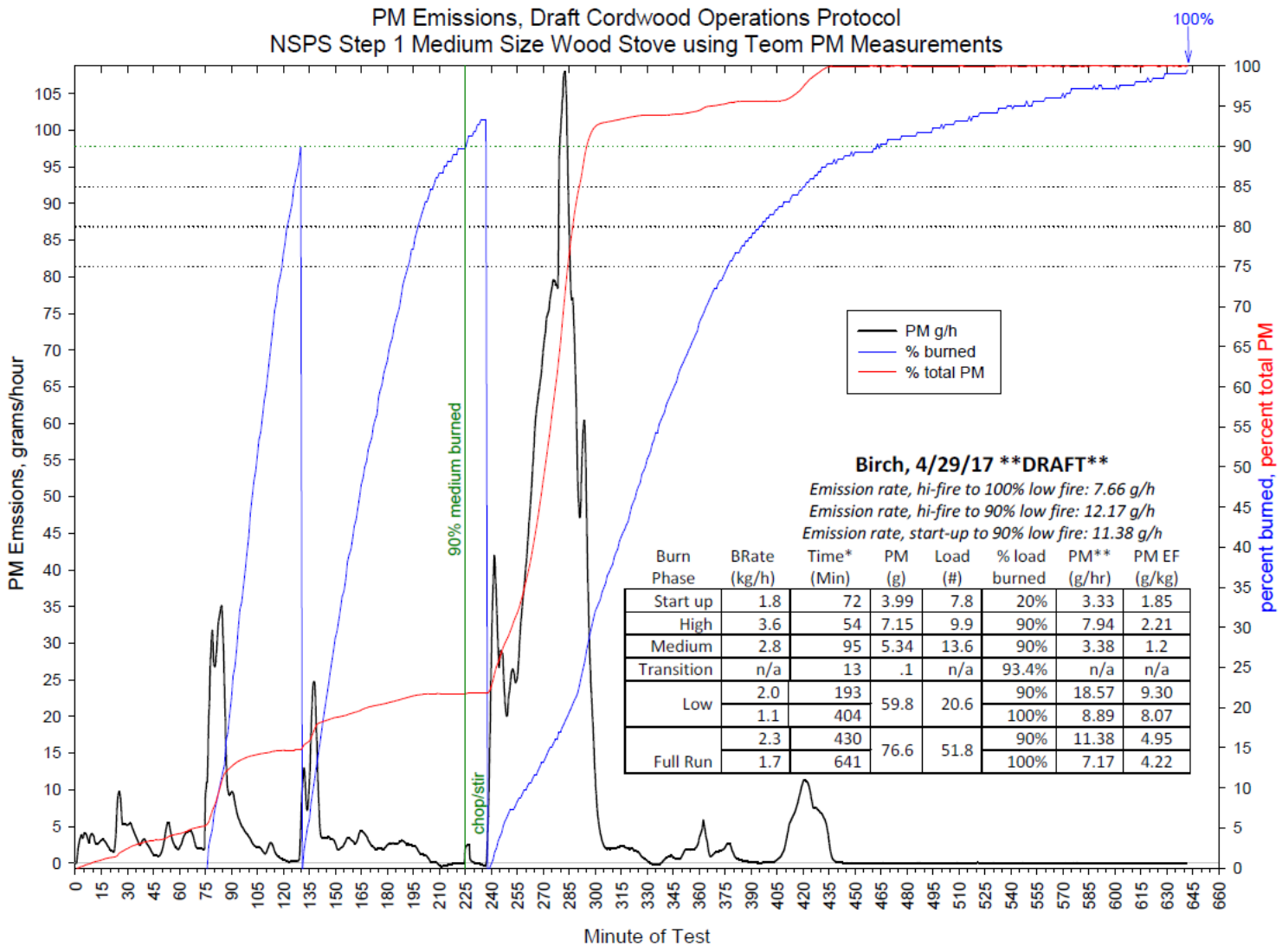
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.6	48	3.05	7.8	20%	3.81	1.47
High	3.3	55	4.17	9.8	90%	4.55	1.38
Medium	2.1	125	7.77	14.0	90%	3.73	1.78
Transition	n/a	2	.23	n/a	91%	n/a	n/a
Low	1.5	208	32.3	17.7	90%	9.32	6.21
	1.1	321			100%	6.04	5.49
Full Run	2.0	440	47.6	49.3	90%	6.49	3.25
	1.7	553			100%	5.16	3.04



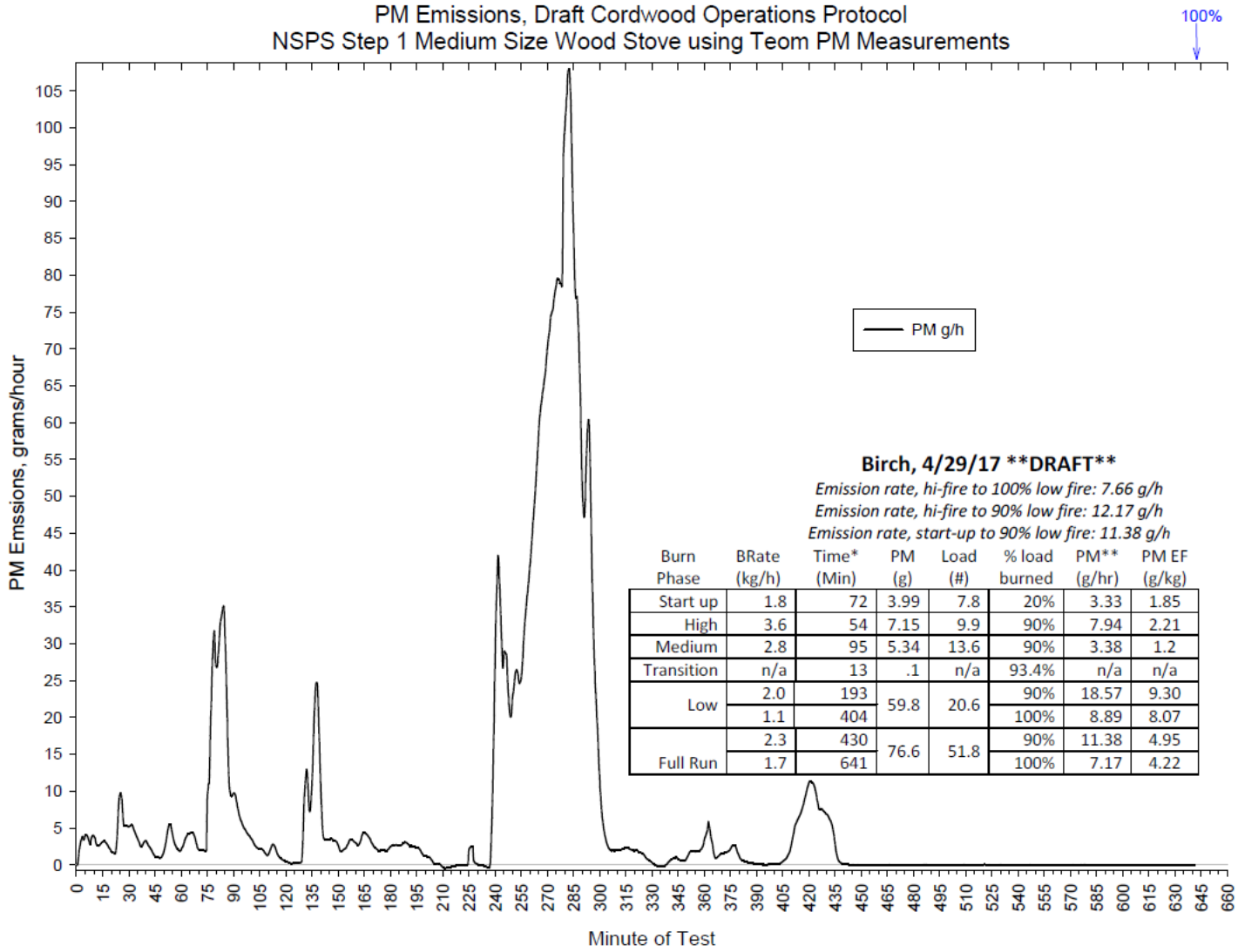
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.0	65	5.47	7.7	80%	5.05	2.52
High	3.3	59	6.08	9.8	90%	6.18	1.87
hMedium	2.9	90	4.45	13.0	90%	2.97	1.02
Transition	n/a	19	0.06	n/a	98.4%	n/a	n/a
Low	1.8	223	35.6	20.4	90%	9.58	5.32
	1.1	420			100%	5.09	4.62
Full Run	2.2	460	51.7	50.9	90%	6.74	3.07
	1.6	657			100%	4.72	2.95



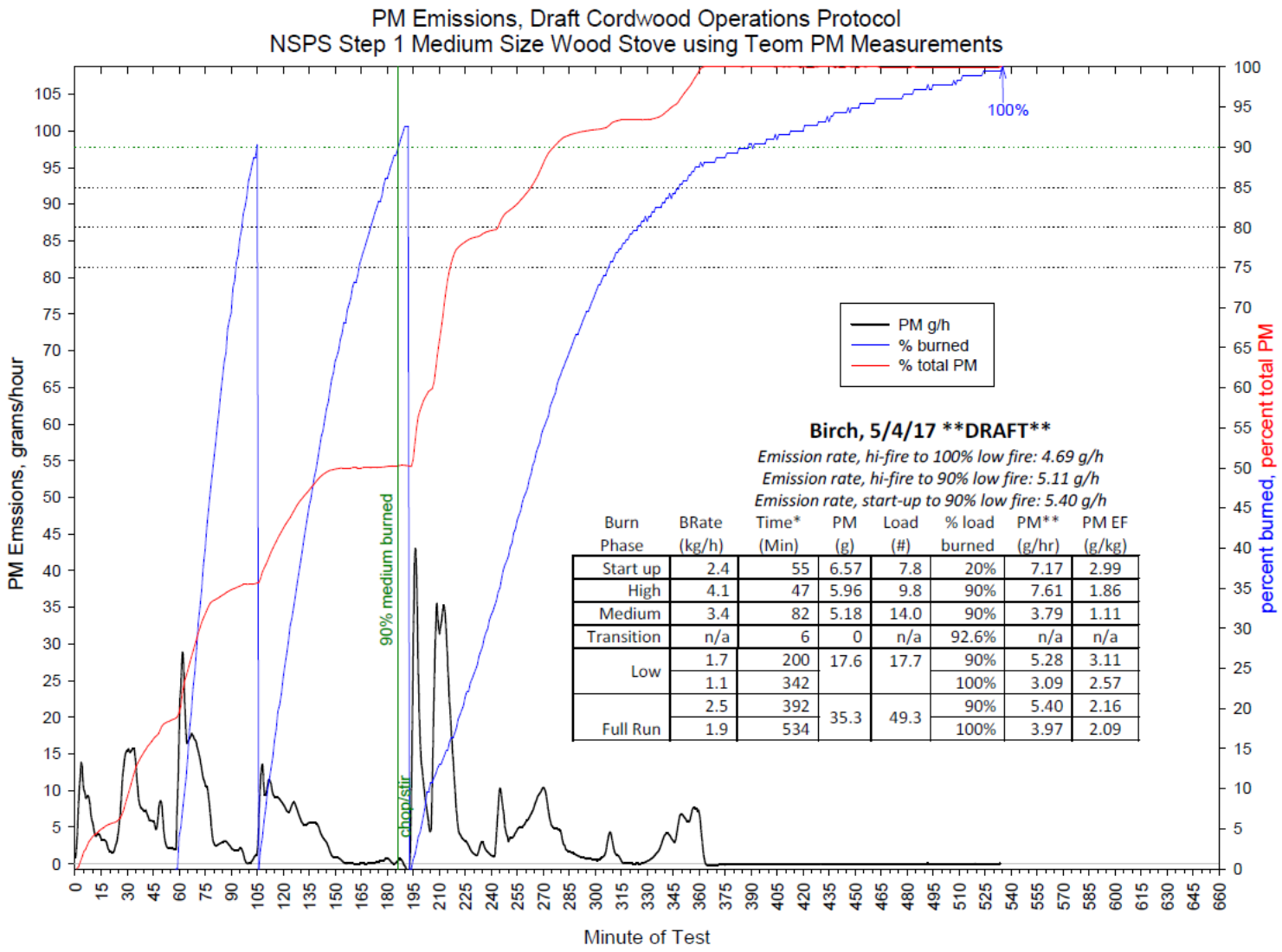
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.0	65	5.47	7.7	80%	5.05	2.52
High	3.3	59	6.08	9.8	90%	6.18	1.87
hMedium	2.9	90	4.45	13.0	90%	2.97	1.02
Transition	n/a	19	0.06	n/a	98.4%	n/a	n/a
Low	1.8	223	35.6	20.4	90%	9.58	5.32
	1.1	420			100%	5.09	4.62
Full Run	2.2	460	51.7	50.9	90%	6.74	3.07
	1.6	657			100%	4.72	2.95



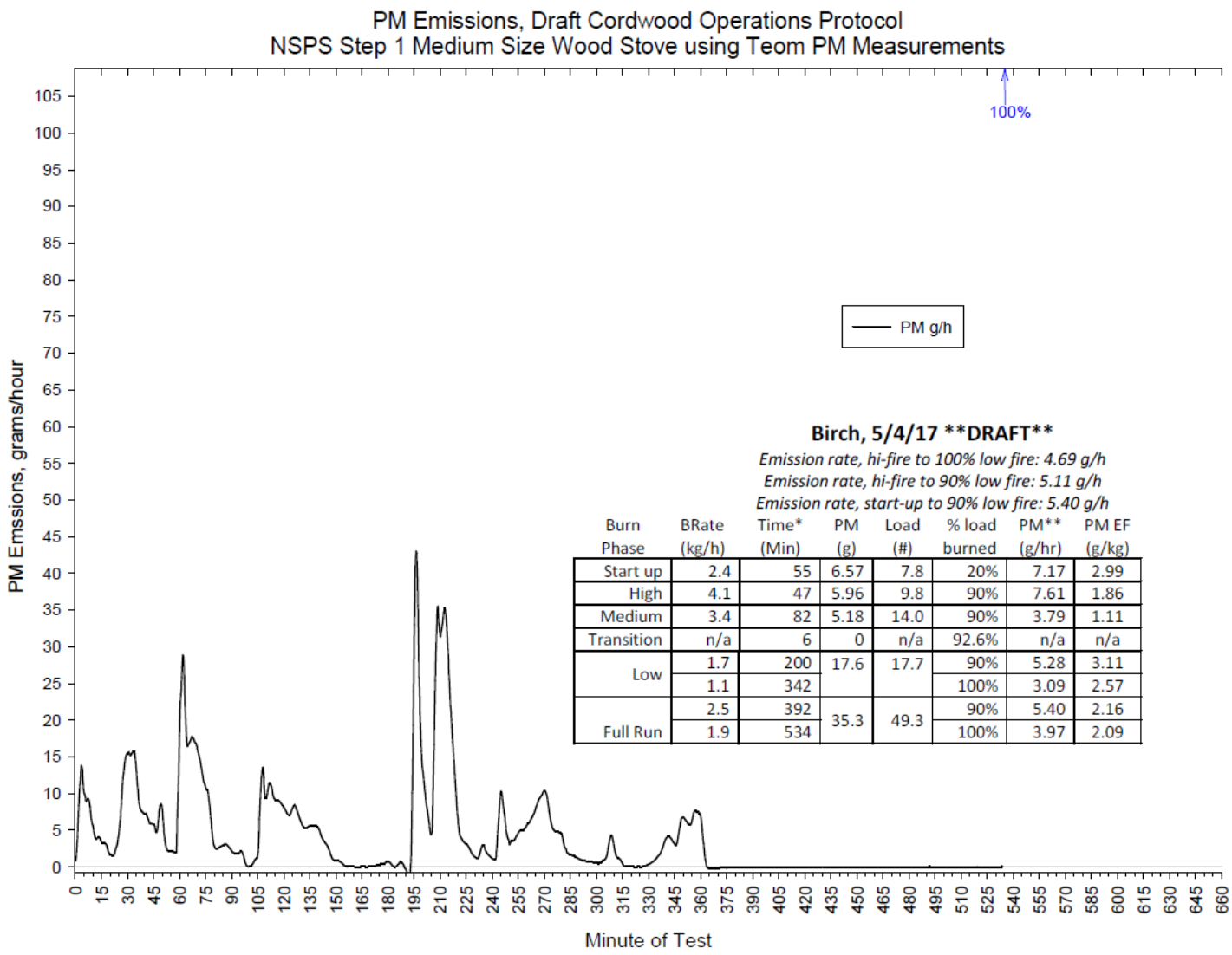
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	1.8	72	3.99	7.8	20%	3.33	1.85
High	3.6	54	7.15	9.9	90%	7.94	2.21
Medium	2.8	95	5.34	13.6	90%	3.38	1.2
Transition	n/a	13	.1	n/a	93.4%	n/a	n/a
Low	2.0	193	59.8	20.6	90%	18.57	9.30
	1.1	404			100%	8.89	8.07
Full Run	2.3	430	76.6	51.8	90%	11.38	4.95
	1.7	641			100%	7.17	4.22



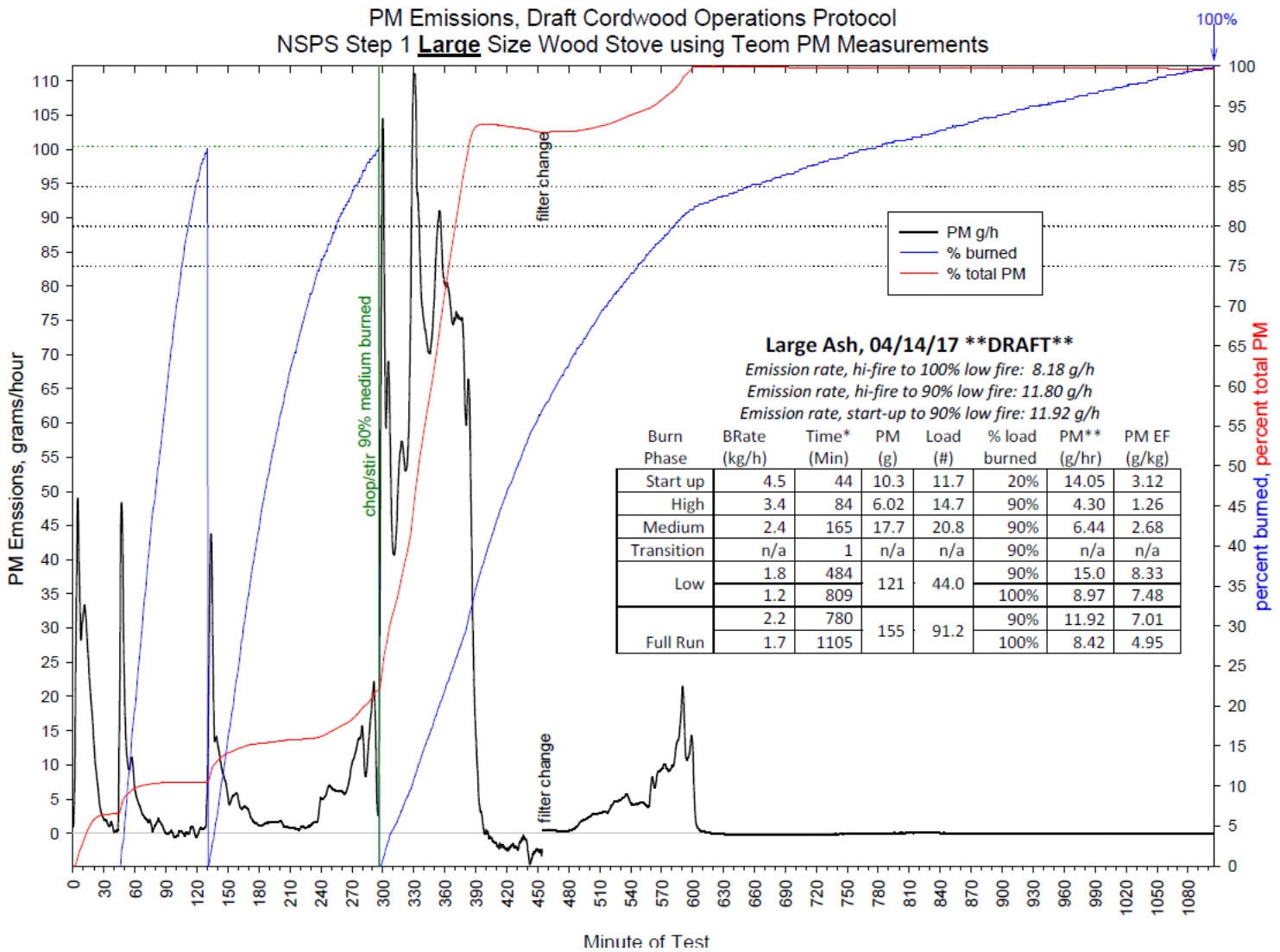
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	1.8	72	3.99	7.8	20%	3.33	1.85
High	3.6	54	7.15	9.9	90%	7.94	2.21
Medium	2.8	95	5.34	13.6	90%	3.38	1.2
Transition	n/a	13	.1	n/a	93.4%	n/a	n/a
Low	2.0	193	59.8	20.6	90%	18.57	9.30
	1.1	404			100%	8.89	8.07
Full Run	2.3	430	76.6	51.8	90%	11.38	4.95
	1.7	641			100%	7.17	4.22



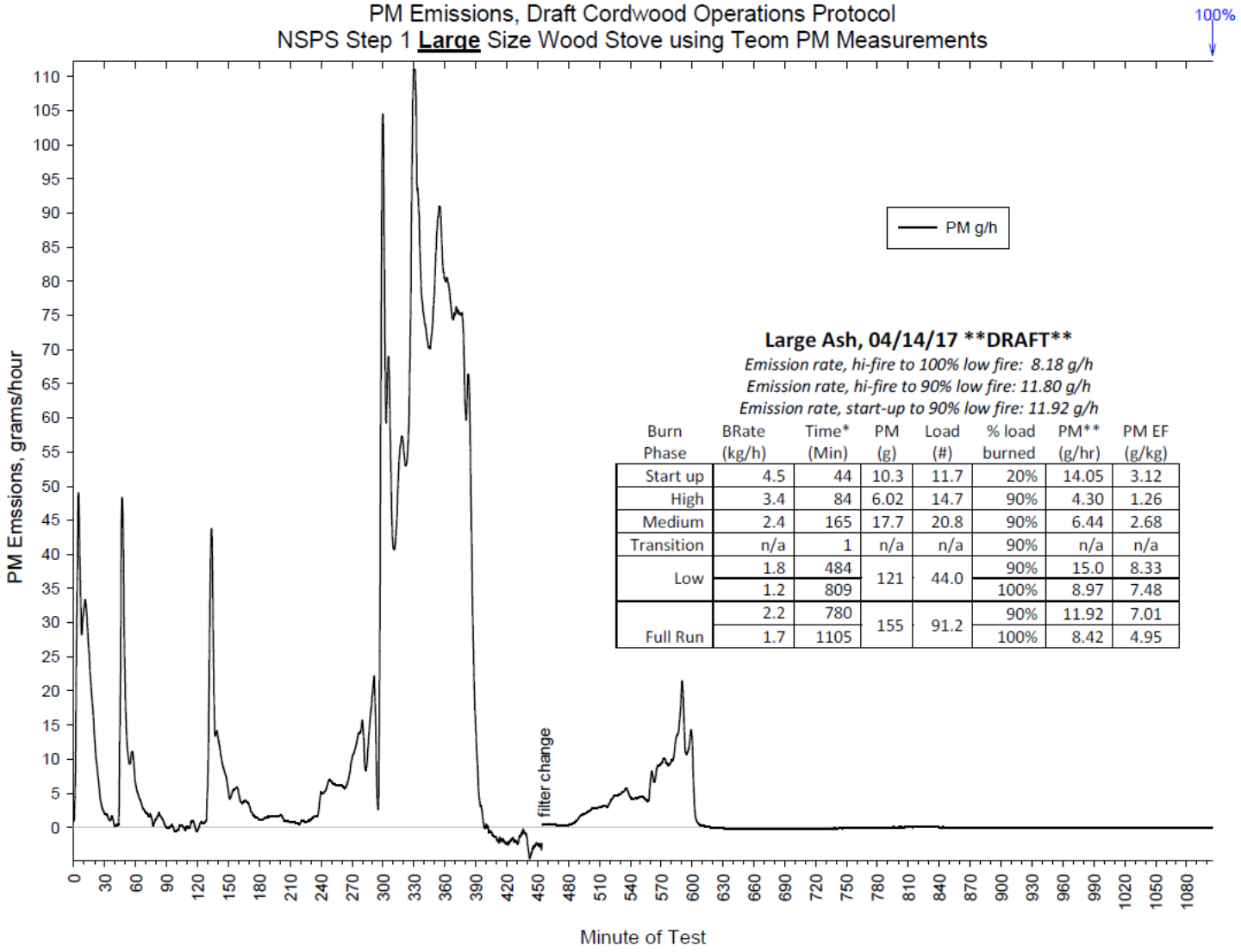
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.4	55	6.57	7.8	20%	7.17	2.99
High	4.1	47	5.96	9.8	90%	7.61	1.86
Medium	3.4	82	5.18	14.0	90%	3.79	1.11
Transition	n/a	6	0	n/a	92.6%	n/a	n/a
Low	1.7	200	17.6	17.7	90%	5.28	3.11
	1.1	342			100%	3.09	2.57
Full Run	2.5	392	35.3	49.3	90%	5.40	2.16
	1.9	534			100%	3.97	2.09



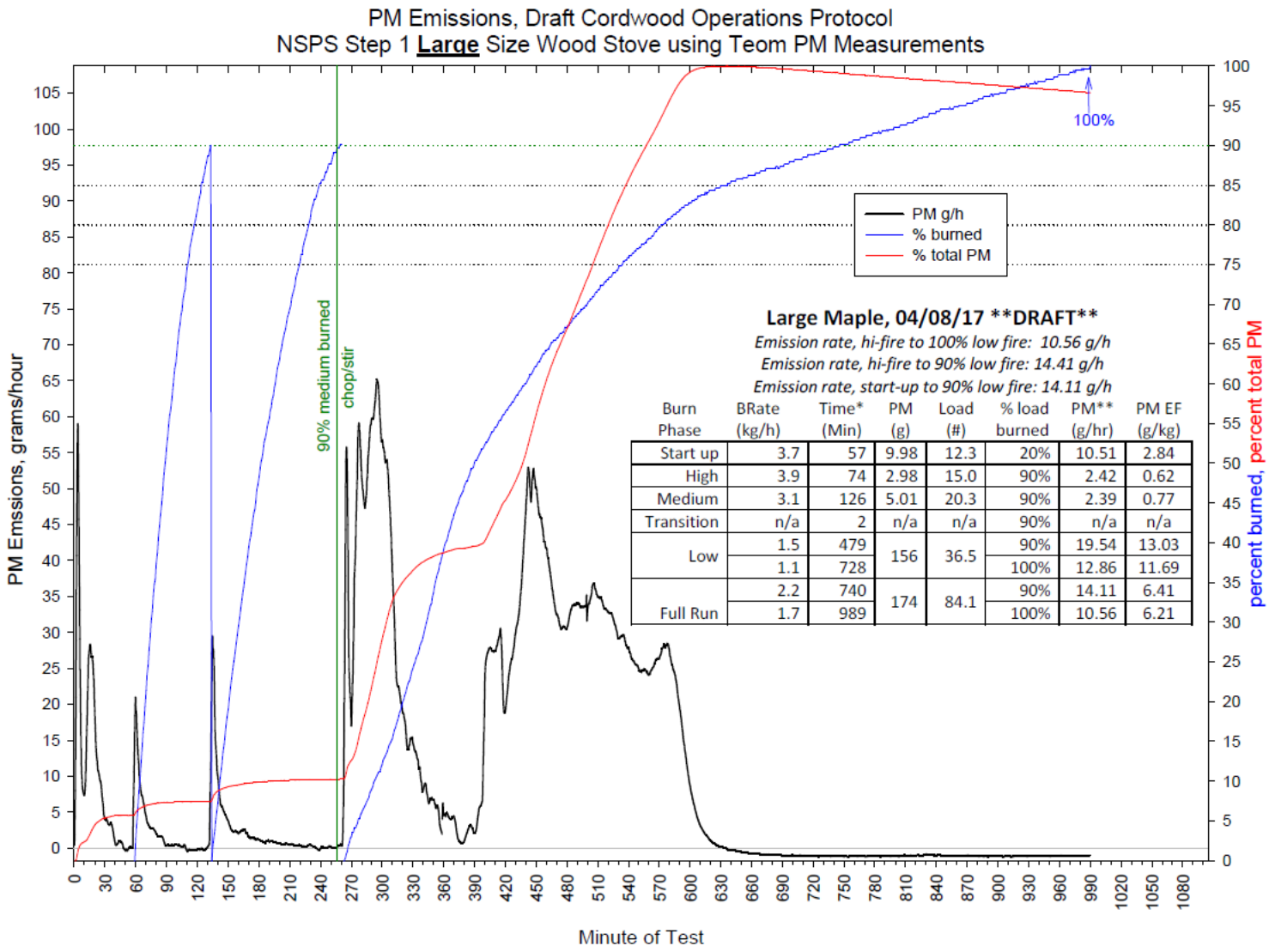
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	2.4	55	6.57	7.8	20%	7.17	2.99
High	4.1	47	5.96	9.8	90%	7.61	1.86
Medium	3.4	82	5.18	14.0	90%	3.79	1.11
Transition	n/a	6	0	n/a	92.6%	n/a	n/a
Low	1.7	200	17.6	17.7	90%	5.28	3.11
	1.1	342			100%	3.09	2.57
Full Run	2.5	392	35.3	49.3	90%	5.40	2.16
	1.9	534			100%	3.97	2.09



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	4.5	44	10.3	11.7	20%	14.05	3.12
High	3.4	84	6.02	14.7	90%	4.30	1.26
Medium	2.4	165	17.7	20.8	90%	6.44	2.68
Transition	n/a	1	n/a	n/a	90%	n/a	n/a
Low	1.8	484	121	44.0	90%	15.0	8.33
	1.2	809			100%	8.97	7.48
Full Run	2.2	780	155	91.2	90%	11.92	7.01
	1.7	1105			100%	8.42	4.95

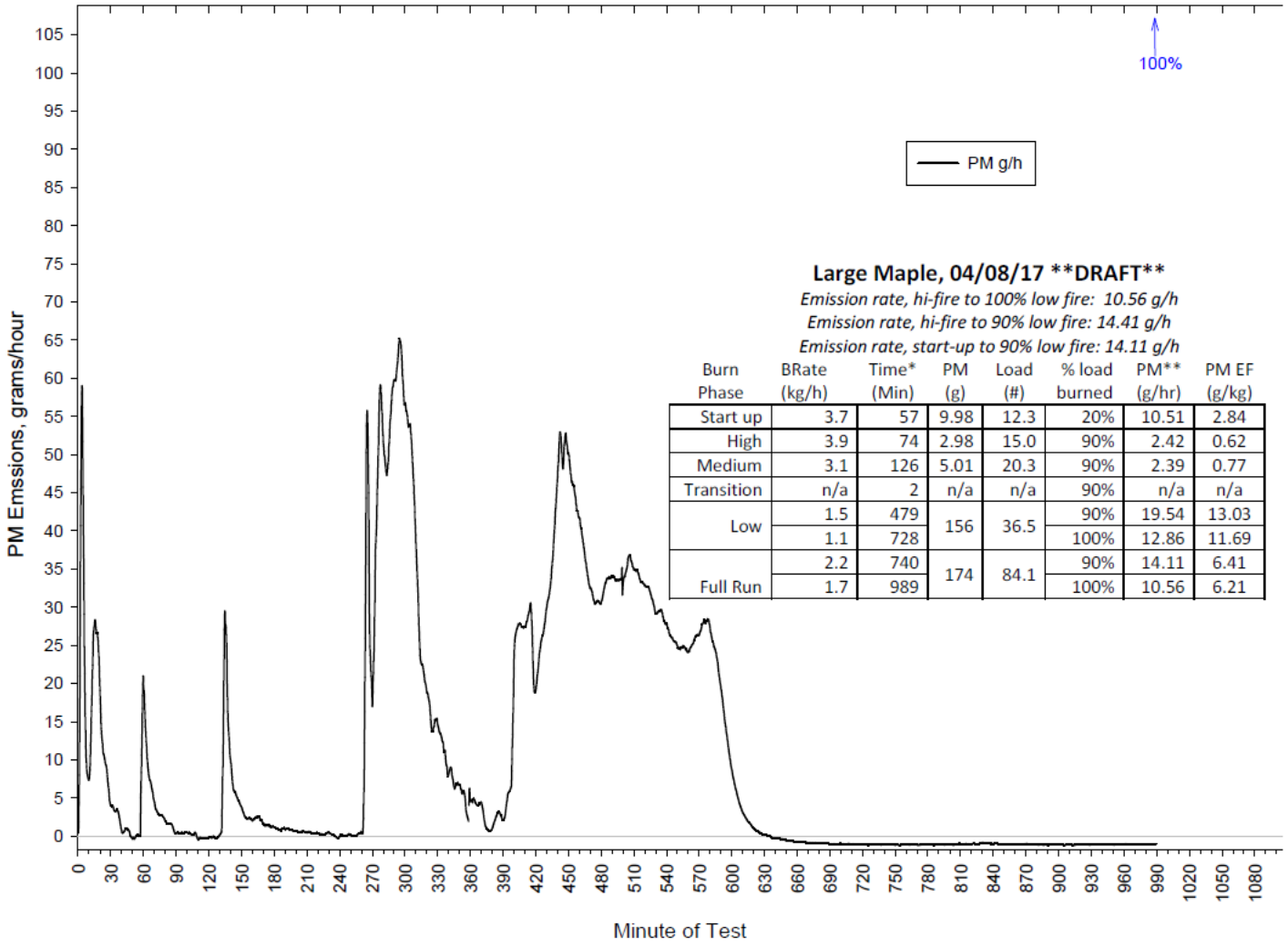


Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	4.5	44	10.3	11.7	20%	14.05	3.12
High	3.4	84	6.02	14.7	90%	4.30	1.26
Medium	2.4	165	17.7	20.8	90%	6.44	2.68
Transition	n/a	1	n/a	n/a	90%	n/a	n/a
Low	1.8	484	121	44.0	90%	15.0	8.33
	1.2	809			100%	8.97	7.48
Full Run	2.2	780	155	91.2	90%	11.92	7.01
	1.7	1105			100%	8.42	4.95



Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
	1.7	989			100%	10.56	6.21

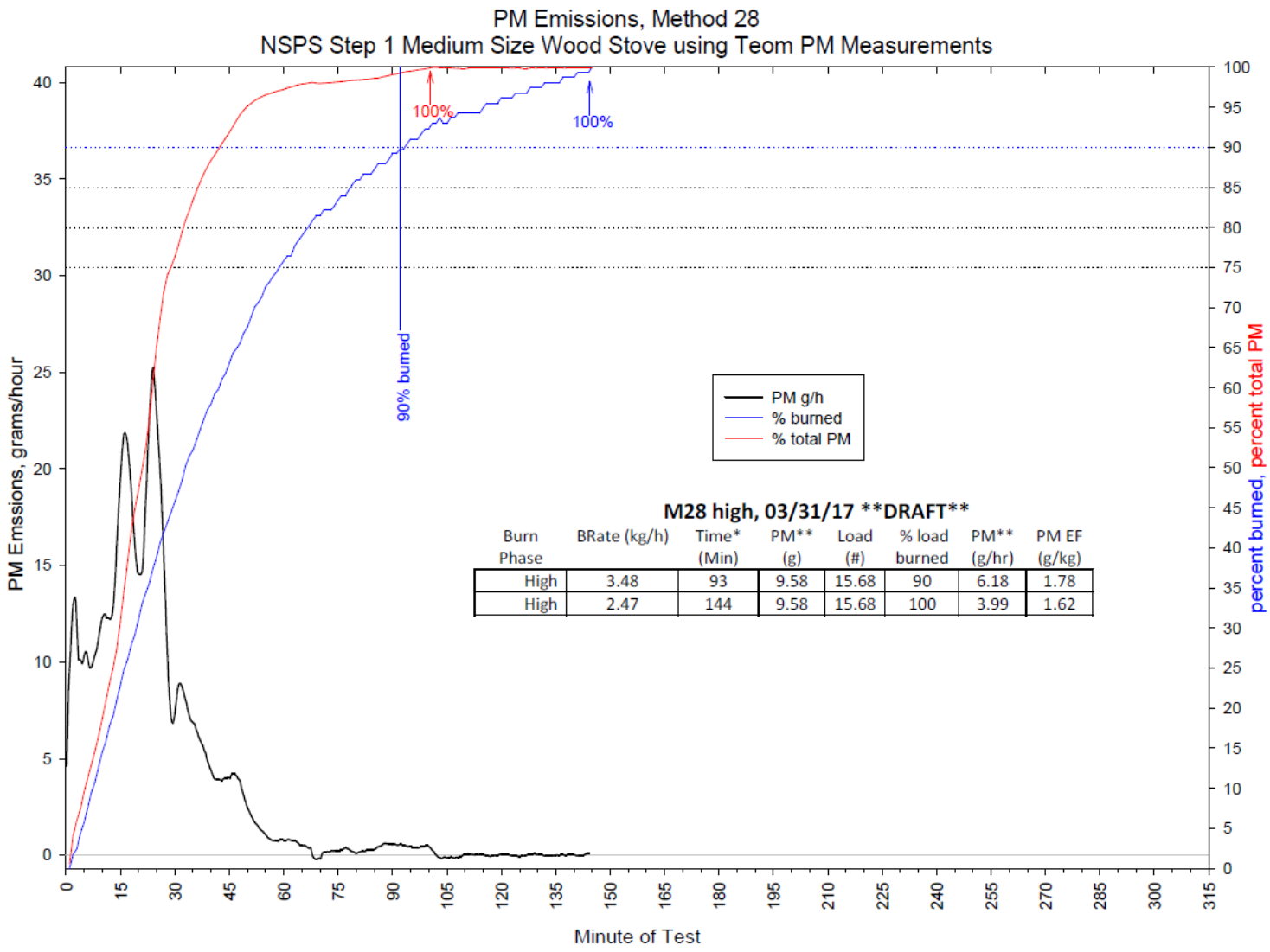
PM Emissions, Draft Cordwood Operations Protocol
NSPS Step 1 **Large** Size Wood Stove using Teom PM Measurements



Large Maple, 04/08/17 **DRAFT**

Emission rate, hi-fire to 100% low fire: 10.56 g/h
Emission rate, hi-fire to 90% low fire: 14.41 g/h
Emission rate, start-up to 90% low fire: 14.11 g/h

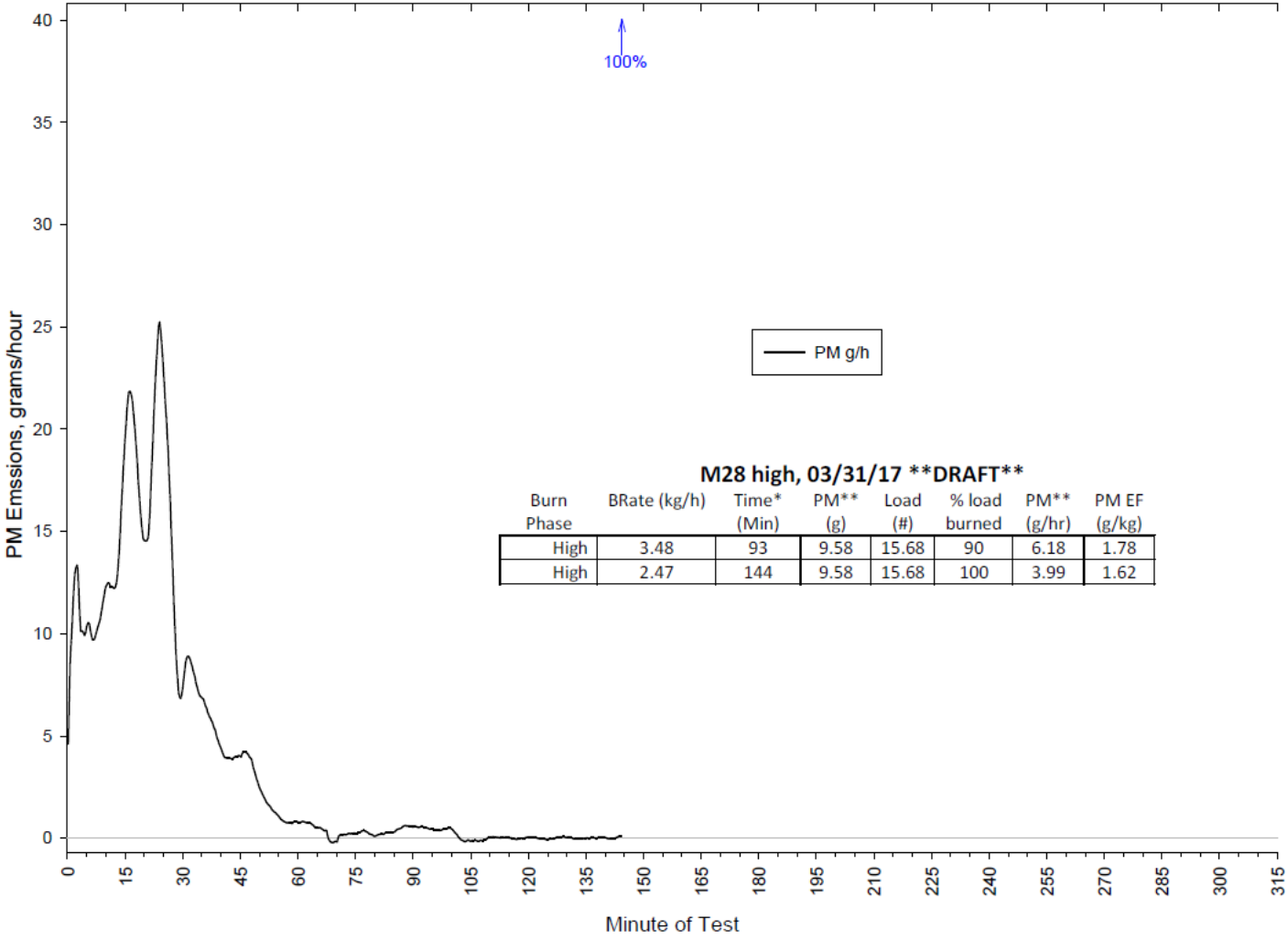
Burn Phase	BRate (kg/h)	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Start up	3.7	57	9.98	12.3	20%	10.51	2.84
High	3.9	74	2.98	15.0	90%	2.42	0.62
Medium	3.1	126	5.01	20.3	90%	2.39	0.77
Transition	n/a	2	n/a	n/a	90%	n/a	n/a
Low	1.5	479	156	36.5	90%	19.54	13.03
	1.1	728			100%	12.86	11.69
Full Run	2.2	740	174	84.1	90%	14.11	6.41
	1.7	989			100%	10.56	6.21



M28 high, 03/31/17 **DRAFT**

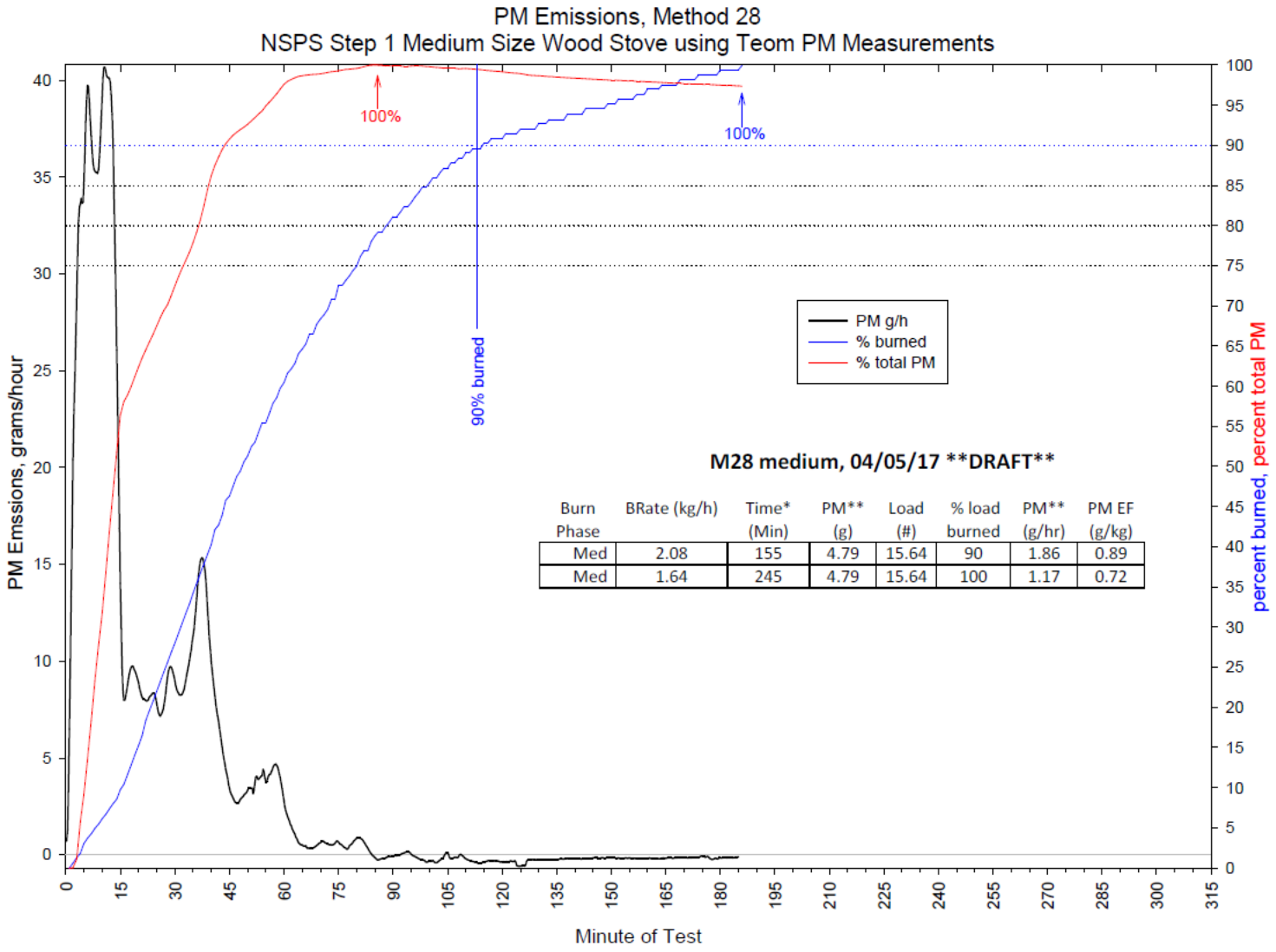
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62

PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements

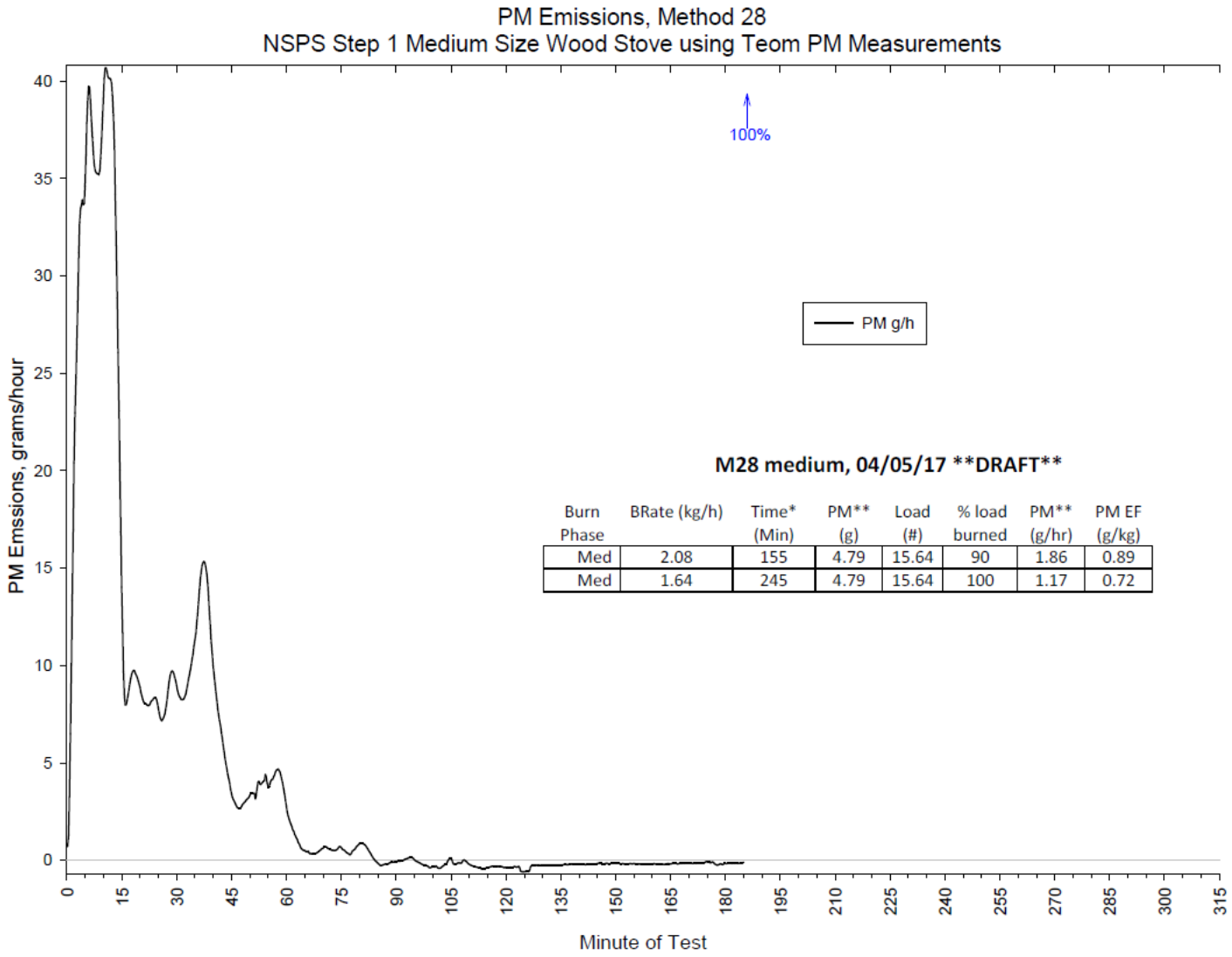


M28 high, 03/31/17 **DRAFT**

Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
High	3.48	93	9.58	15.68	90	6.18	1.78
High	2.47	144	9.58	15.68	100	3.99	1.62

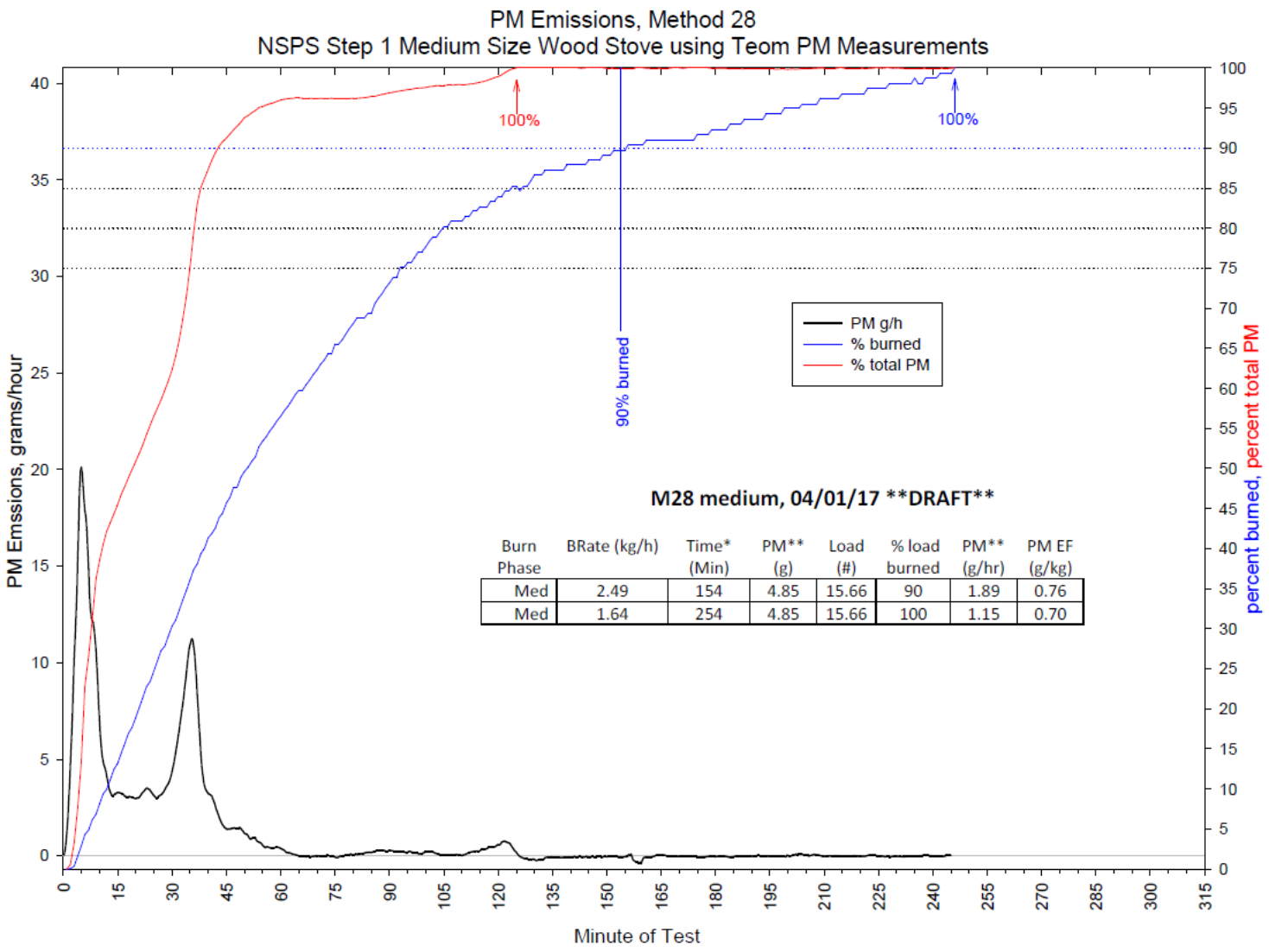


Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



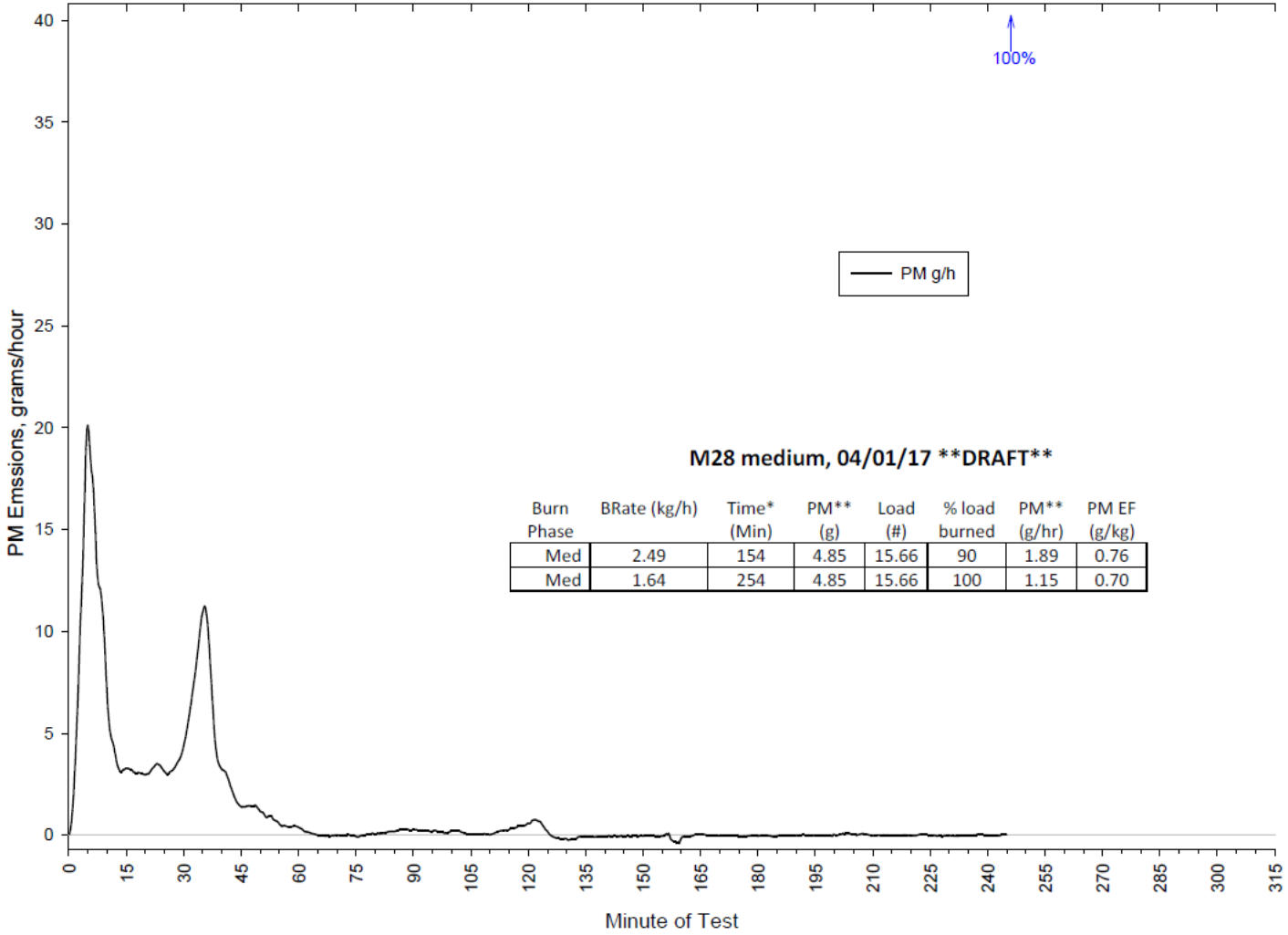
M28 medium, 04/05/17 **DRAFT**

Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.08	155	4.79	15.64	90	1.86	0.89
Med	1.64	245	4.79	15.64	100	1.17	0.72



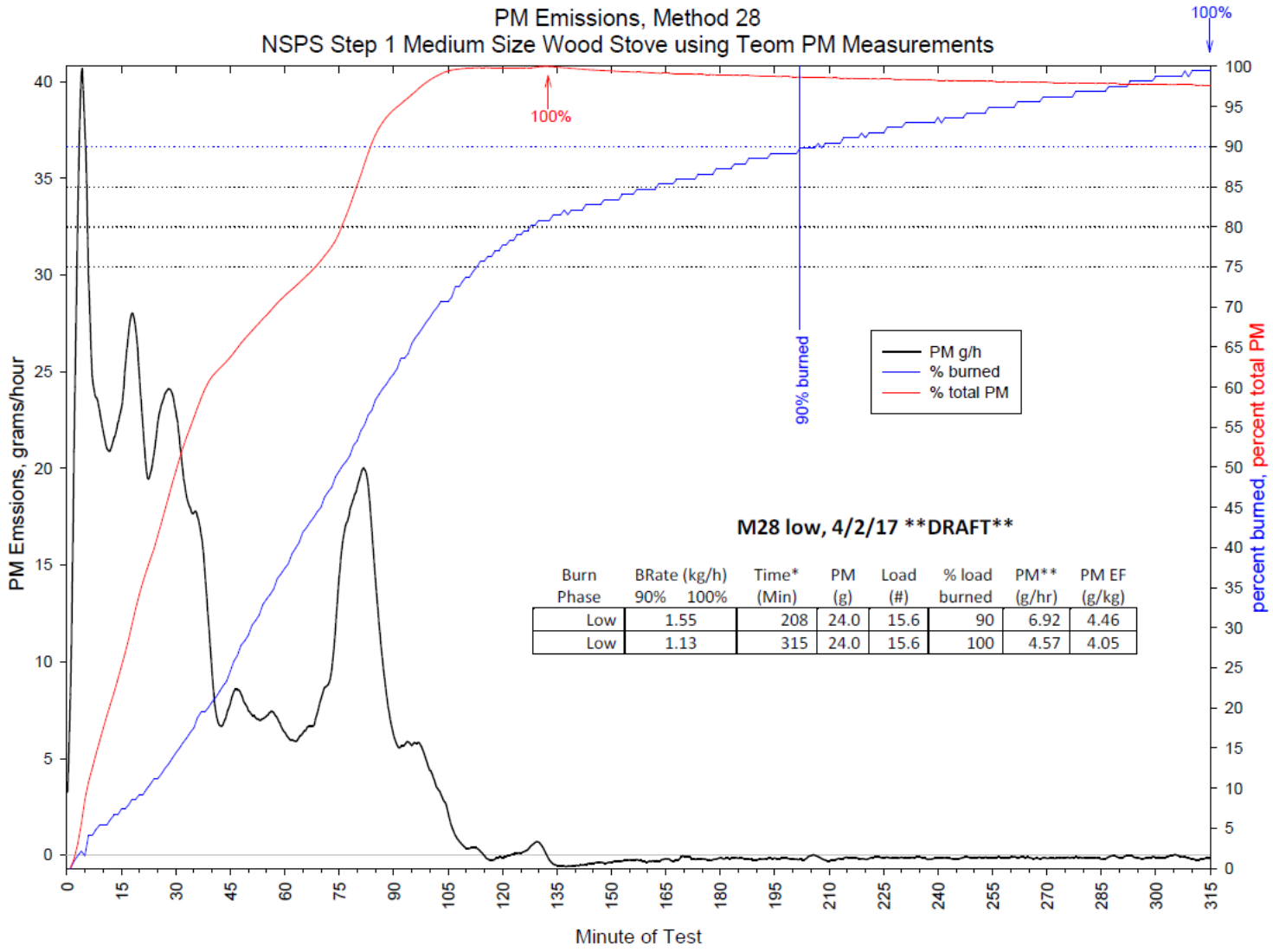
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70

PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements

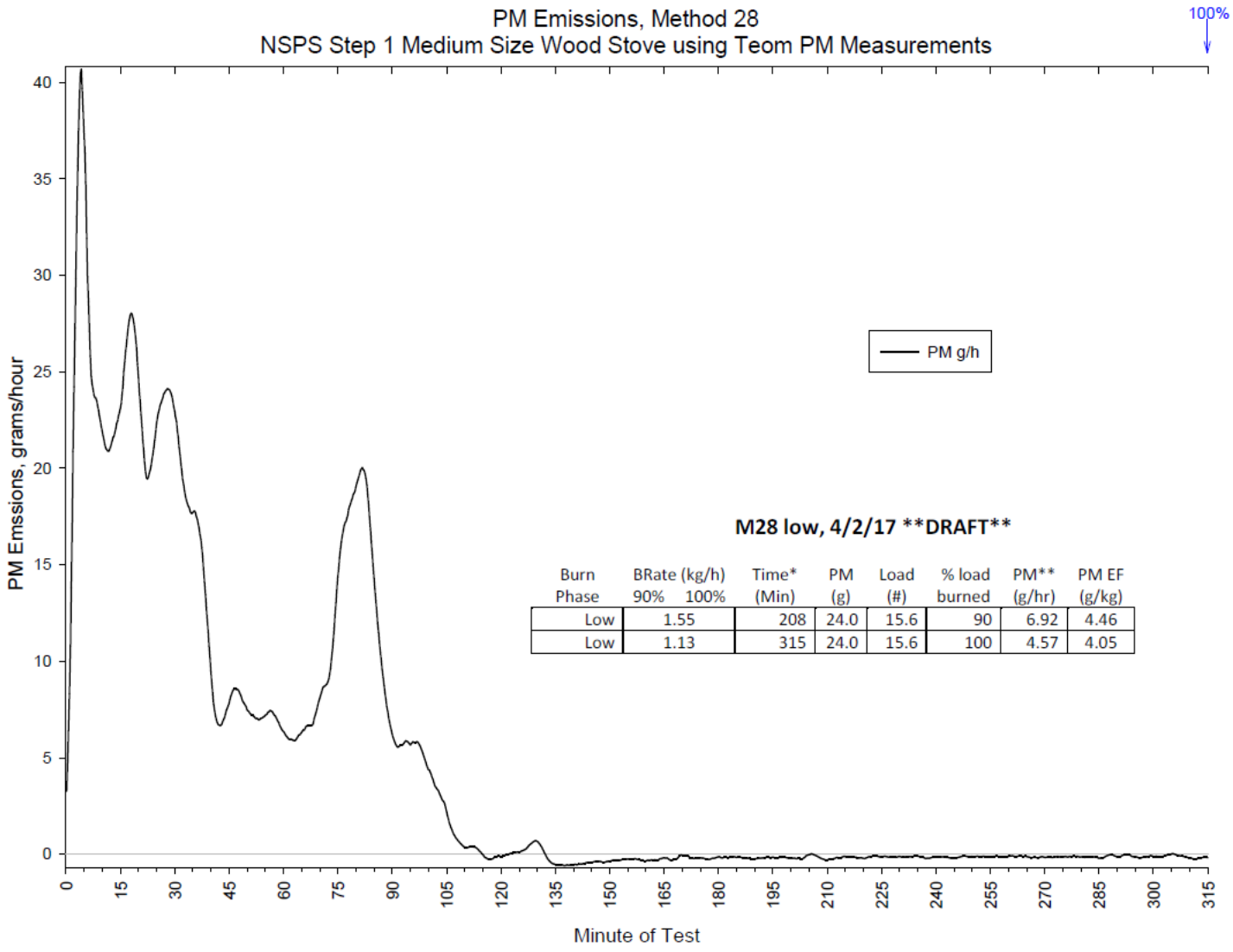


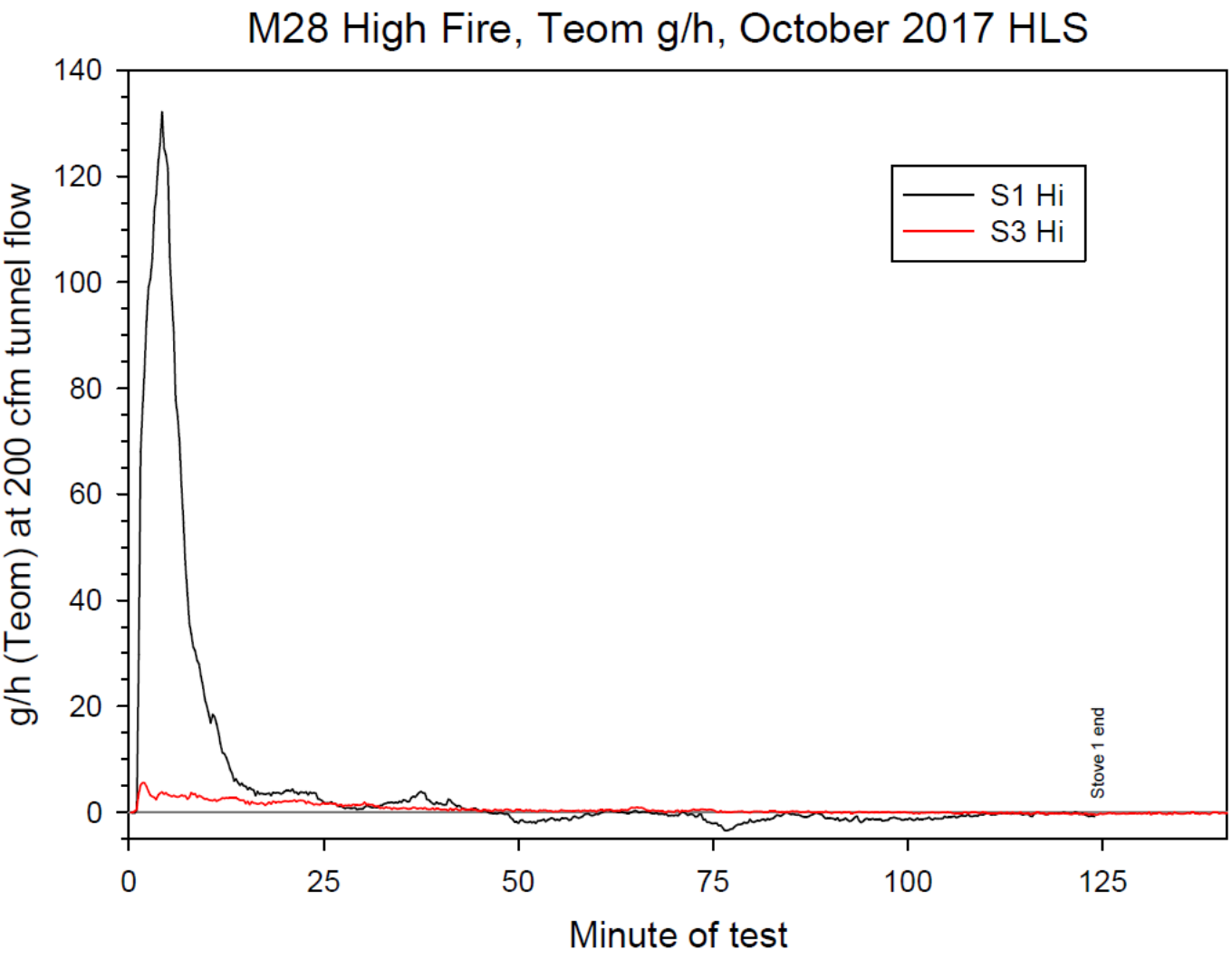
M28 medium, 04/01/17 **DRAFT**

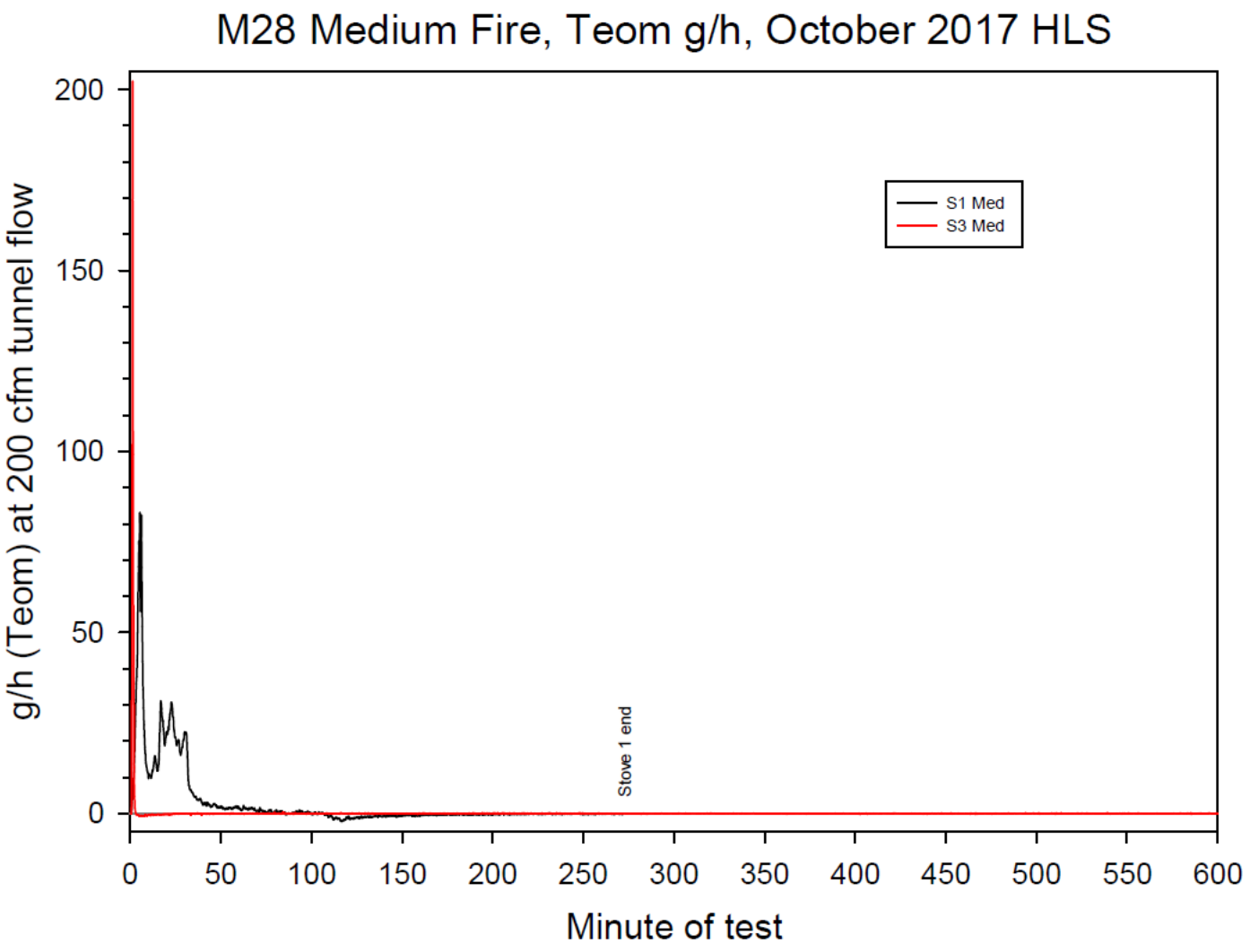
Burn Phase	BRate (kg/h)	Time* (Min)	PM** (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Med	2.49	154	4.85	15.66	90	1.89	0.76
Med	1.64	254	4.85	15.66	100	1.15	0.70

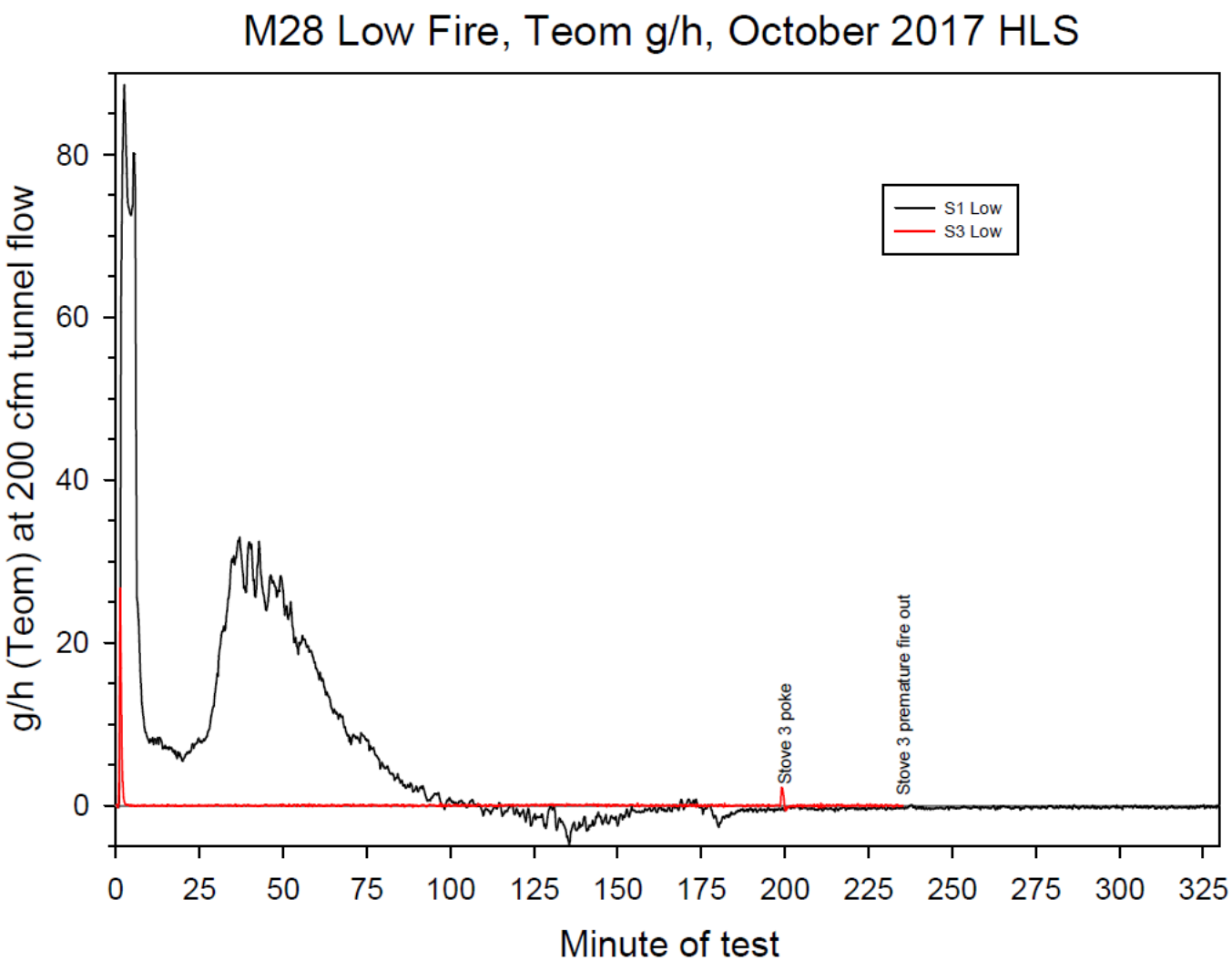


Burn Phase	BRate (kg/h) 90%	BRate (kg/h) 100%	Time* (Min)	PM (g)	Load (#)	% load burned	PM** (g/hr)	PM EF (g/kg)
Low	1.55		208	24.0	15.6	90	6.92	4.46
Low	1.13		315	24.0	15.6	100	4.57	4.05


PM Emissions, Method 28
NSPS Step 1 Medium Size Wood Stove using Teom PM Measurements
100%
PM Emssions, grams/hour
Minute of Test
PM g/h
M28 low, 4/2/17 **DRAFT**
Burn Phase
BRate (kg/h) 90% 100%
Time* (Min)
PM (g)
Load (#)
% load burned
PM** (g/hr)
PM EF (g/kg)
Low 1.55 208 24.0 15.6 90 6.92 4.46
Low 1.13 315 24.0 15.6 100 4.57 4.05


M28 High Fire, Teom g/h, October 2017 HLS
g/h (Teom) at 200 cfm tunnel flow
140
120
100
80
60
40
20
0
0
25
50
75
100
125
Minute of test
S1 Hi
S3 Hi
Stove 1 end


M28 Medium Fire, Teom g/h, October 2017 HLS
g/h (Teom) at 200 cfm tunnel flow
Minute of test
S1 Med
S3 Med
Stove 1 end
0
50
100
150
200
250
300
350
400
450
500
550
600

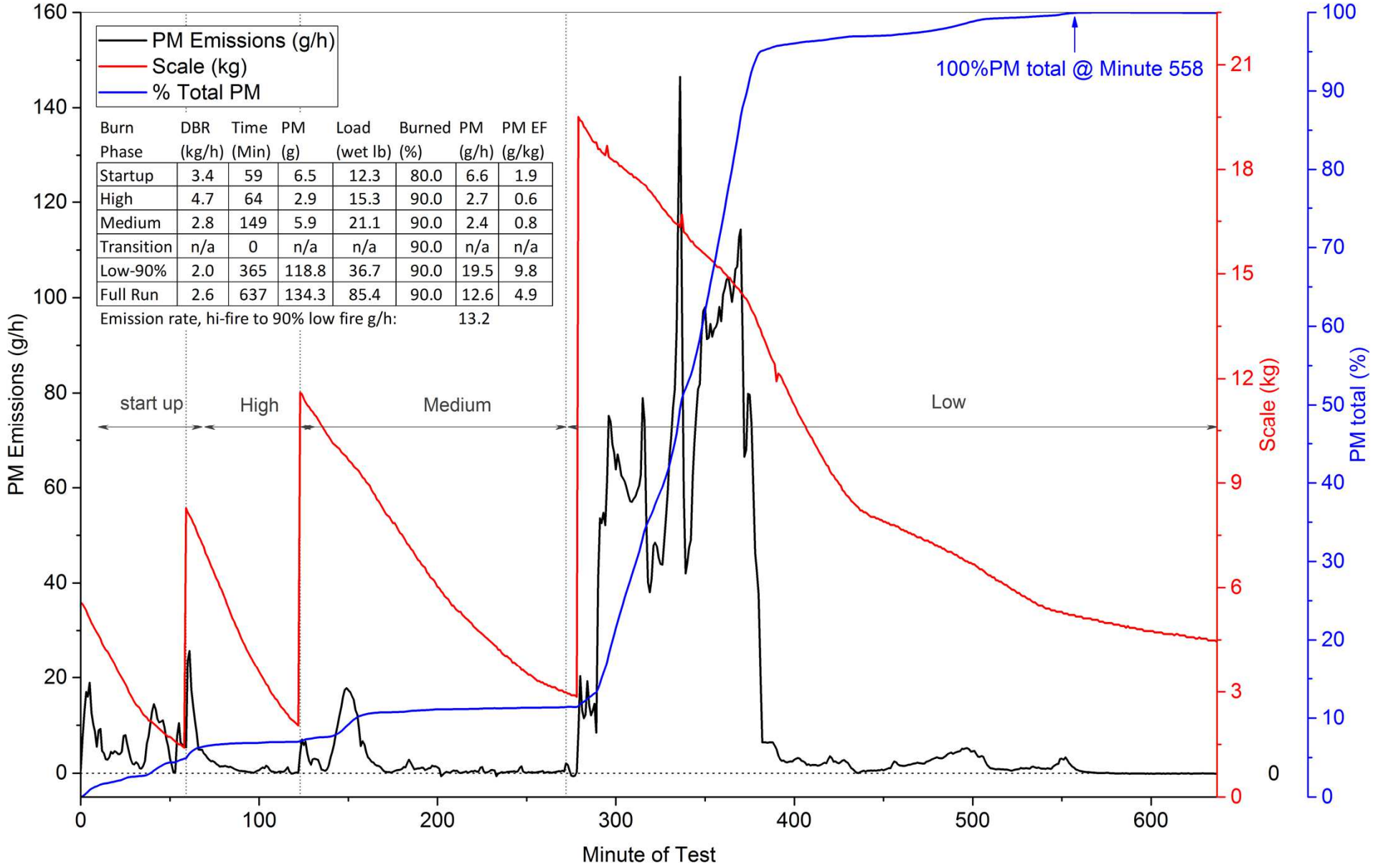

M28 Low Fire, Teom g/h, October 2017 HLS
g/h (Teom) at 200 cfm tunnel flow
Minute of test
S1 Low
S3 Low
Stove 3 poke
Stove 3 premature fire out
0
20
40
60
80
0
25
50
75
100
125
150
175
200
225
250
275
300
325

CTM Operation and Fueling Workgroup Meeting March 6, 2018

IDC TESTING

Stove 1

Stove1: IDC - PM Emissions 1/18/2018



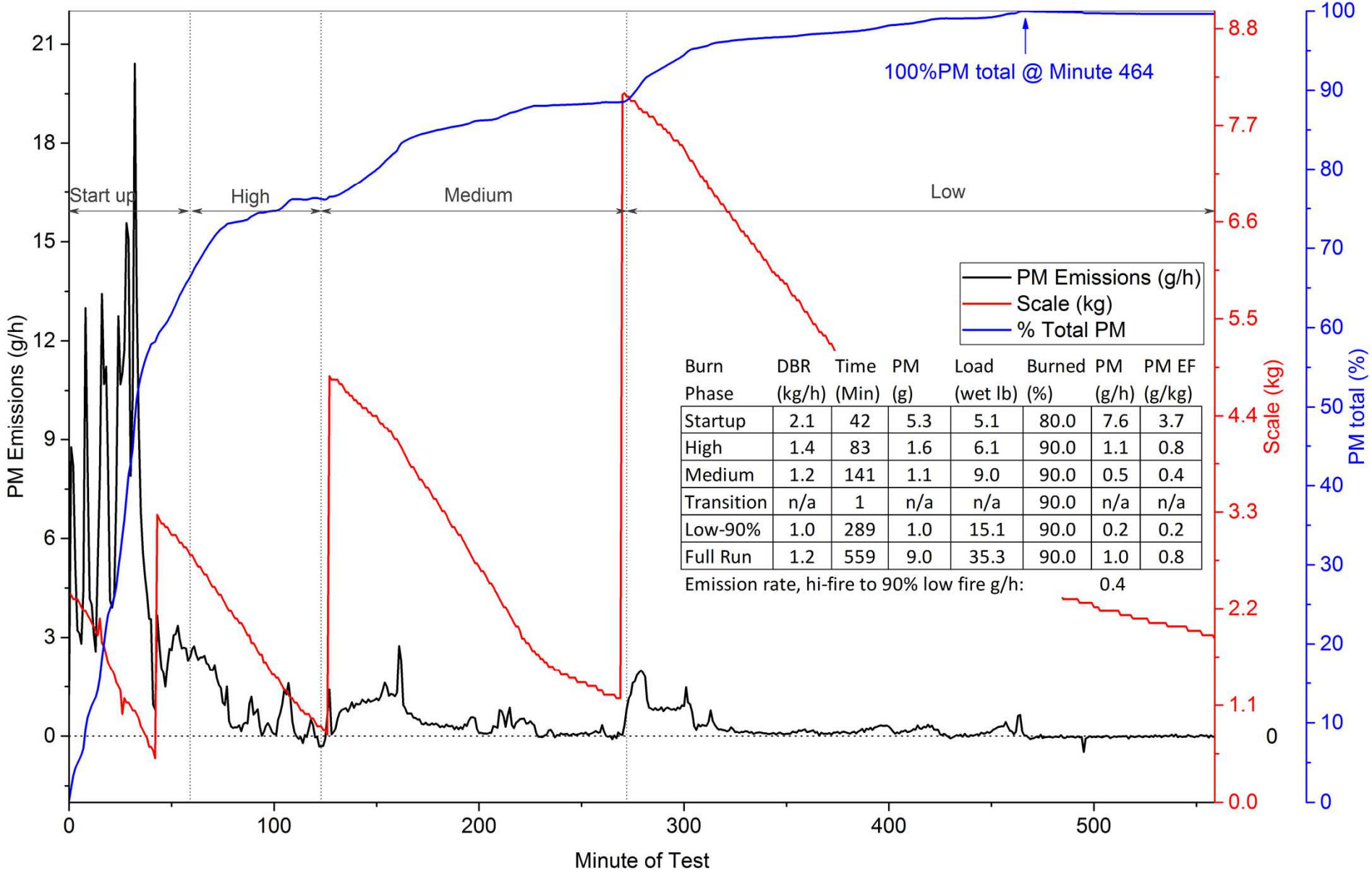
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	3.4	59	6.5	12.3	80.0	6.6	1.9
High	4.7	64	2.9	15.3	90.0	2.7	0.6
Medium	2.8	149	5.9	21.1	90.0	2.4	0.8
Transition	n/a	0	n/a	n/a	90.0	n/a	n/a
Low-90%	2.0	365	118.8	36.7	90.0	19.5	9.8
Full Run	2.6	637	134.3	85.4	90.0	12.6	4.9

Emission rate, hi-fire to 90% low fire g/h: 13.2

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Stove 2

Stove 2: IDC - PM Emissions 1/24/2018



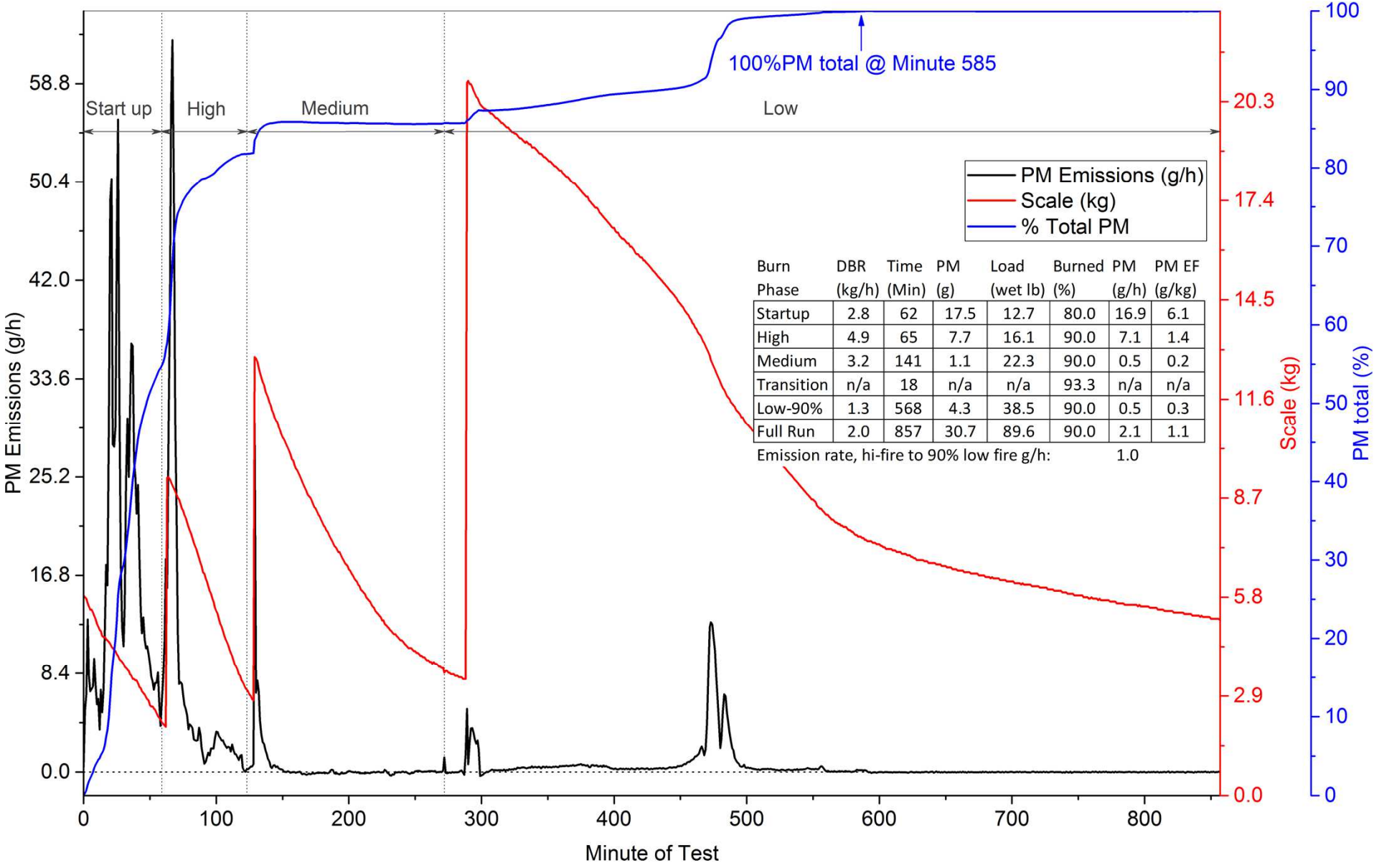
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	2.1	42	5.3	5.1	80.0	7.6	3.7
High	1.4	83	1.6	6.1	90.0	1.1	0.8
Medium	1.2	141	1.1	9.0	90.0	0.5	0.4
Transition	n/a	1	n/a	n/a	90.0	n/a	n/a
Low-90%	1.0	289	1.0	15.1	90.0	0.2	0.2
Full Run	1.2	559	9.0	35.3	90.0	1.0	0.8

Emission rate, hi-fire to 90% low fire g/h: 0.4

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Stove 3

Stove 3: IDC - PM Emissions 1/26/2018

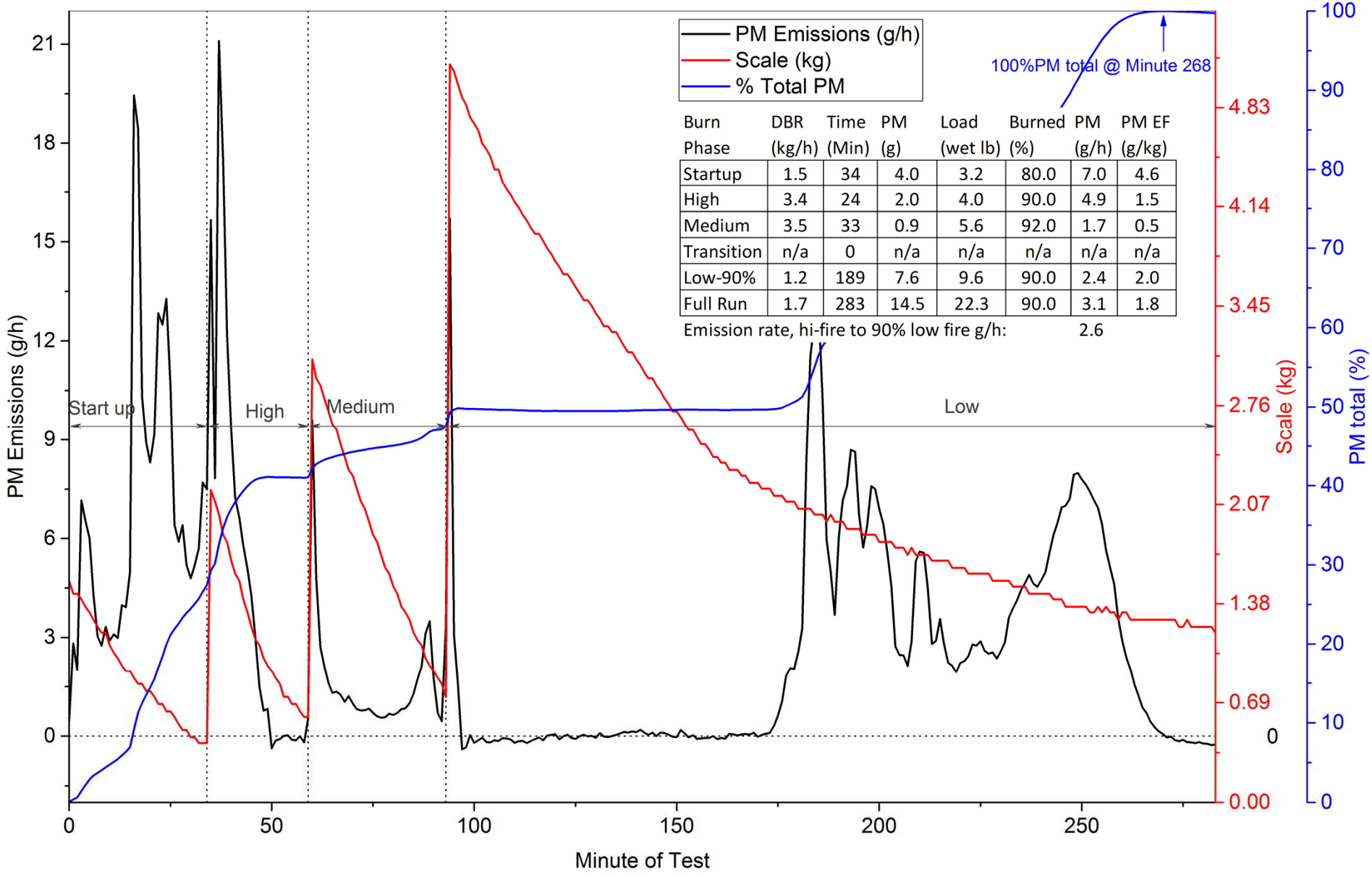


Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	2.8	62	17.5	12.7	80.0	16.9	6.1
High	4.9	65	7.7	16.1	90.0	7.1	1.4
Medium	3.2	141	1.1	22.3	90.0	0.5	0.2
Transition	n/a	18	n/a	n/a	93.3	n/a	n/a
Low-90%	1.3	568	4.3	38.5	90.0	0.5	0.3
Full Run	2.0	857	30.7	89.6	90.0	2.1	1.1
Emission rate, hi-fire to 90% low fire g/h:						1.0	

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Stove 4

Stove 4: IDC - PM Emissions 1/16/2018

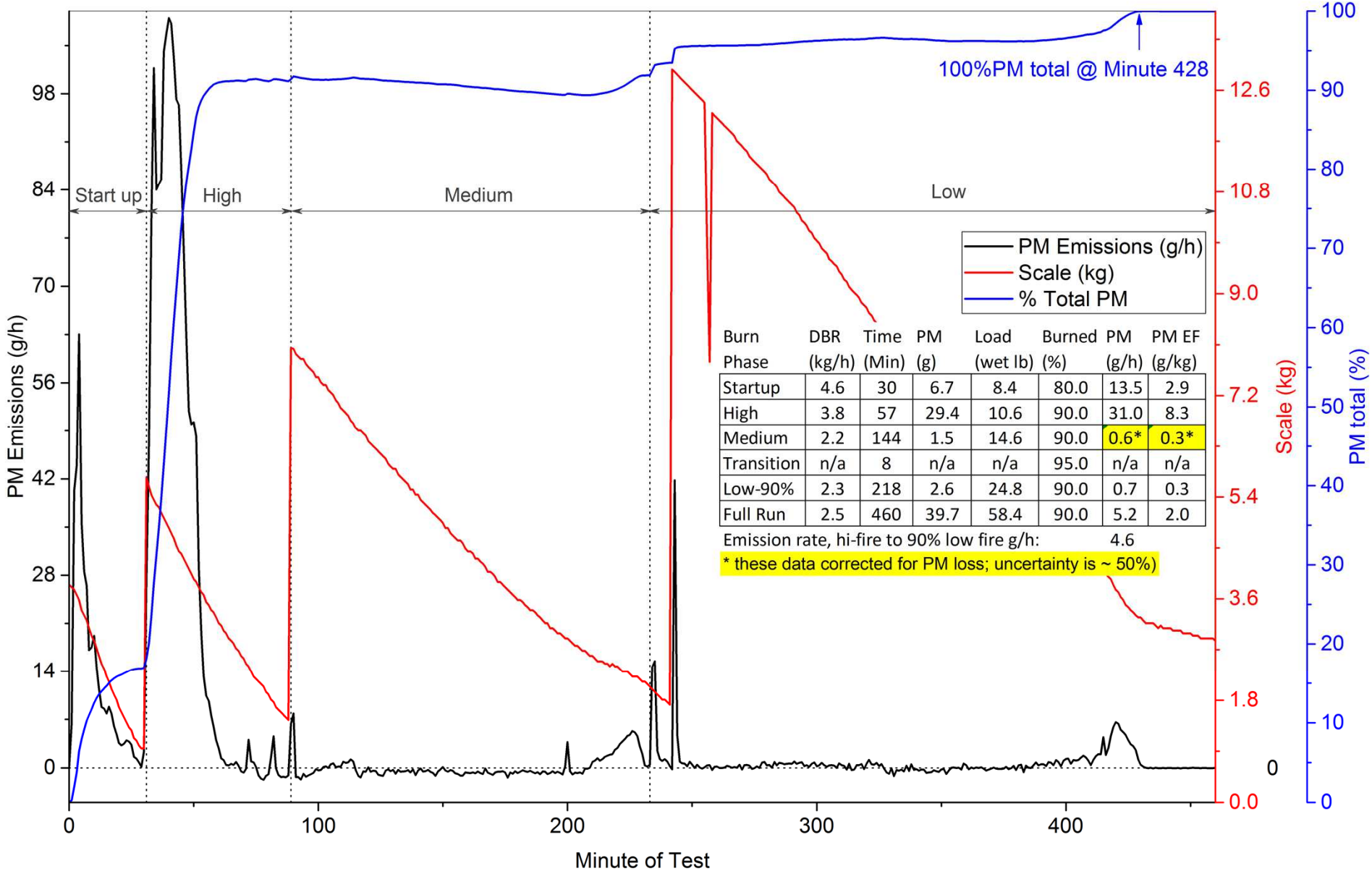


Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	1.5	34	4.0	3.2	80.0	7.0	4.6
High	3.4	24	2.0	4.0	90.0	4.9	1.5
Medium	3.5	33	0.9	5.6	92.0	1.7	0.5
Transition	n/a	0	n/a	n/a	n/a	n/a	n/a
Low-90%	1.2	189	7.6	9.6	90.0	2.4	2.0
Full Run	1.7	283	14.5	22.3	90.0	3.1	1.8
Emission rate, hi-fire to 90% low fire g/h:						2.6	

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Stove 5

Stove 5: IDC - PM Emissions 1/12/2018



Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	4.6	30	6.7	8.4	80.0	13.5	2.9
High	3.8	57	29.4	10.6	90.0	31.0	8.3
Medium	2.2	144	1.5	14.6	90.0	0.6*	0.3*
Transition	n/a	8	n/a	n/a	95.0	n/a	n/a
Low-90%	2.3	218	2.6	24.8	90.0	0.7	0.3
Full Run	2.5	460	39.7	58.4	90.0	5.2	2.0

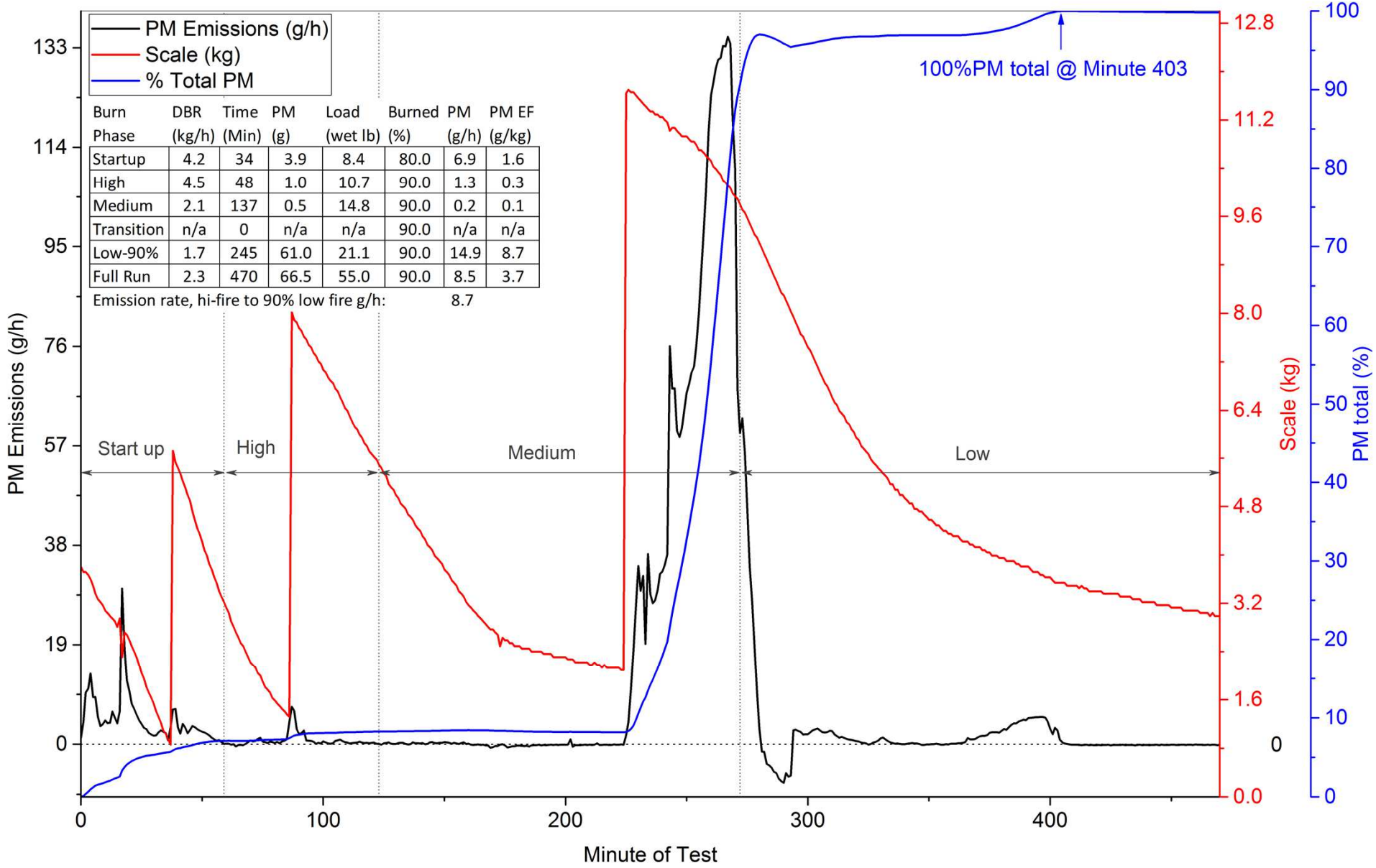
Emission rate, hi-fire to 90% low fire g/h: 4.6

* these data corrected for PM loss; uncertainty is ~ 50%)

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Stove 6

Stove 6: IDC - PM Emissions 1/9/2018



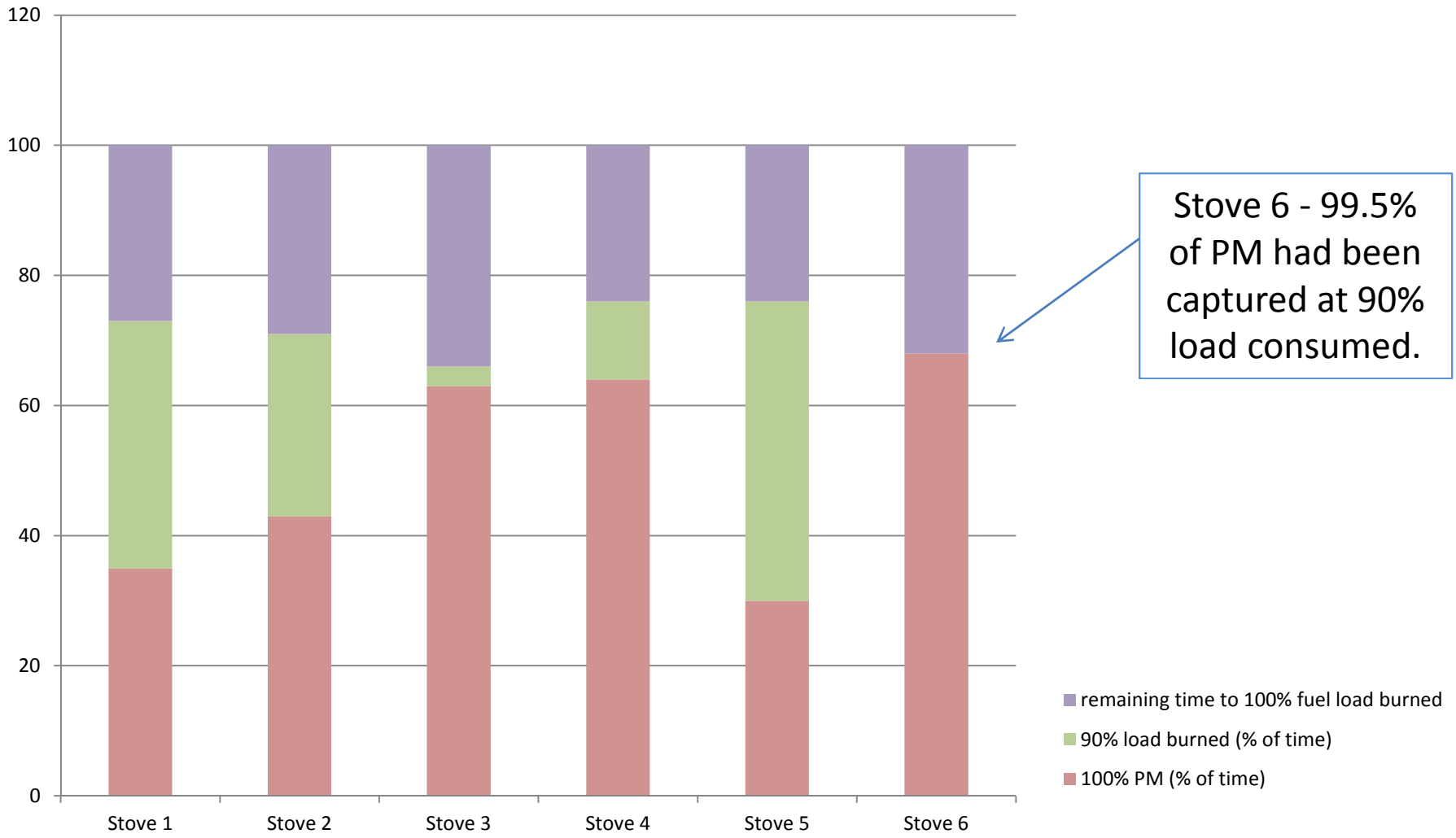
Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb)	Burned (%)	PM (g/h)	PM EF (g/kg)
Startup	4.2	34	3.9	8.4	80.0	6.9	1.6
High	4.5	48	1.0	10.7	90.0	1.3	0.3
Medium	2.1	137	0.5	14.8	90.0	0.2	0.1
Transition	n/a	0	n/a	n/a	90.0	n/a	n/a
Low-90%	1.7	245	61.0	21.1	90.0	14.9	8.7
Full Run	2.3	470	66.5	55.0	90.0	8.5	3.7
Emission rate, hi-fire to 90% low fire g/h:						8.7	

* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

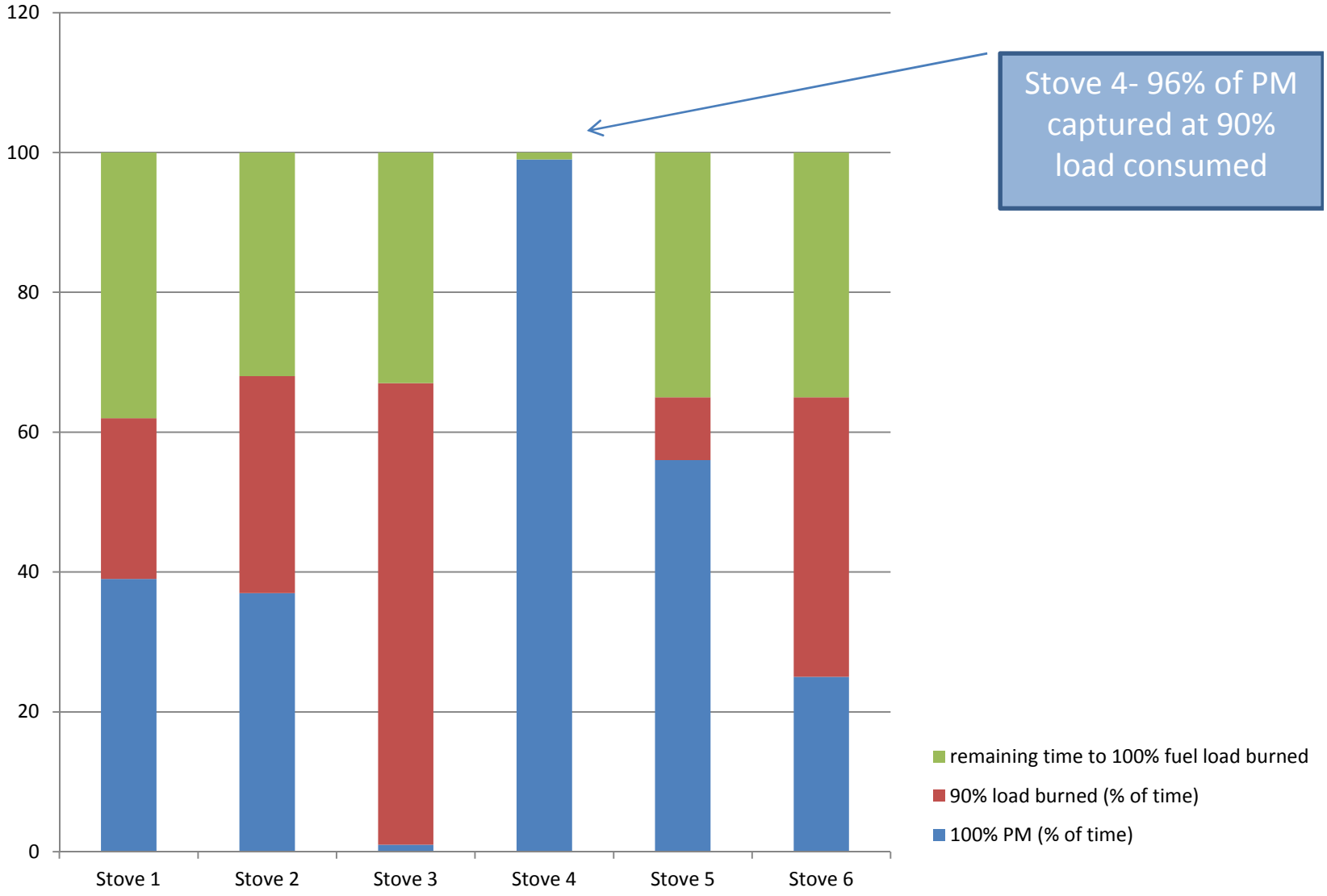
3/3/2018

PM CAPTURE

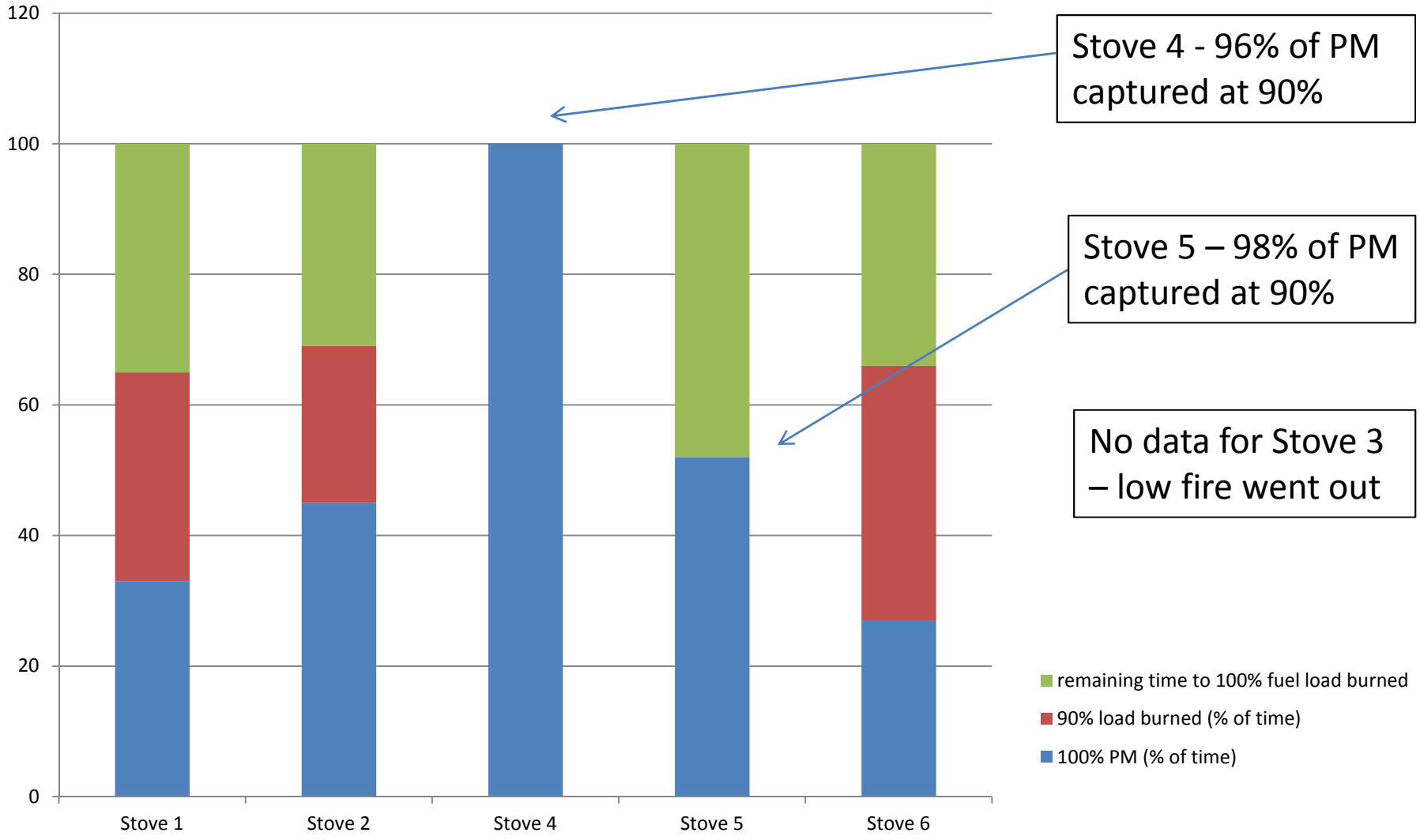
PM Capture M28 High Burn



PM Capture M28 Medium Burn



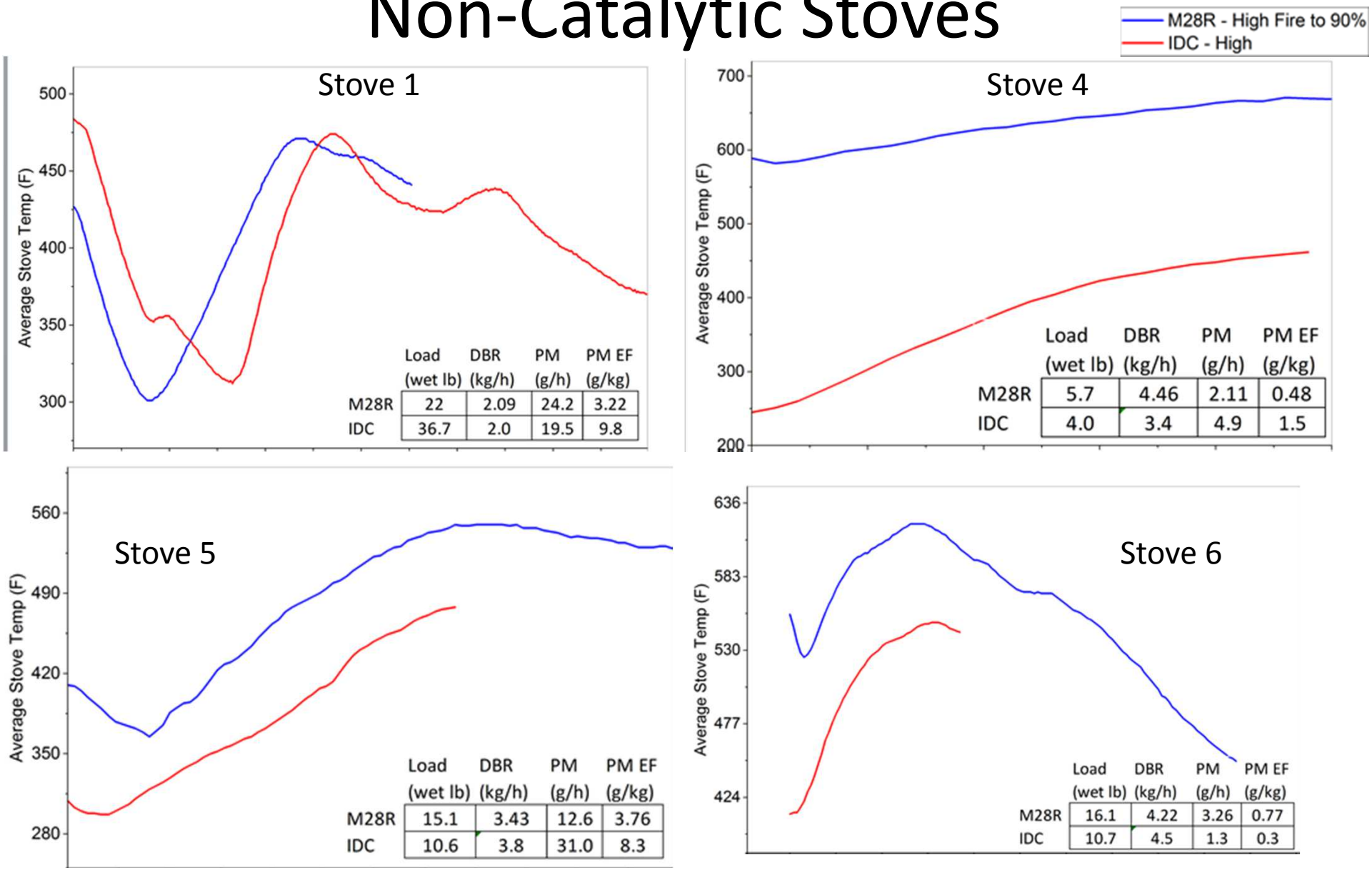
PM Capture M28 Low Burn



3/3/2018

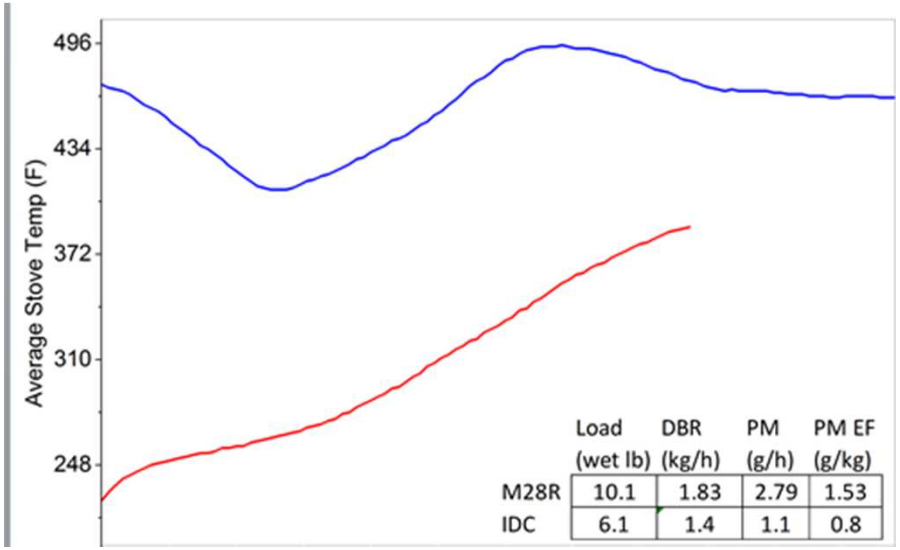
STOVE TEMPERATURE DATA

Stove Temp – Max Air Setting
Non-Catalytic Stoves



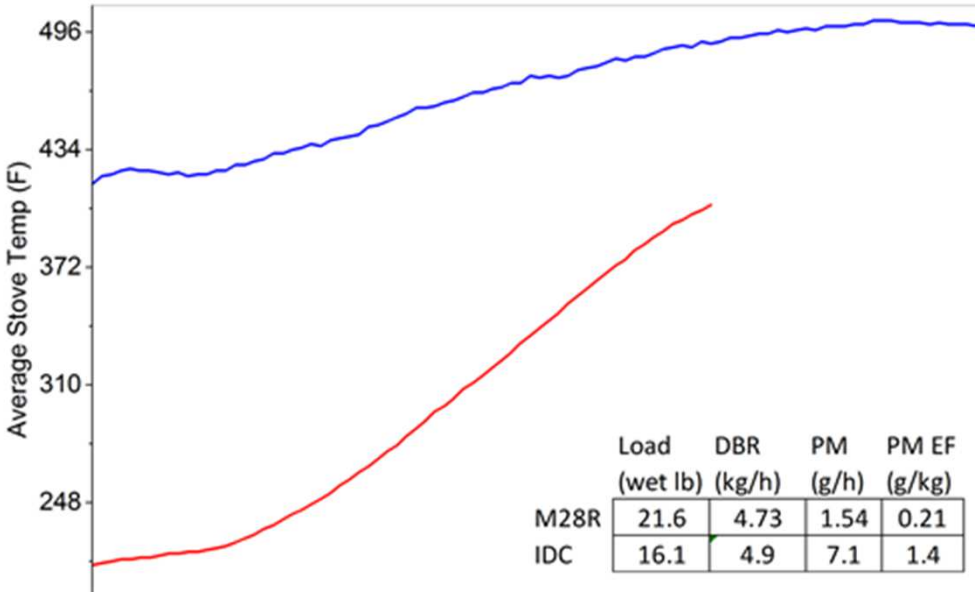
Stove Temp – Max Air Setting
Catalytic Stoves

Stove 2



	Load (wet lb)	DBR (kg/h)	PM (g/h)	PM EF (g/kg)
M28R	10.1	1.83	2.79	1.53
IDC	6.1	1.4	1.1	0.8

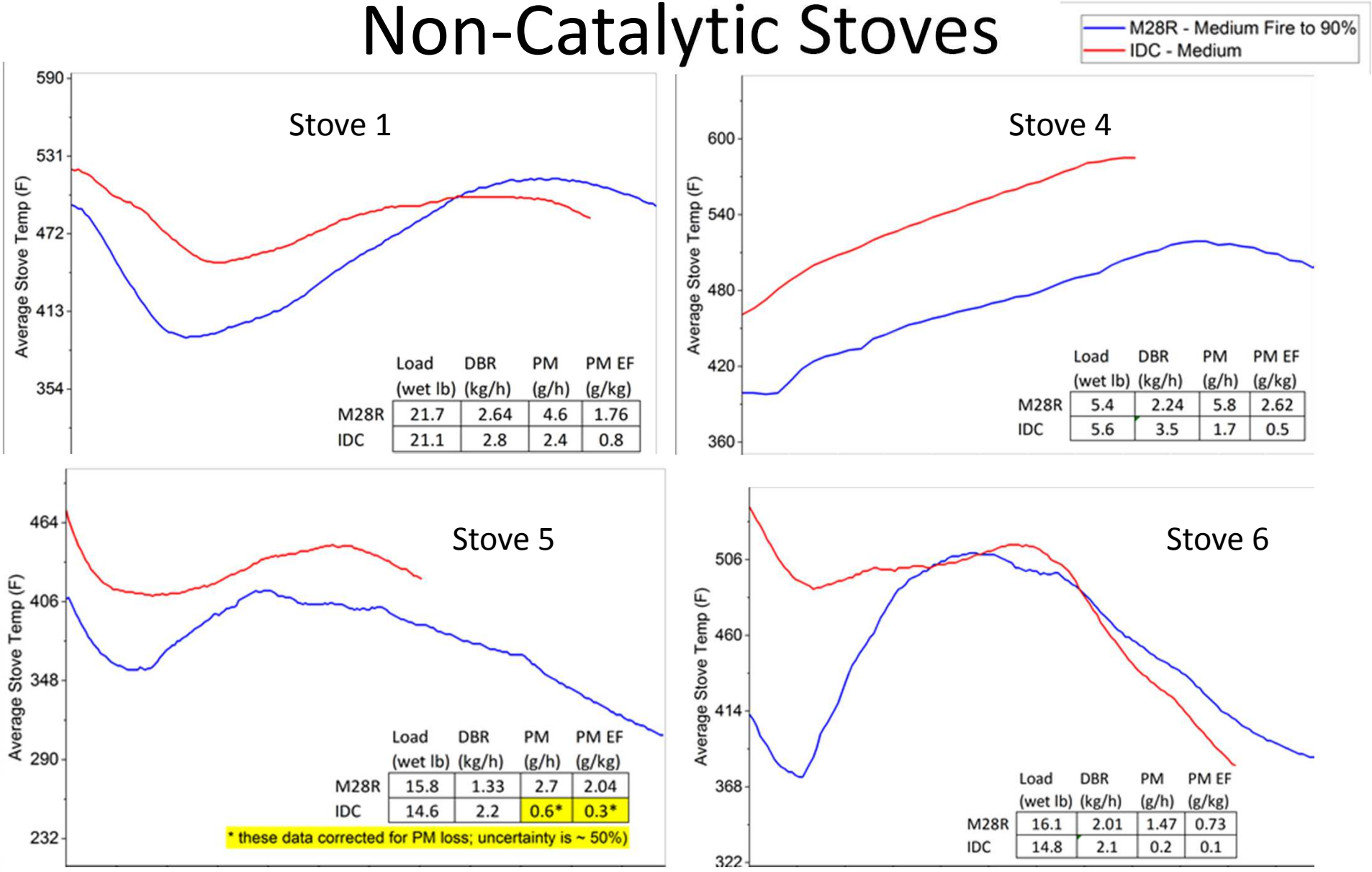
Stove 3



	Load (wet lb)	DBR (kg/h)	PM (g/h)	PM EF (g/kg)
M28R	21.6	4.73	1.54	0.21
IDC	16.1	4.9	7.1	1.4

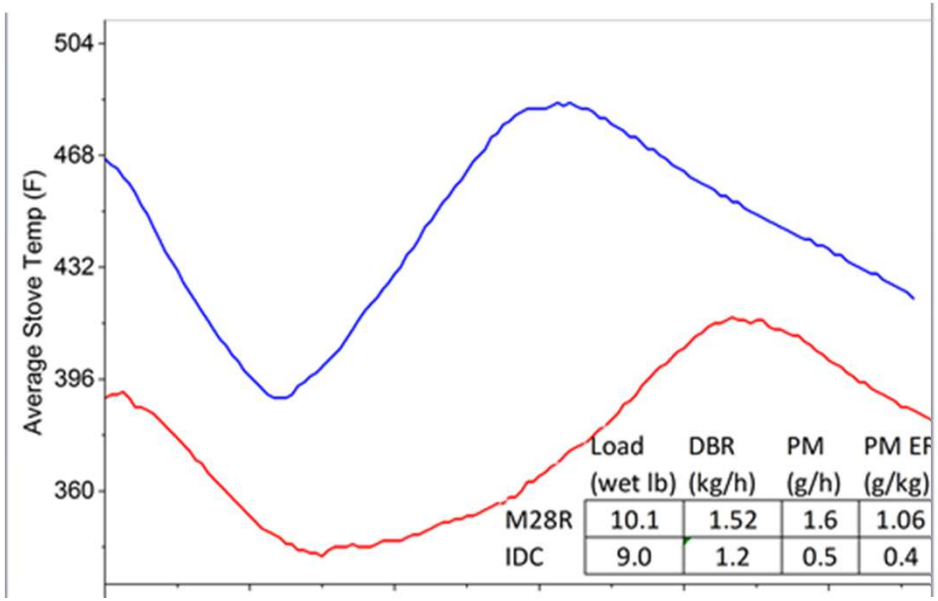
M28R - High Fire to 90%
IDC - High

Stove Temp – Medium Air Setting
Non-Catalytic Stoves



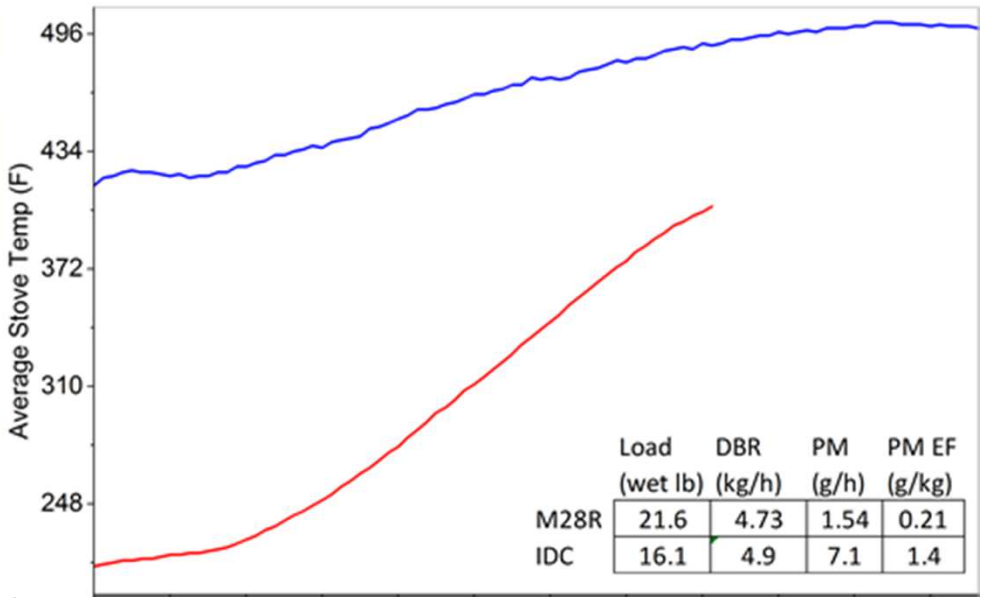
Stove Temp – Medium Air Setting
Catalytic Stoves

Stove 2



	Load (wet lb)	DBR (kg/h)	PM (g/h)	PM EF (g/kg)
M28R	10.1	1.52	1.6	1.06
IDC	9.0	1.2	0.5	0.4

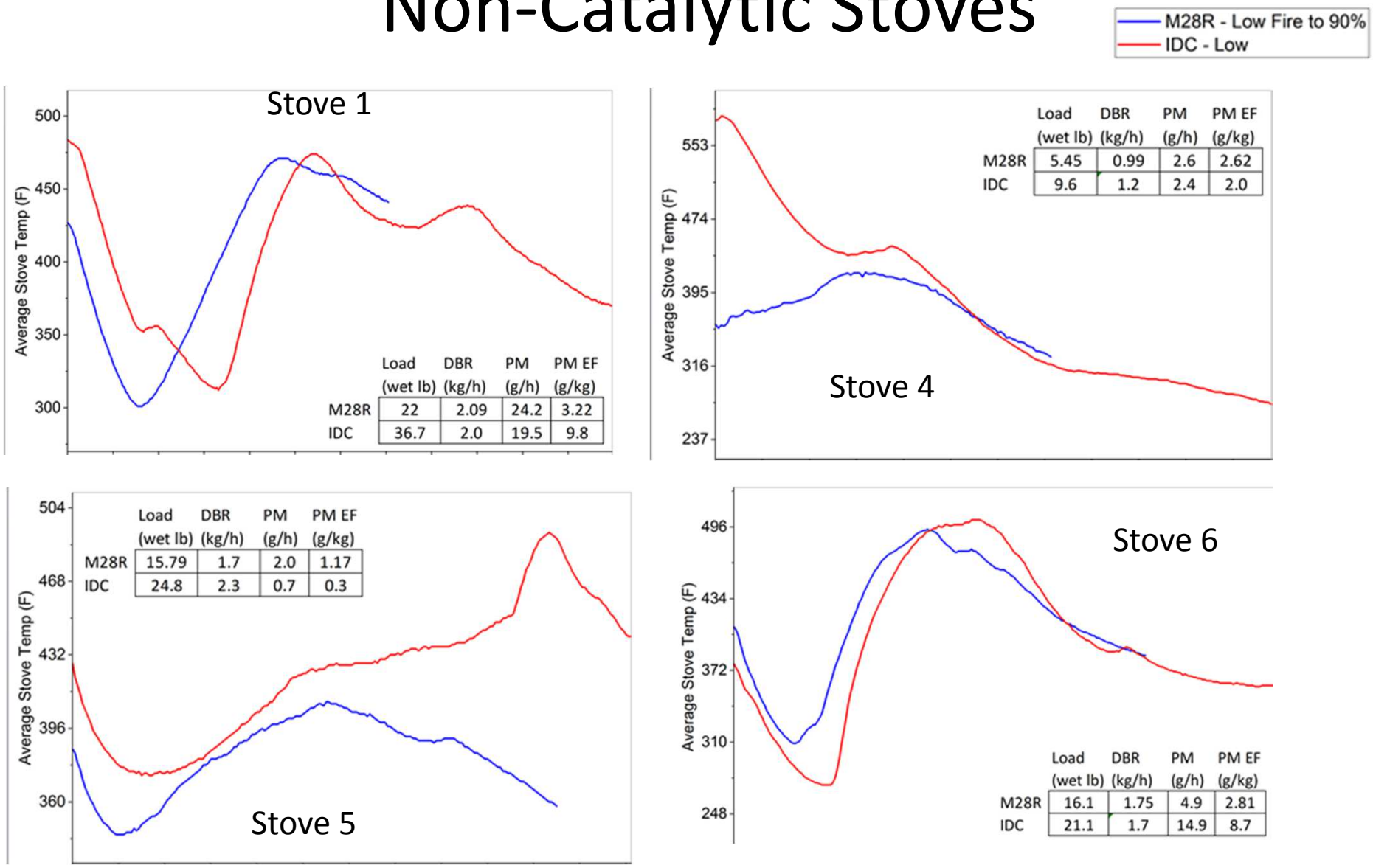
Stove 3



	Load (wet lb)	DBR (kg/h)	PM (g/h)	PM EF (g/kg)
M28R	21.6	4.73	1.54	0.21
IDC	16.1	4.9	7.1	1.4

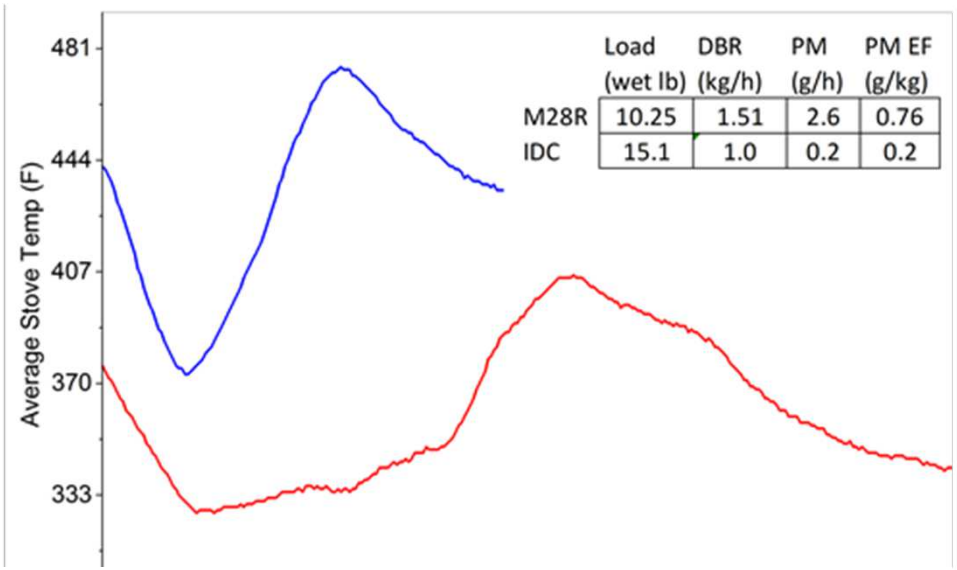
M28R - Medium Fire to 90%
IDC - Medium

Stove Temp – Lowest Air Setting
Non-Catalytic Stoves



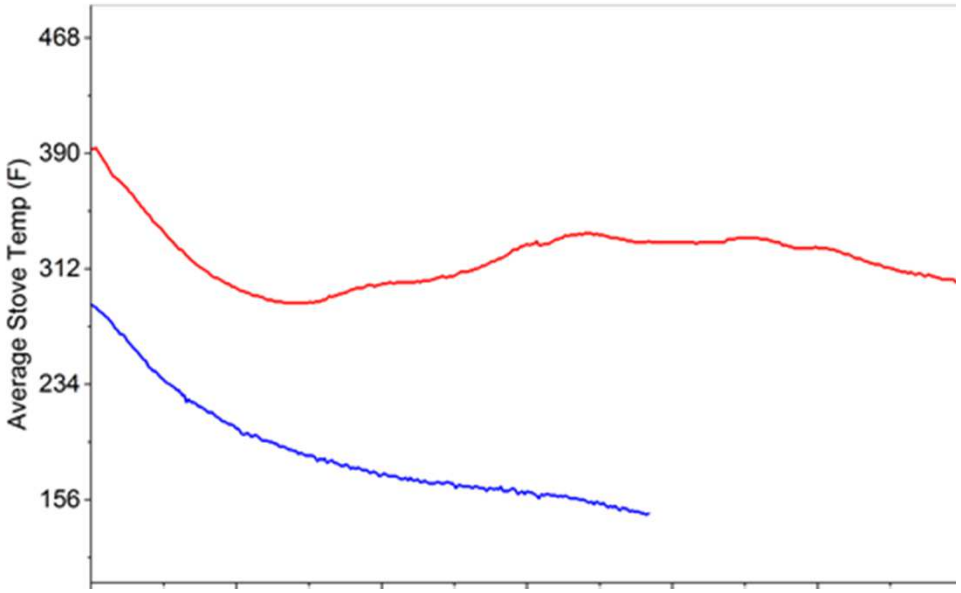
Stove Temp – Lowest Air Setting
Catalytic Stoves

Stove 2



	Load (wet lb)	DBR (kg/h)	PM (g/h)	PM EF (g/kg)
M28R	10.25	1.51	2.6	0.76
IDC	15.1	1.0	0.2	0.2

Stove 3



M28R - Low Fire to 90%
IDC - Low

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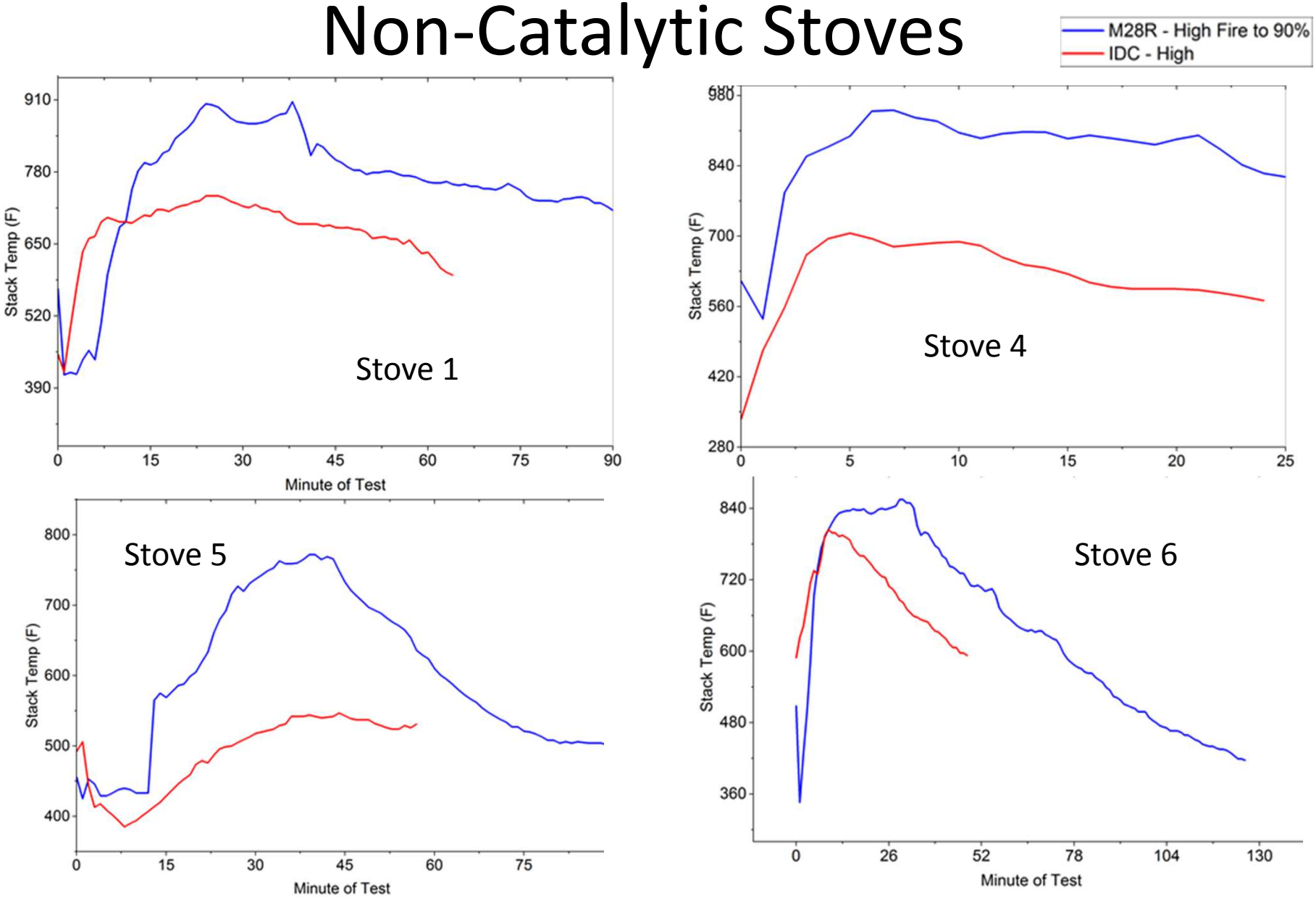
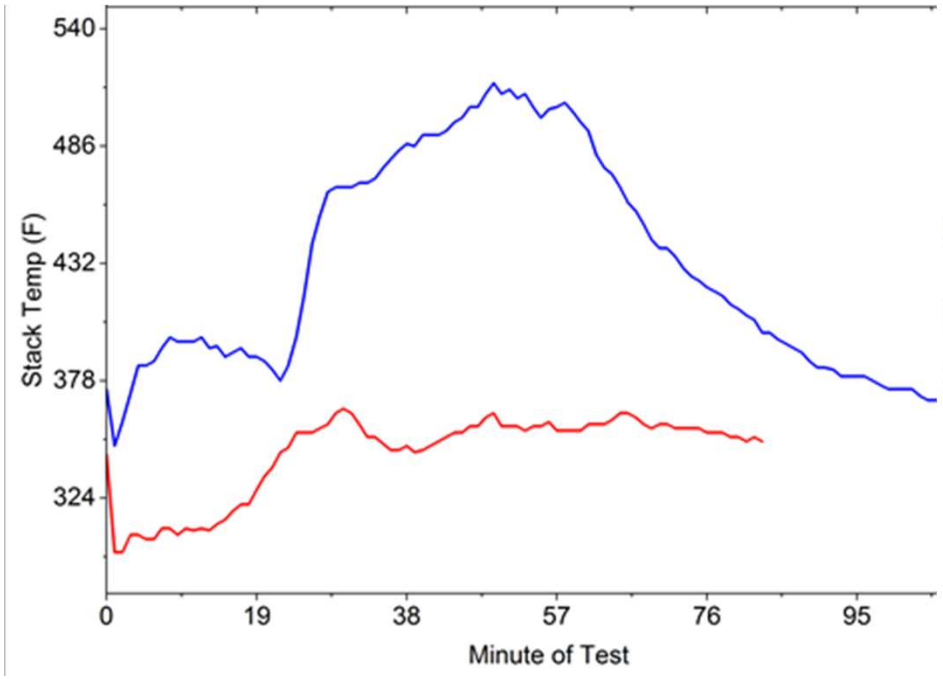
STACK TEMPERATURE DATA

Stack Temp – Max Air Setting
Non-Catalytic Stoves

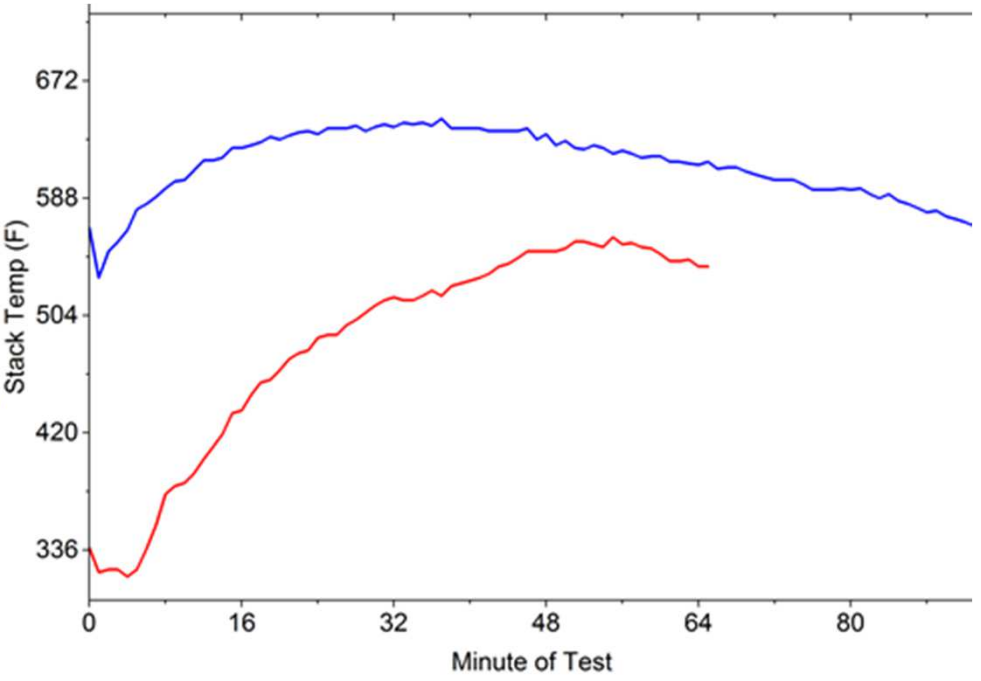


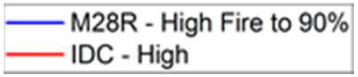
Stack Temp – Max Air Setting
Catalytic Stoves

Stove 2

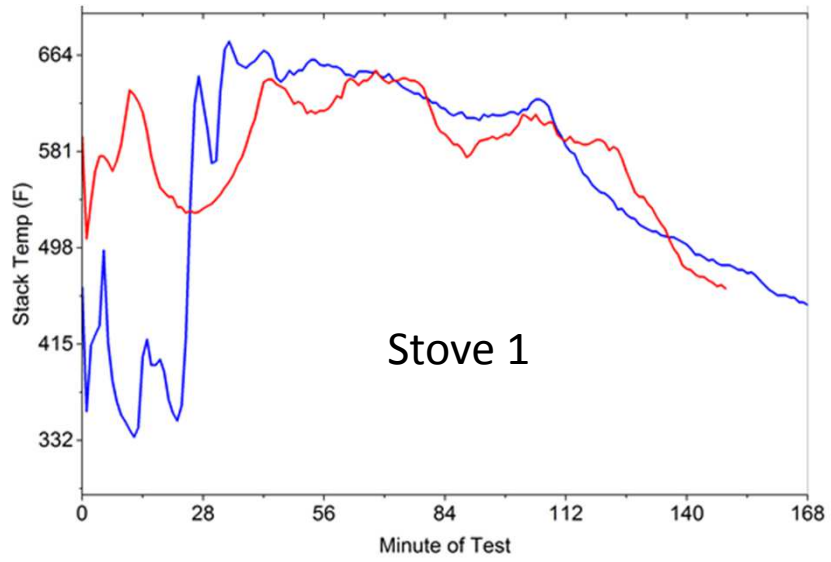


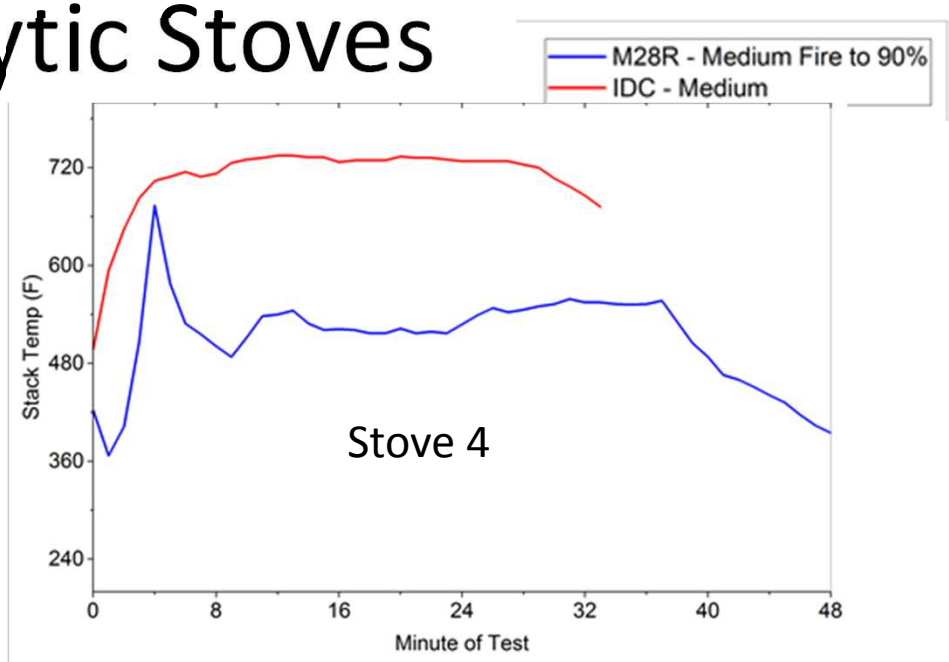
Stove 3

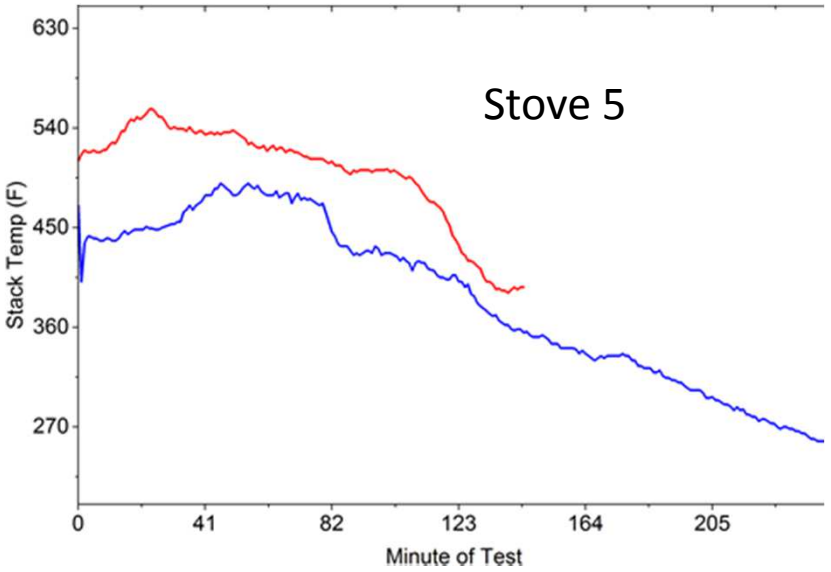


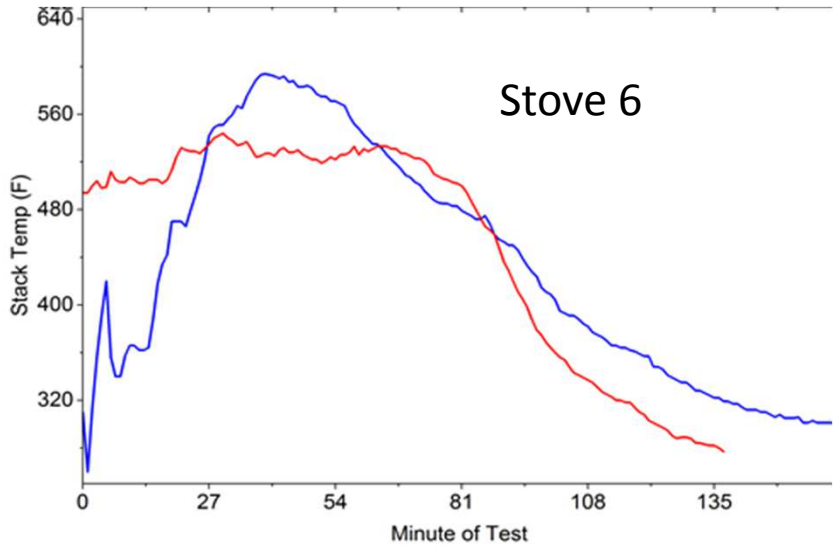


Stack Temp – Medium Air Setting
Non-Catalytic Stoves



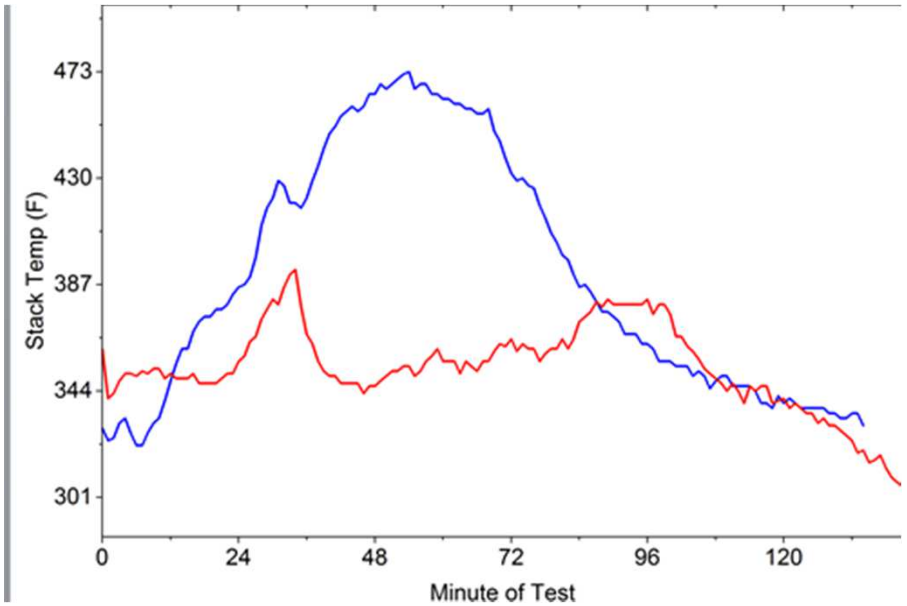




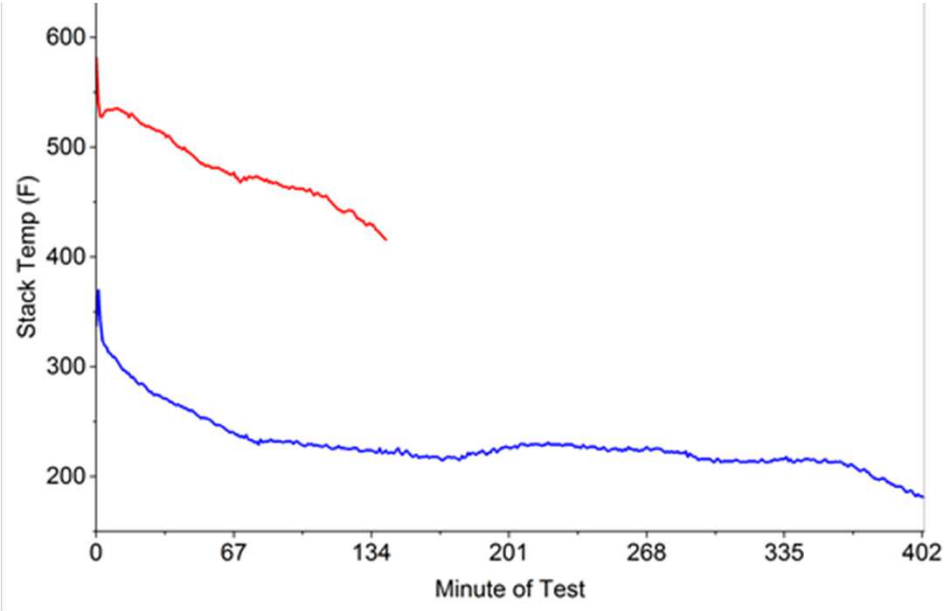


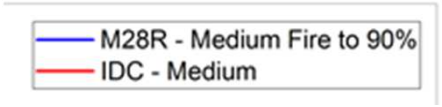
Stack Temp – Medium Air Setting Catalytic Stoves

Stove 2

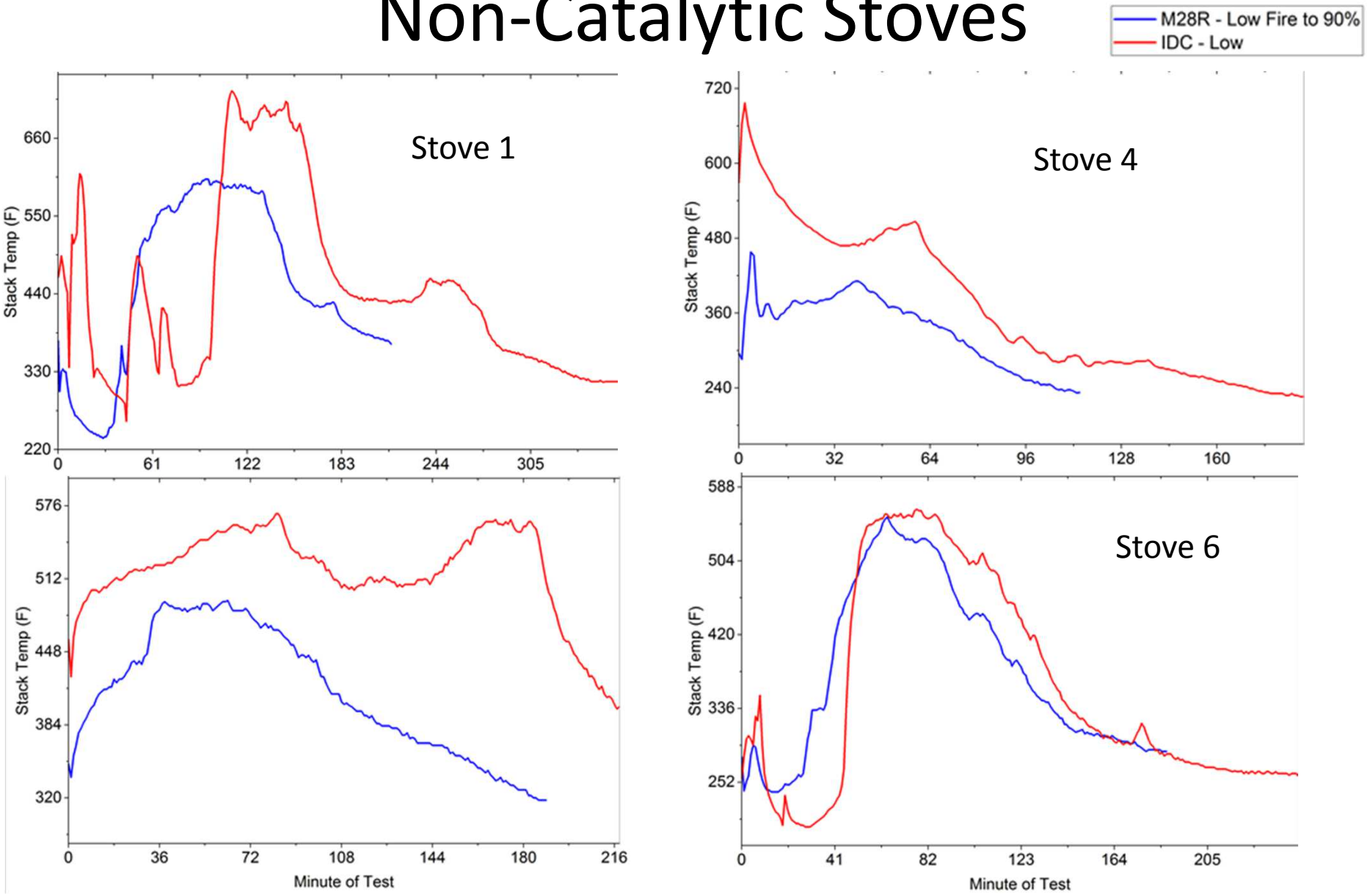


Stove 3



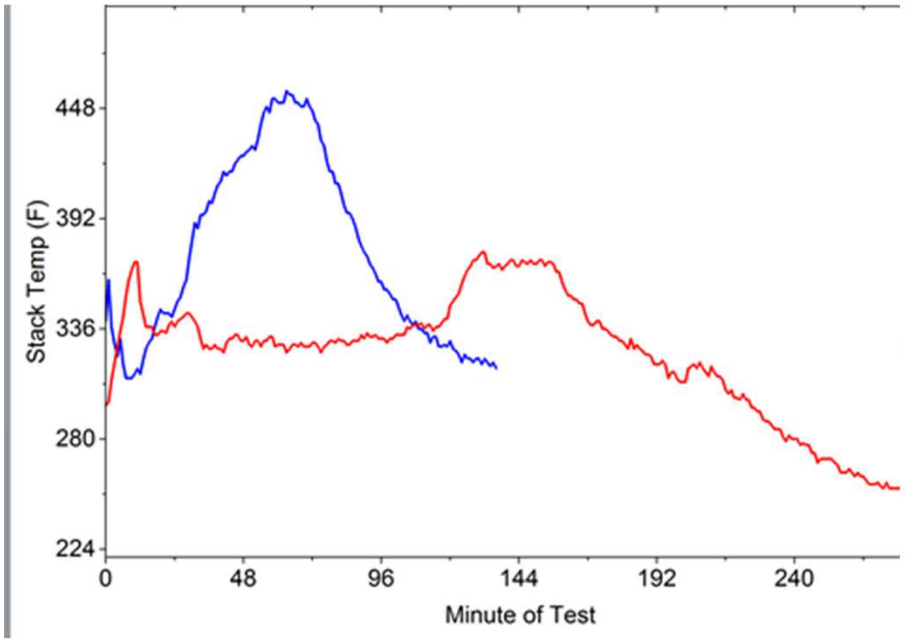


Stack Temp – Lowest Air Setting
Non-Catalytic Stoves

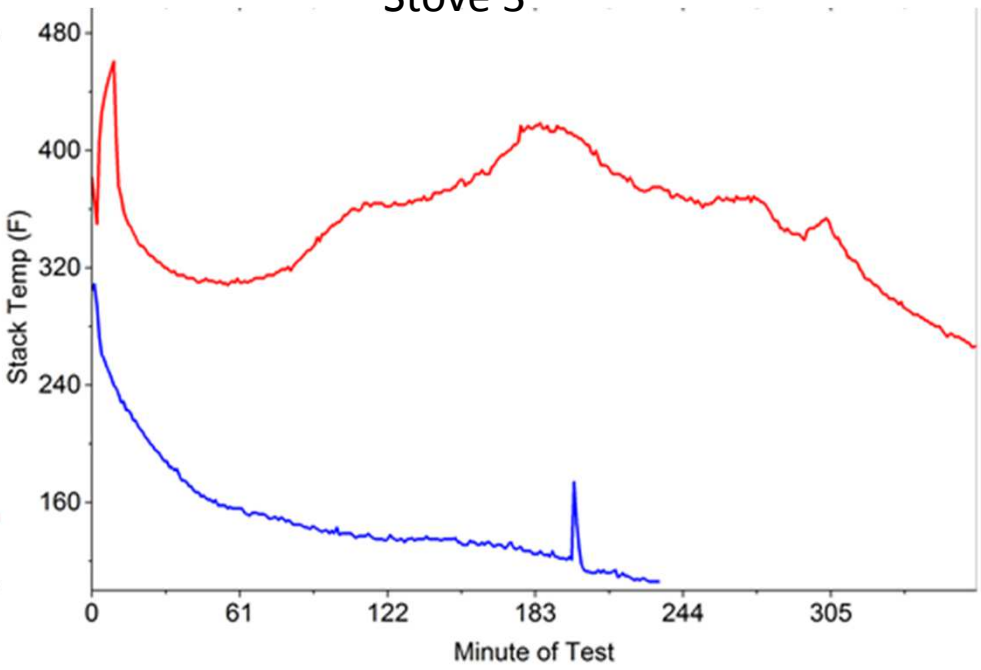


Stack Temp – Lowest Air Setting Catalytic Stoves

Stove 2



Stove 3



M28R - Low Fire to 90%
IDC - Low

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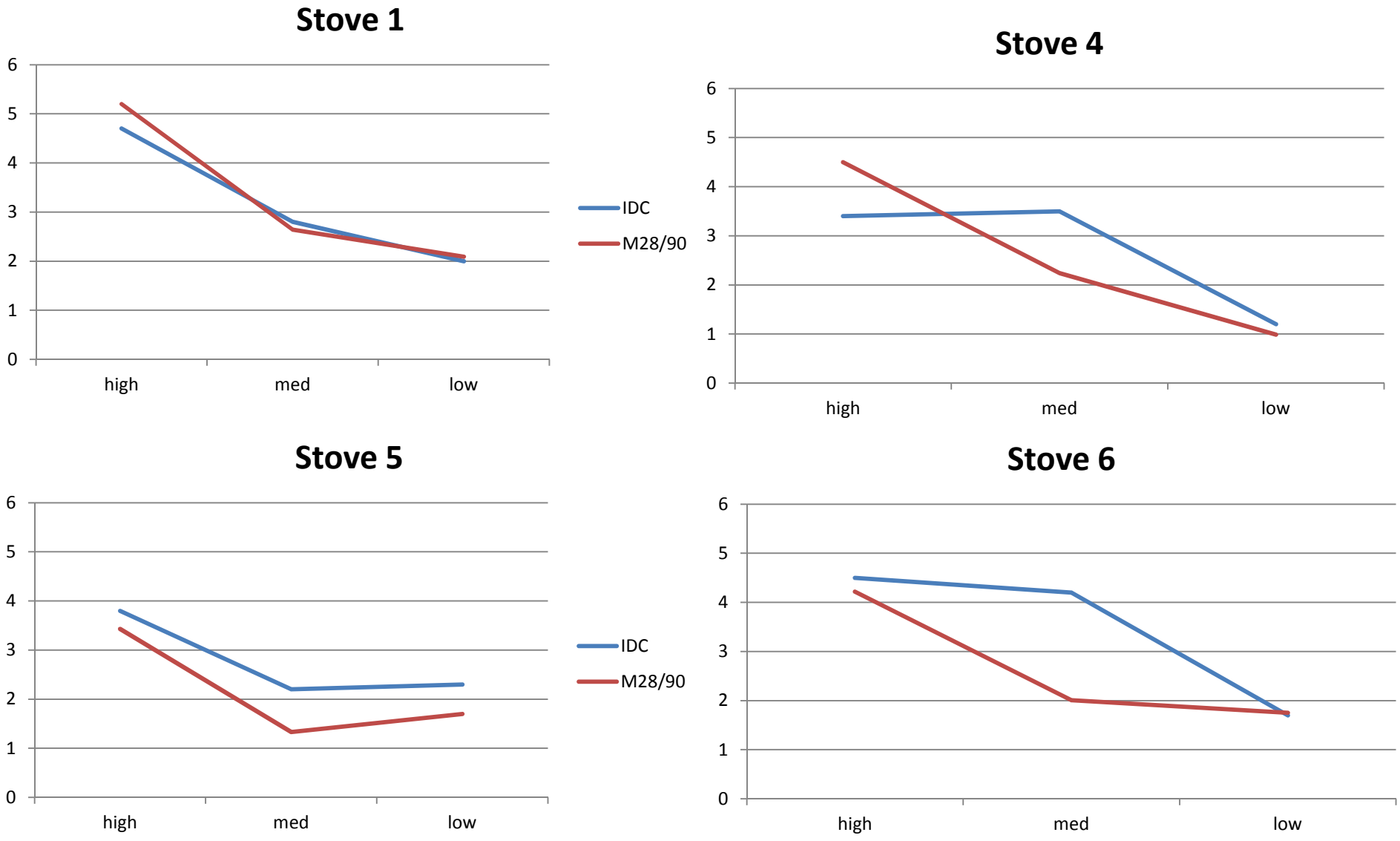
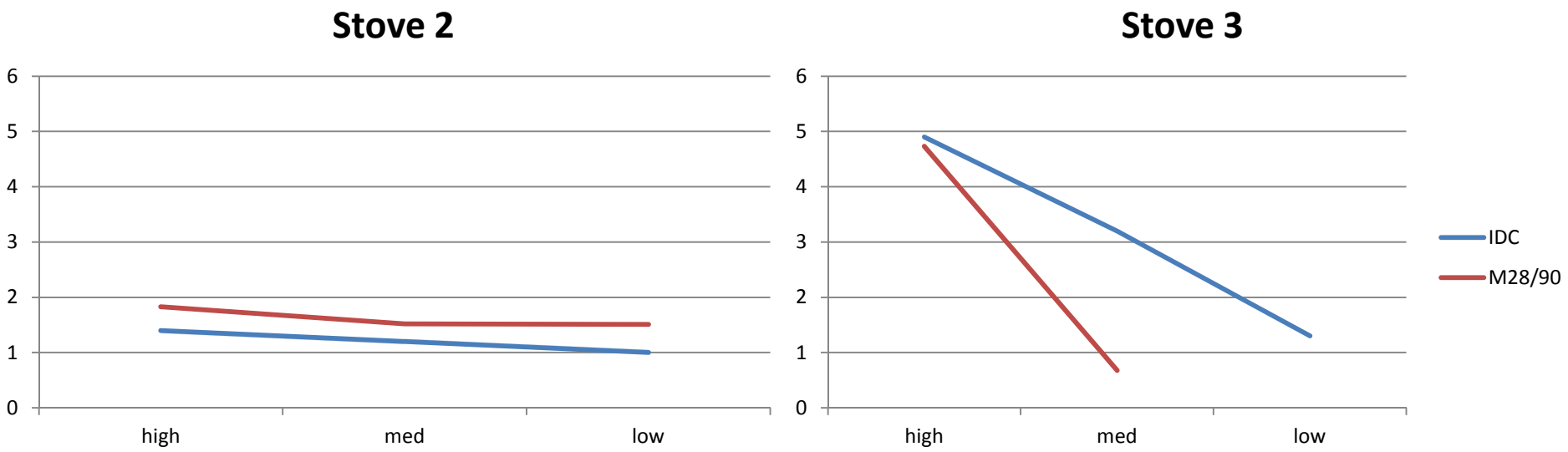
BURN RATE DATA

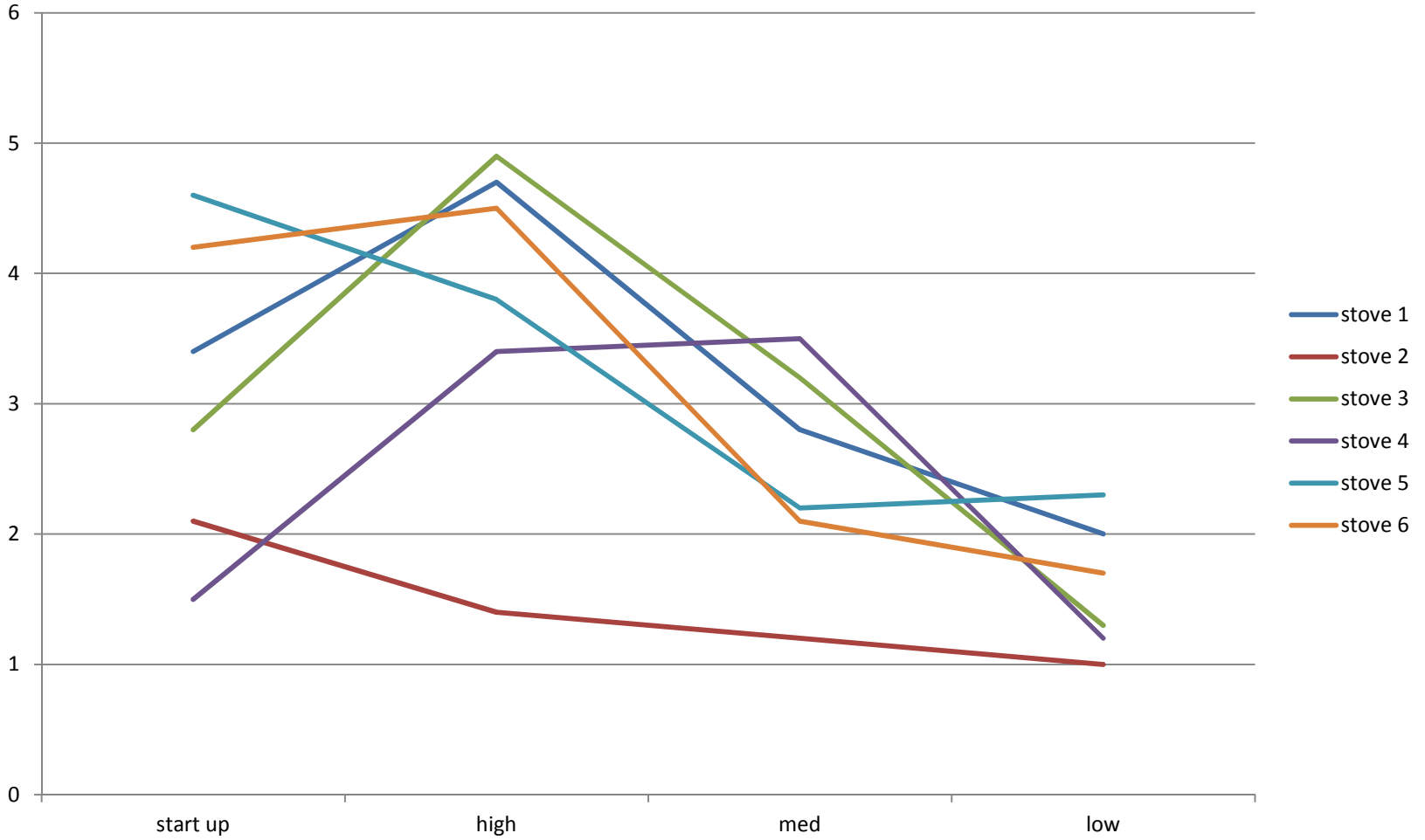
M28 vs. IDC Burn Rates
Non-Catalytic Stoves (kg/hr.)



M28 vs. IDC Burn Rates
Catalytic Stoves (kg/hr.)



IDC Protocol
Burn Rate by Stove



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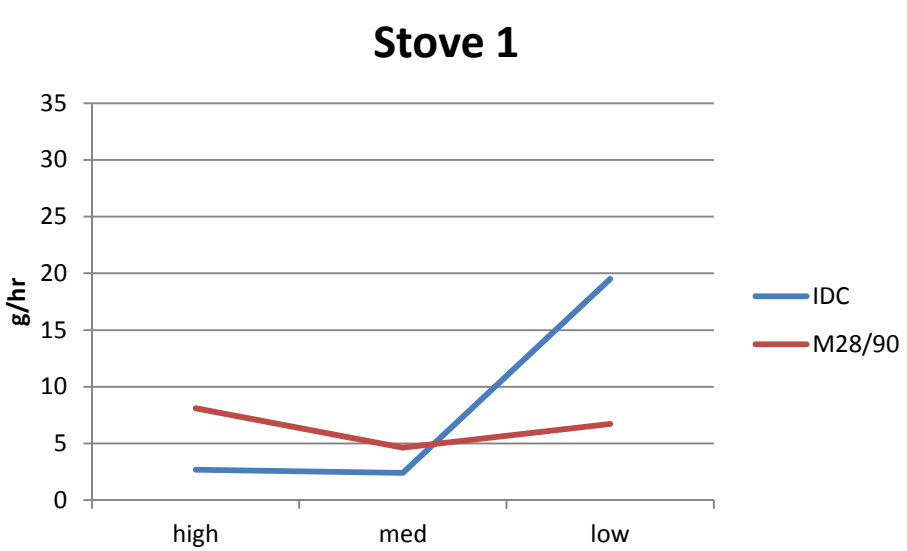
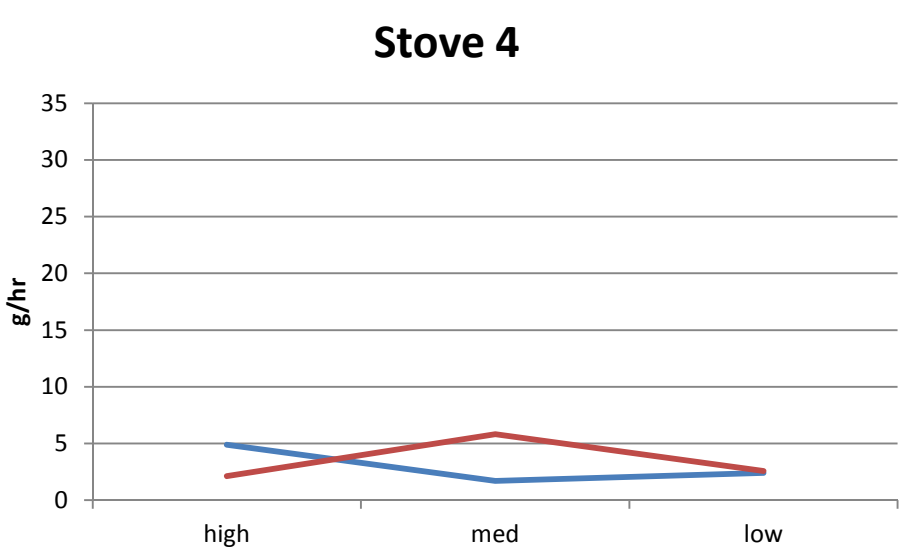
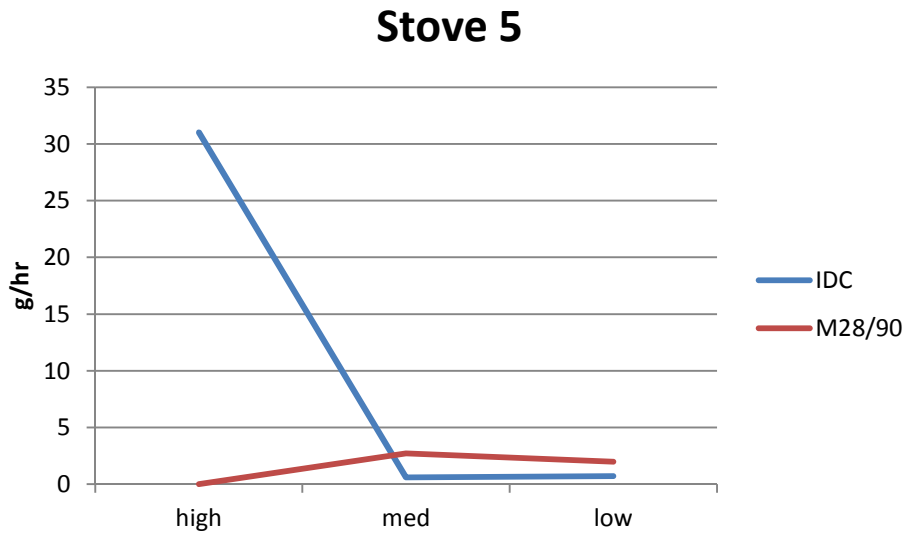
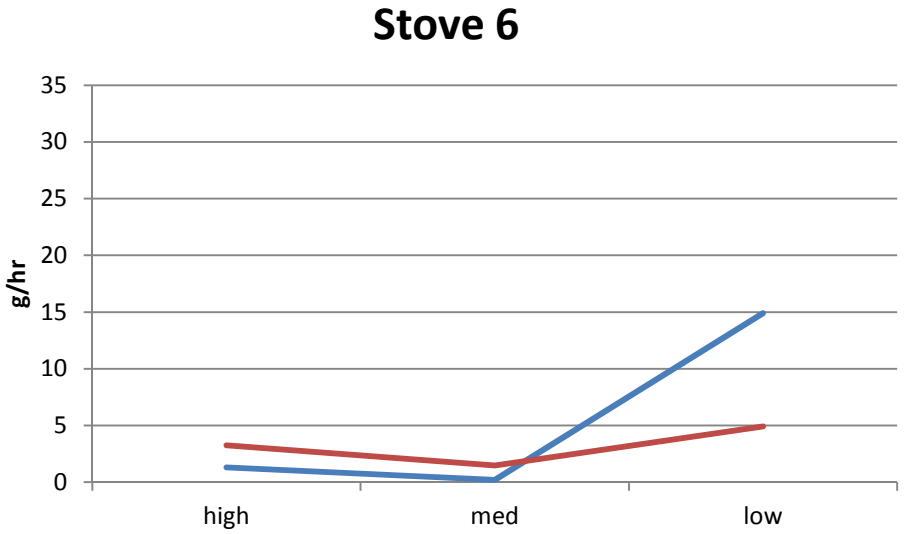
EMISSION FACTOR

M28 vs. IDC Emission Rates Non-Catalytic Stoves (g/hr.)

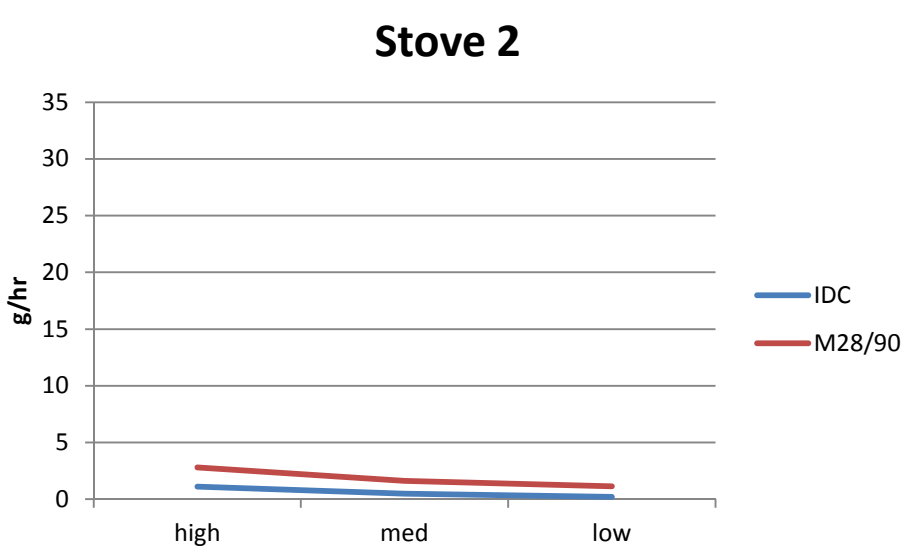


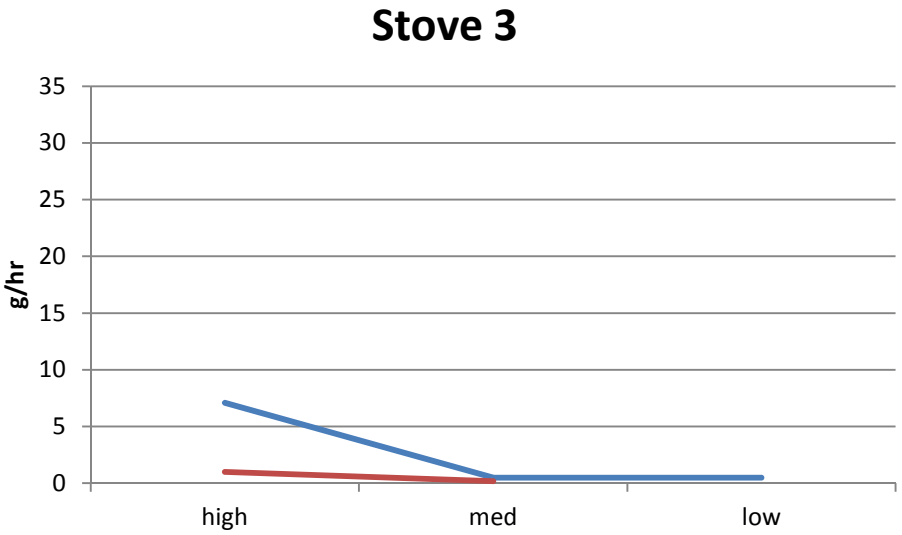




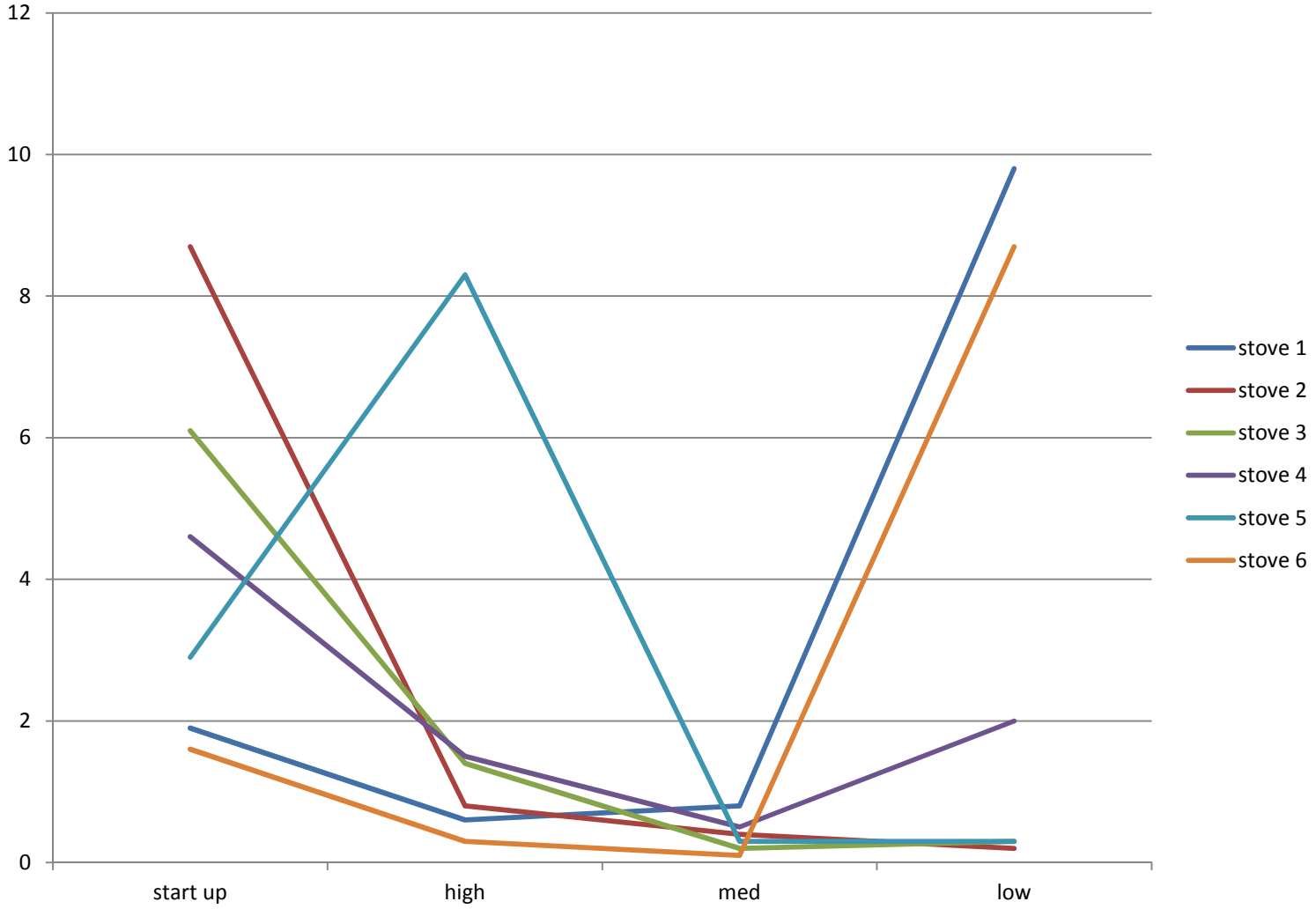


M28 vs. IDC Burn Rates
Catalytic Stoves (g/hr)

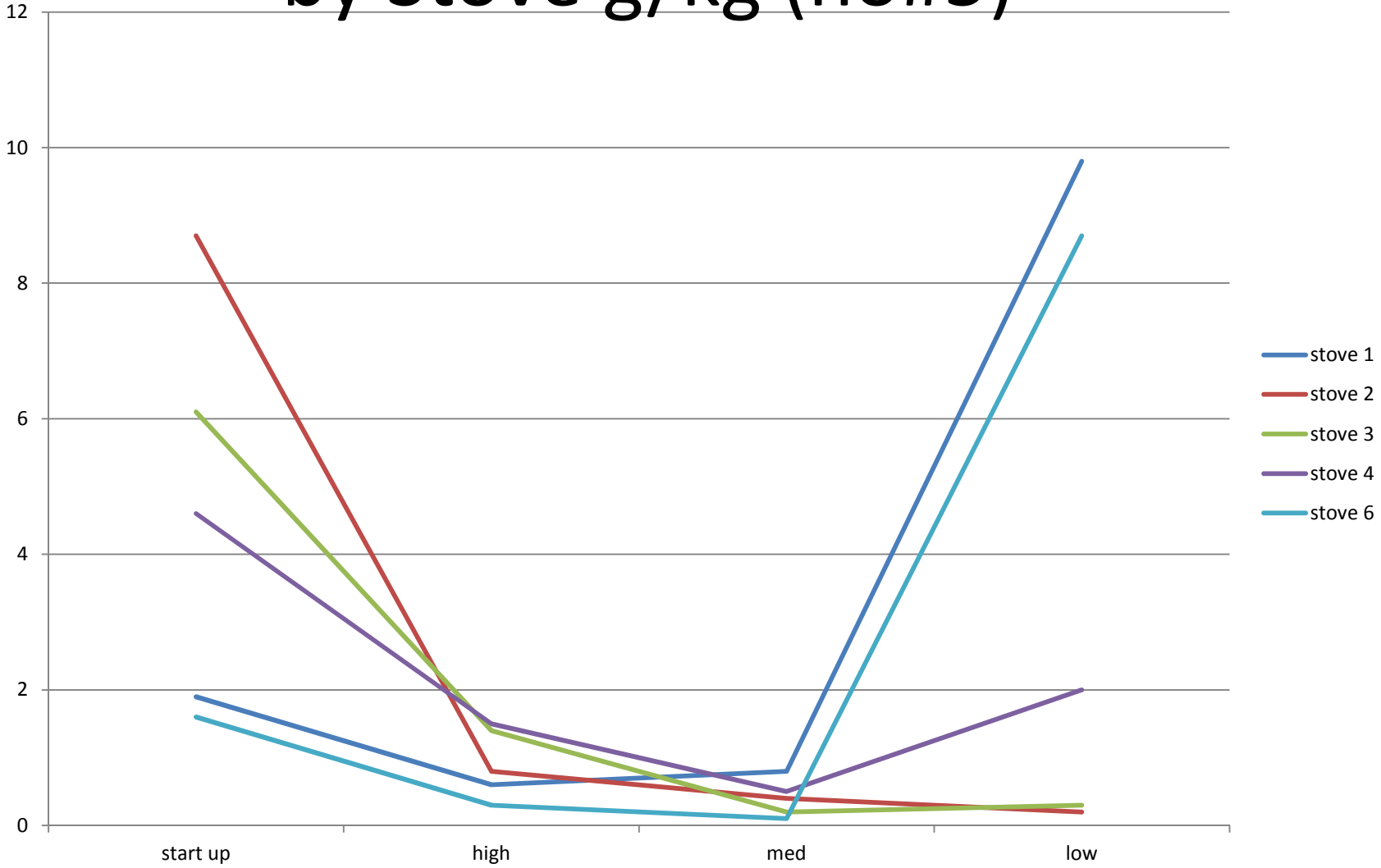




IDC Protocol
g/kg by Stove



IDC Protocol
by Stove g/kg (no#5)



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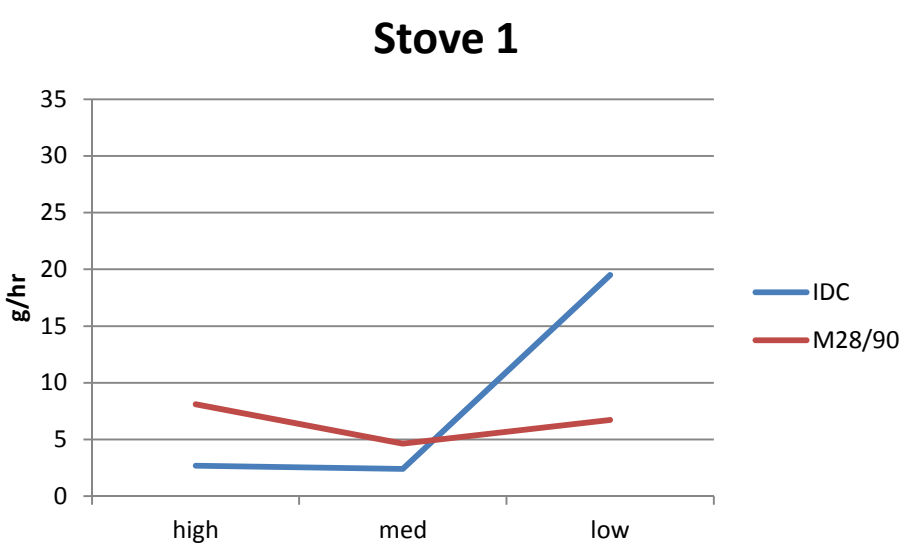
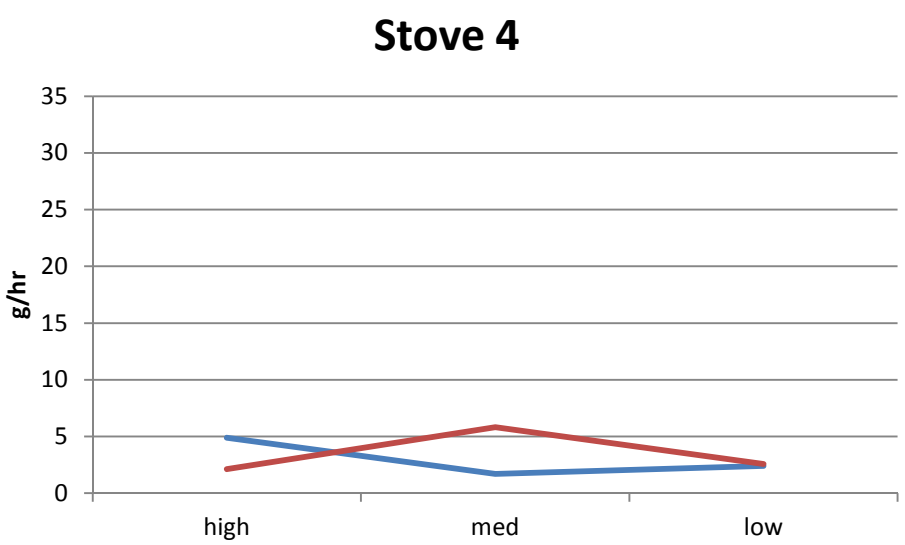
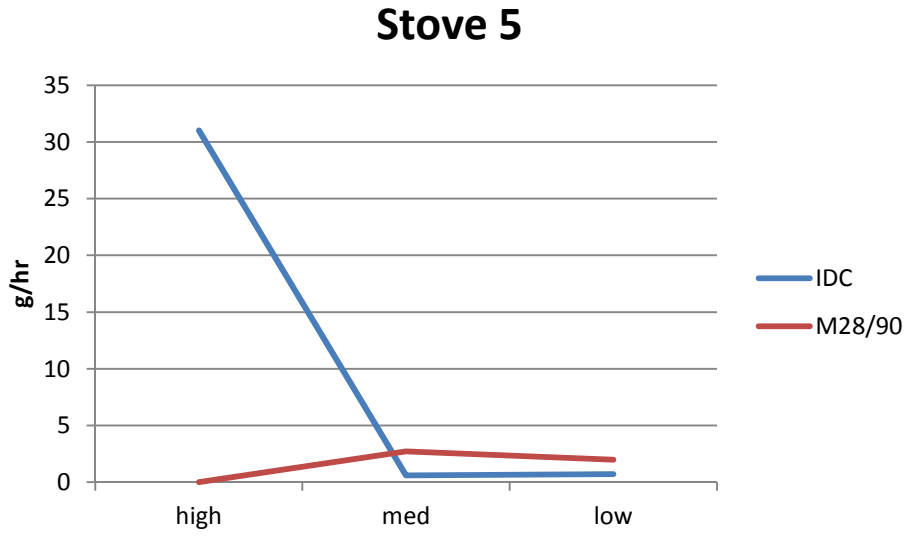
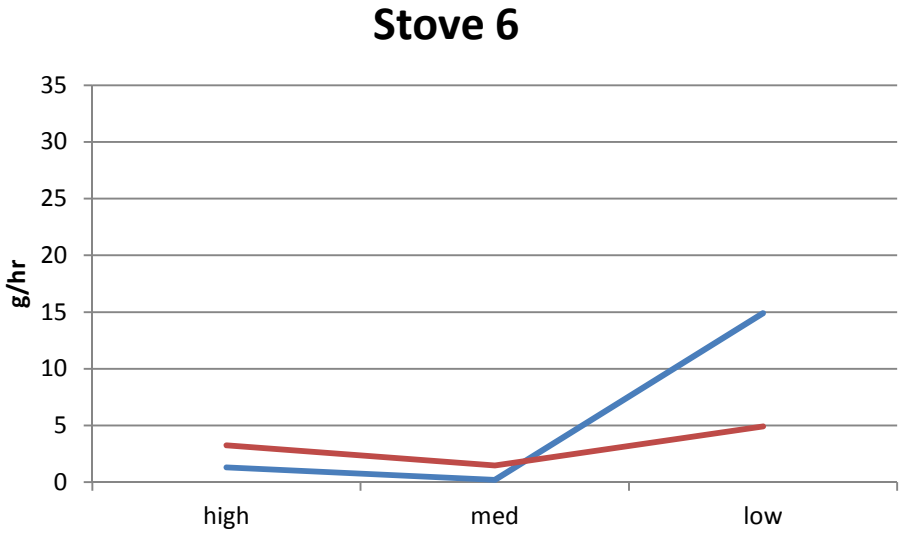
EMISSION RATE DATA

M28 vs. IDC Emission Rates Non-Catalytic Stoves (g/hr)

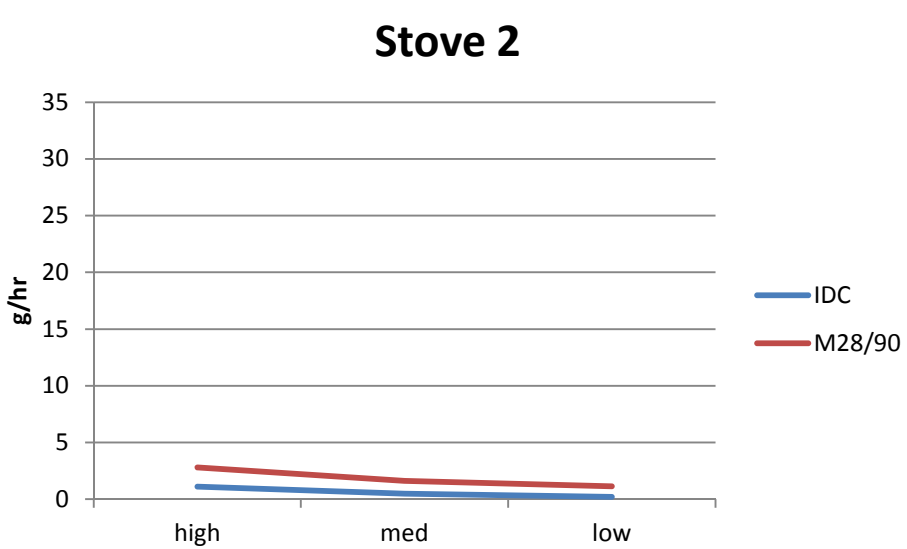


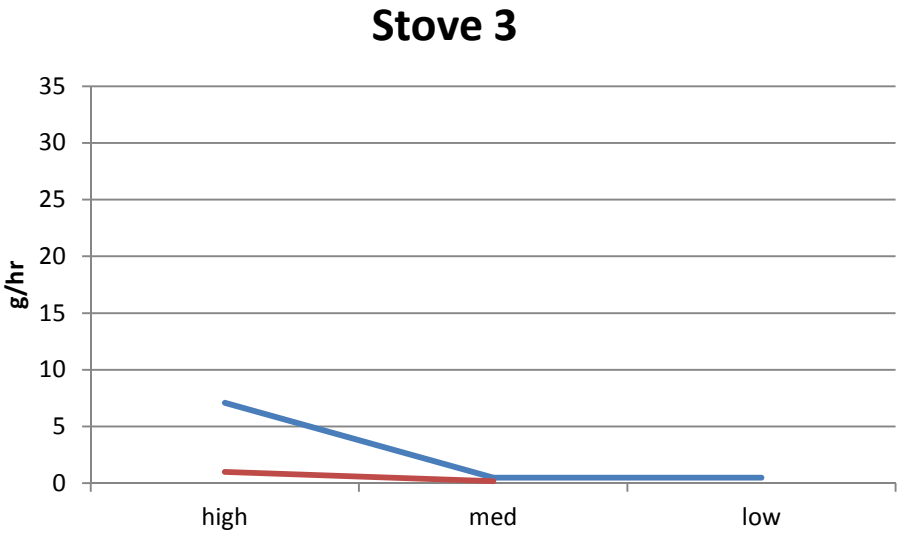




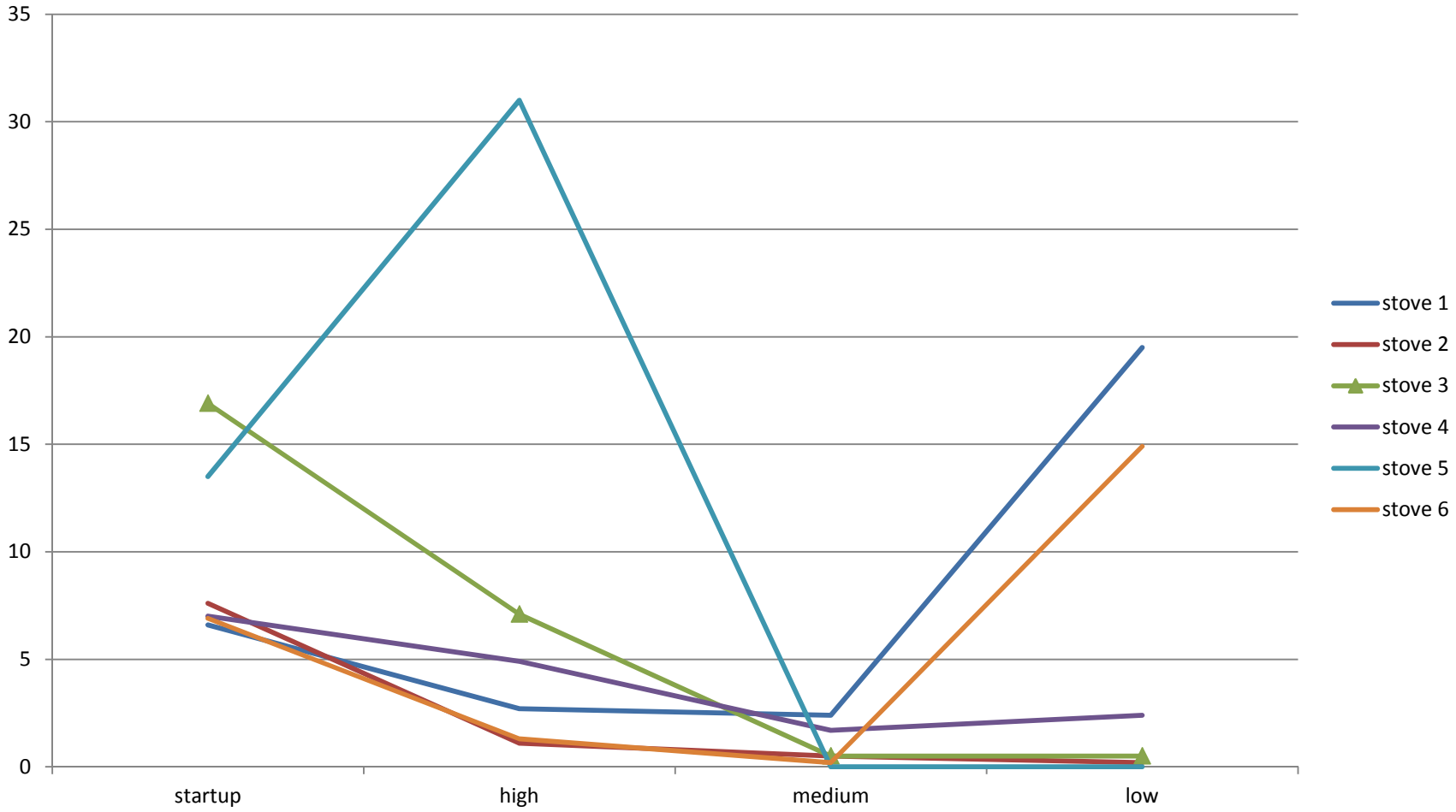


M28 vs. IDC Burn Rates
Catalytic Stoves (g/hr)

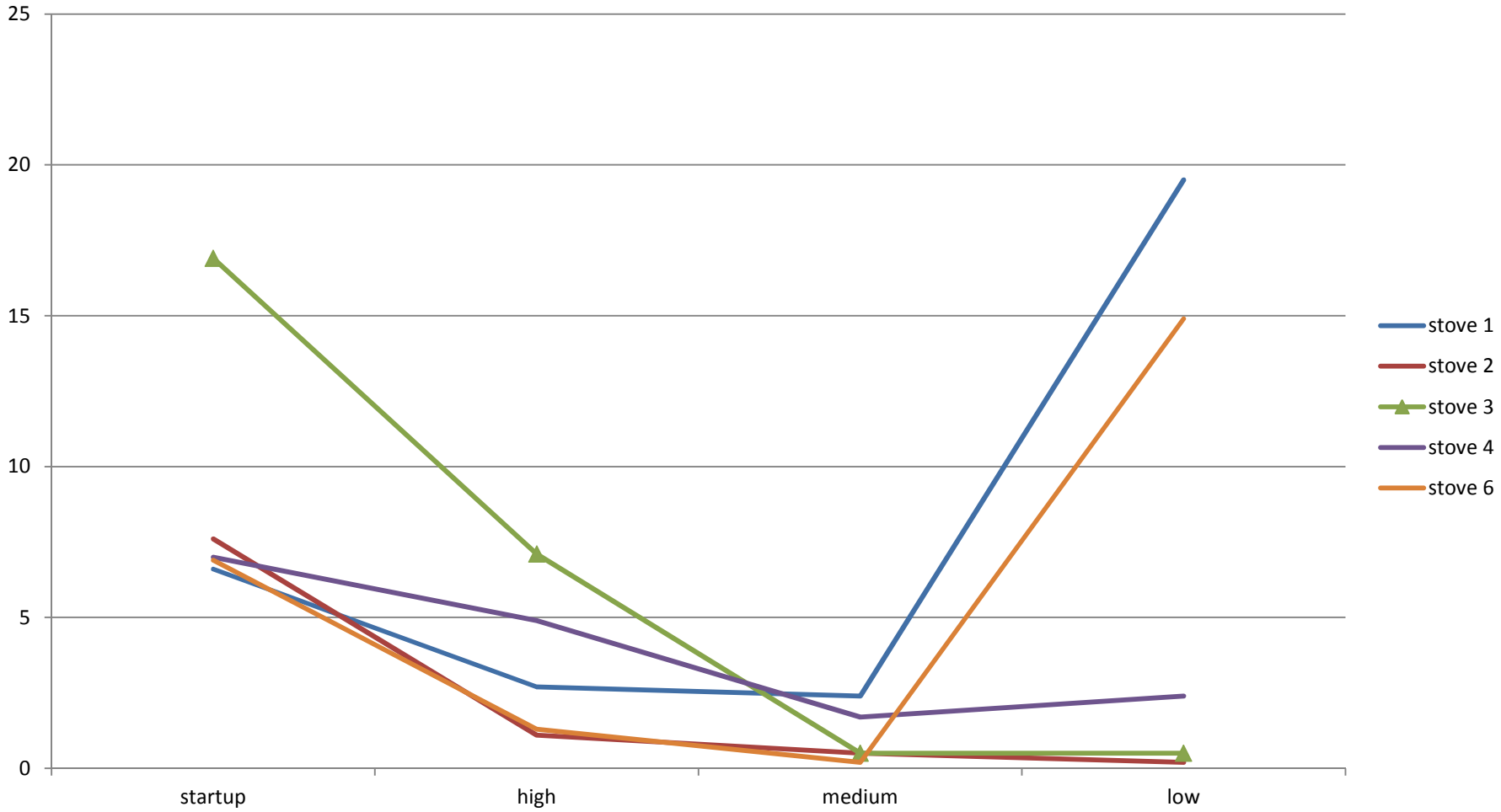




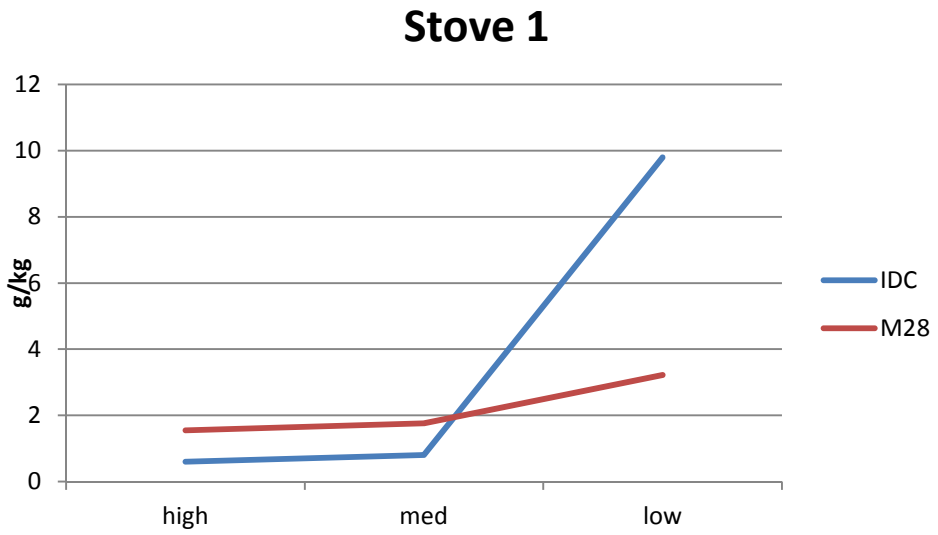
IDC Protocol
g/hr by Stove

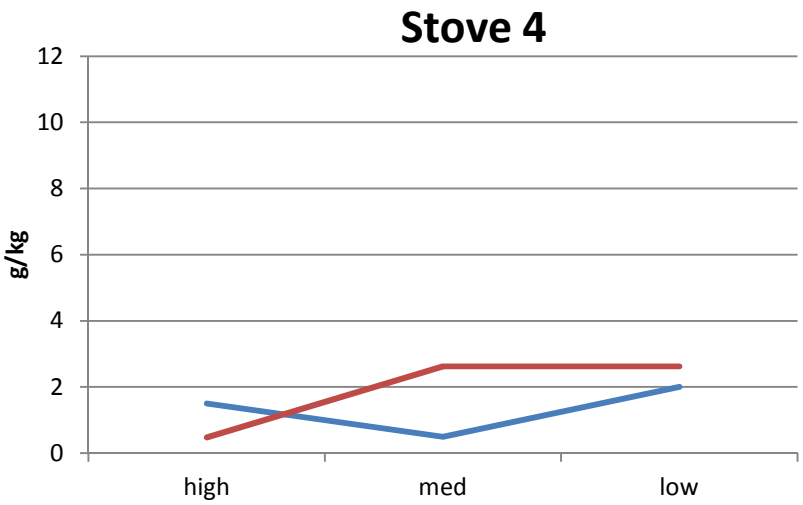


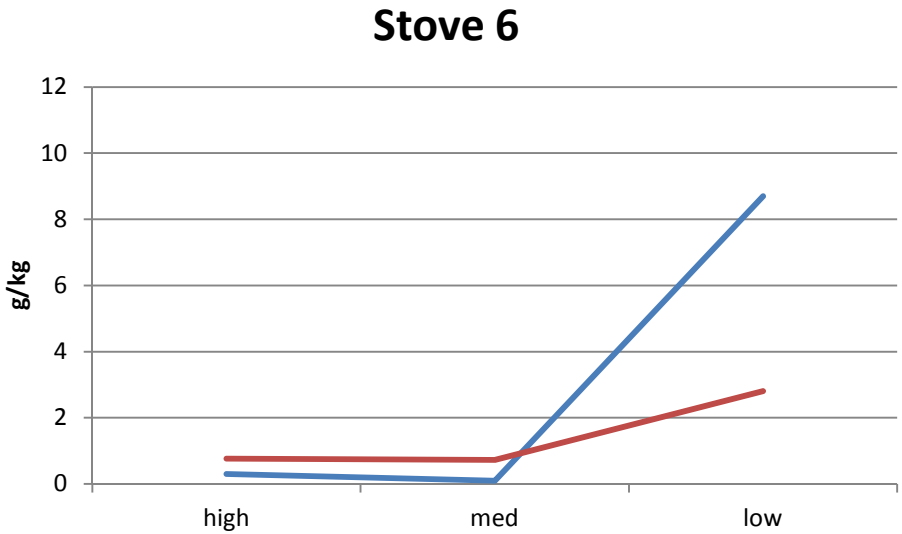
IDC Protocol
by Stove g/hr (no#5)



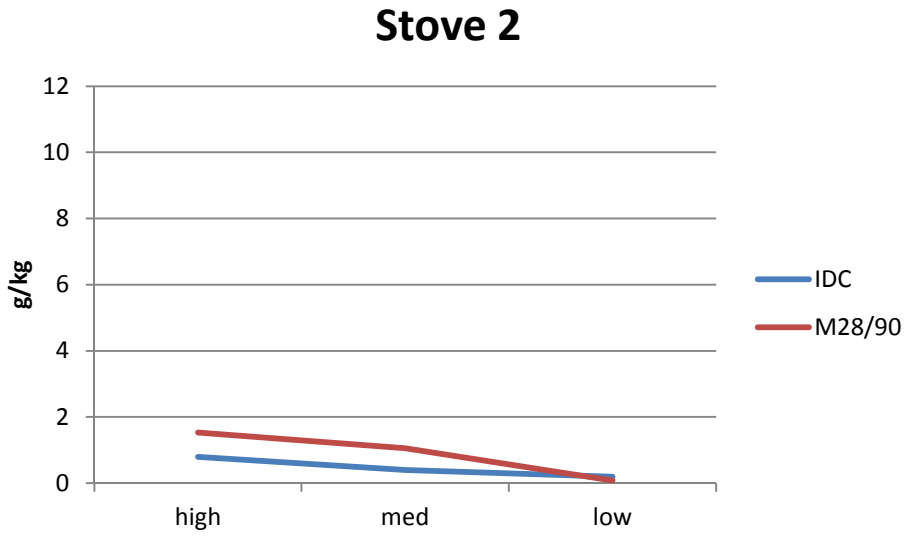
M28 vs. IDC Emission Rates Non-Catalytic Stoves (kg/hr)

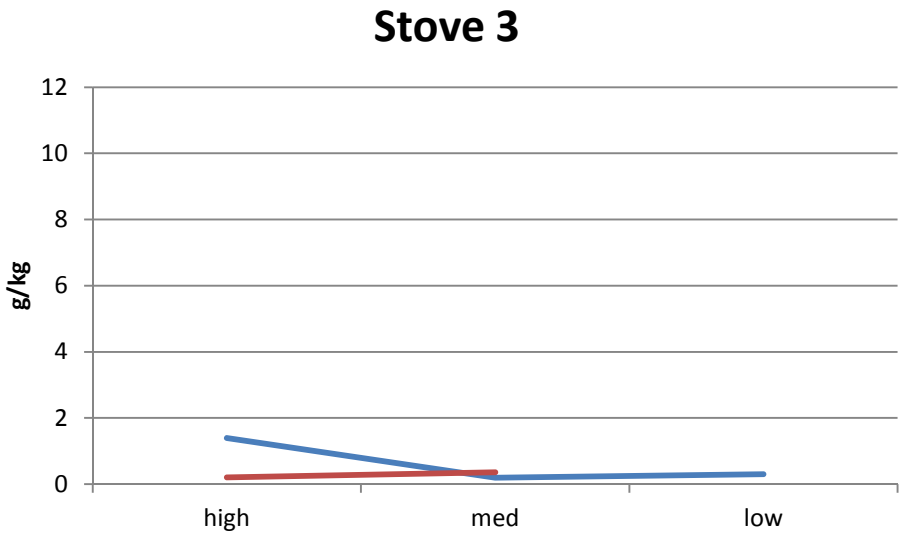






M28 vs. IDC Burn Rates
Catalytic Stoves (kg/hr)

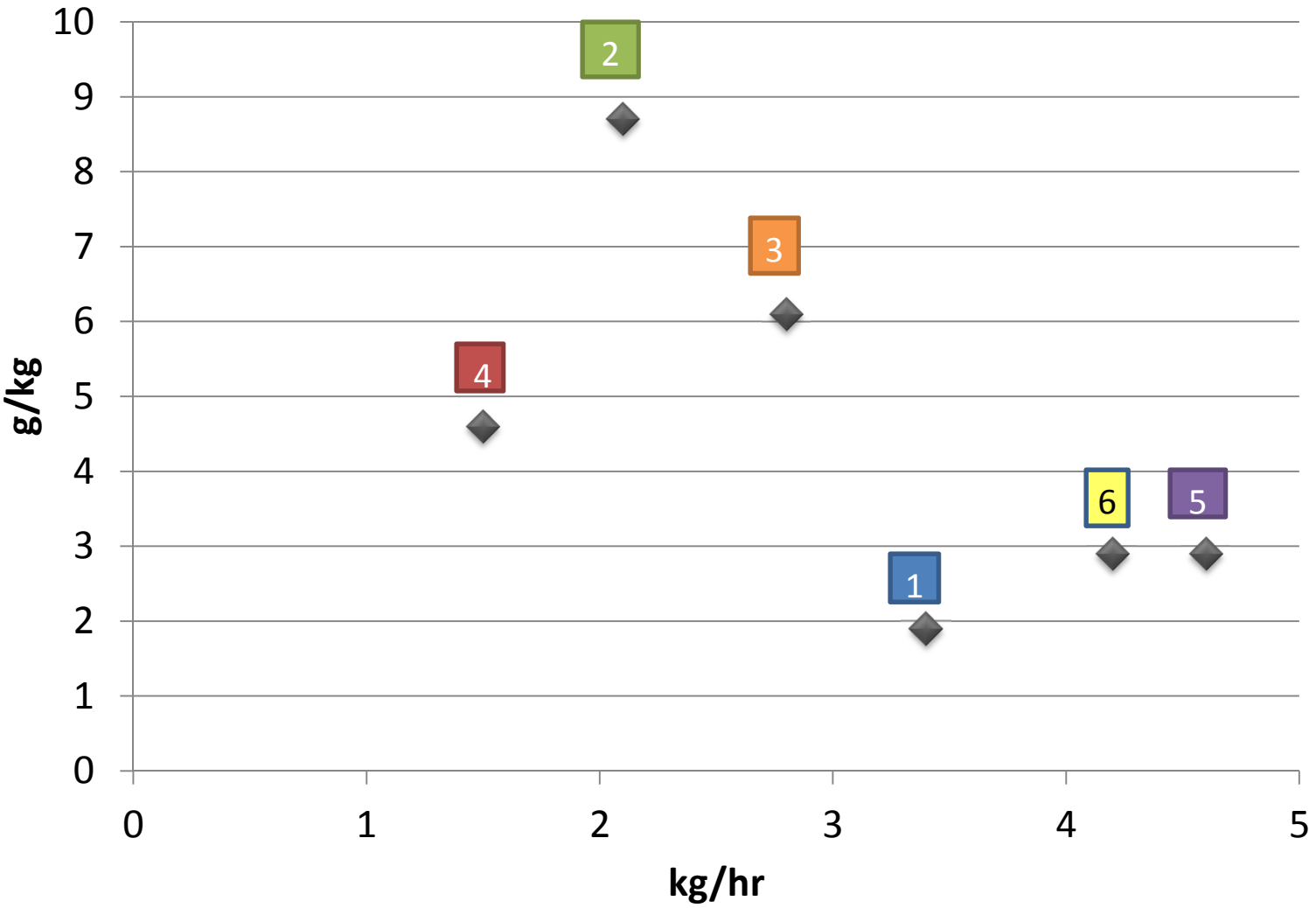




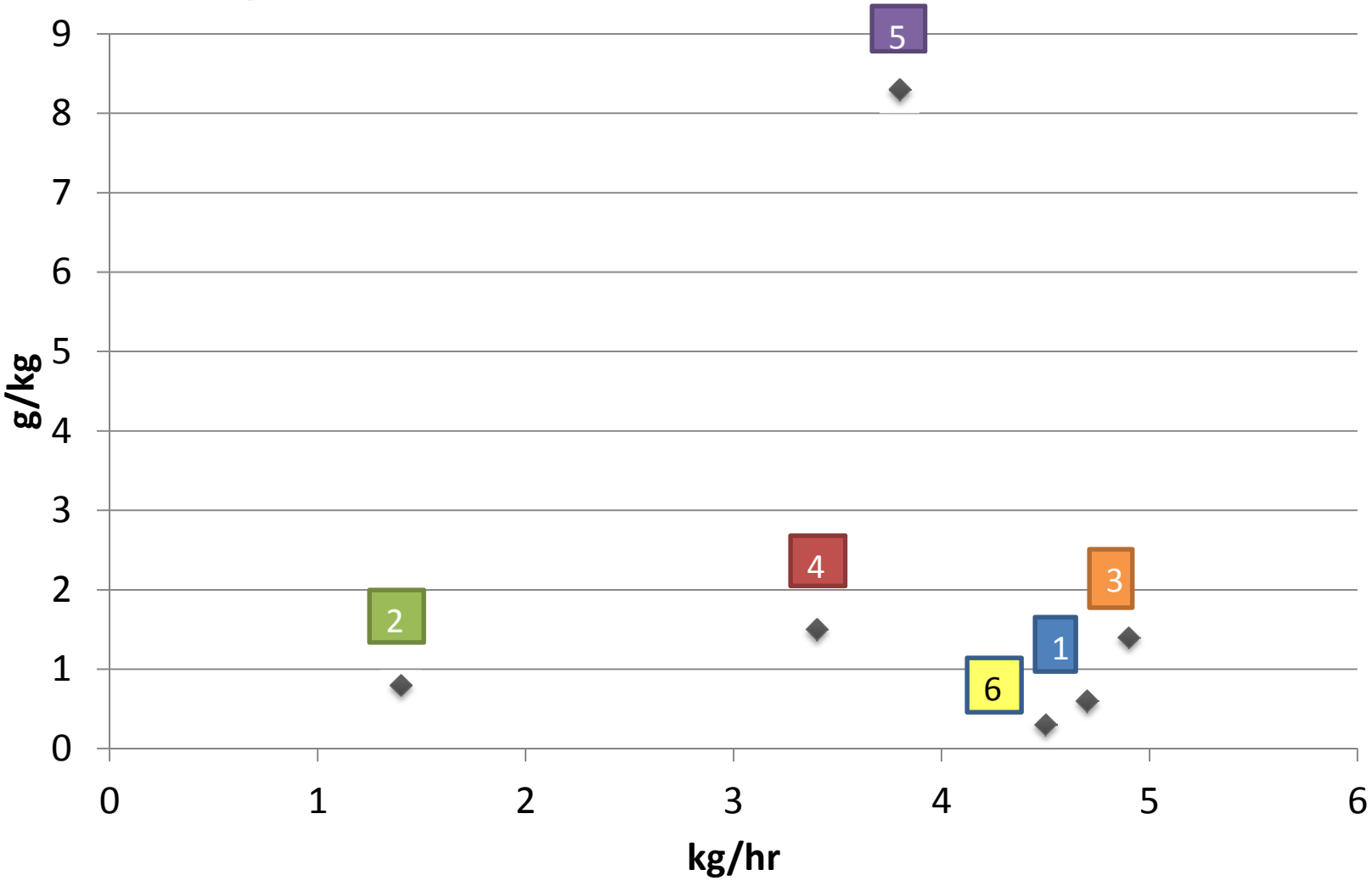
3/3/2018

BURN RATE /EMISSION FACTOR ANALYSIS

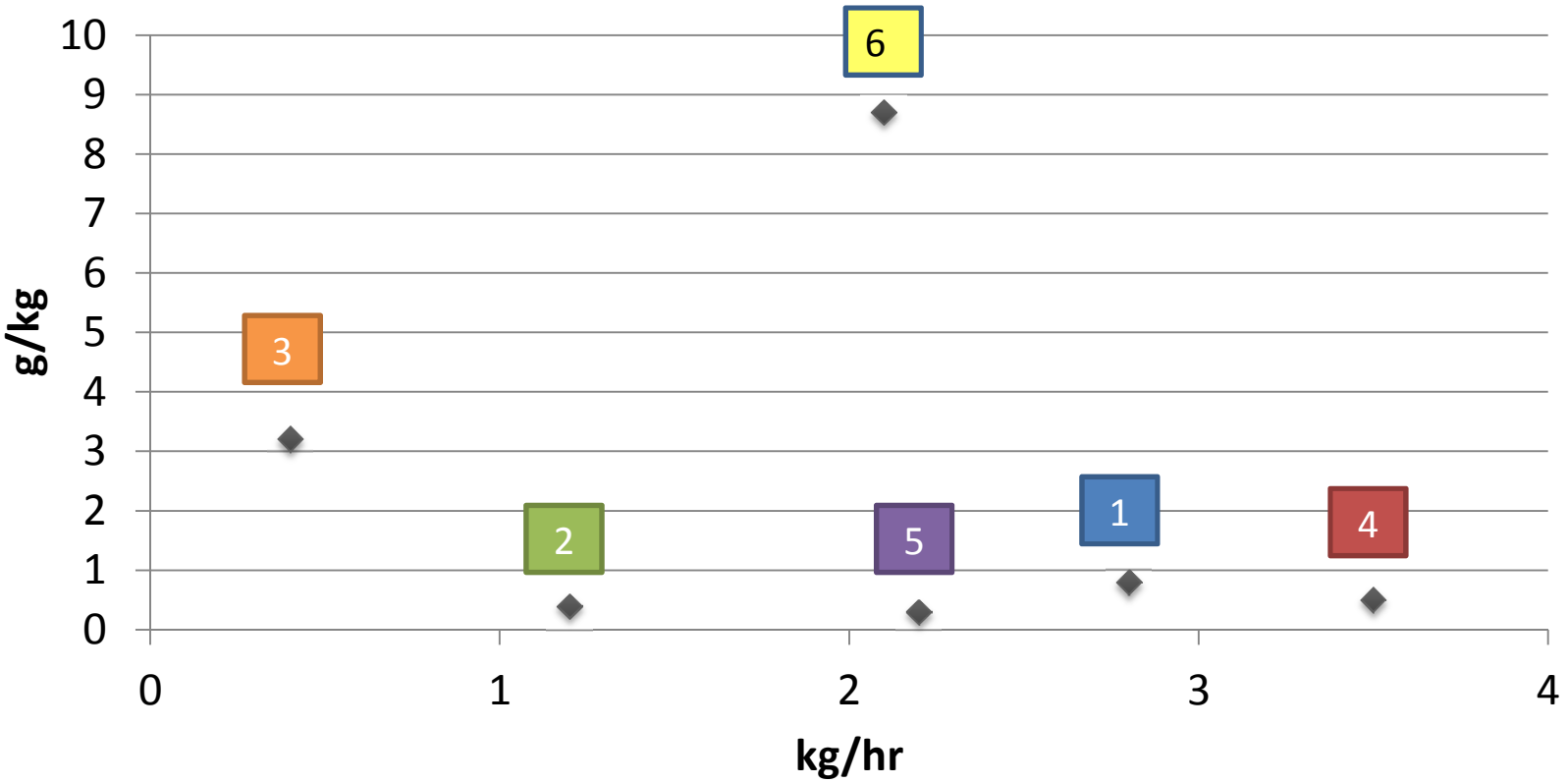
Start-Up Phase – IDC Runs



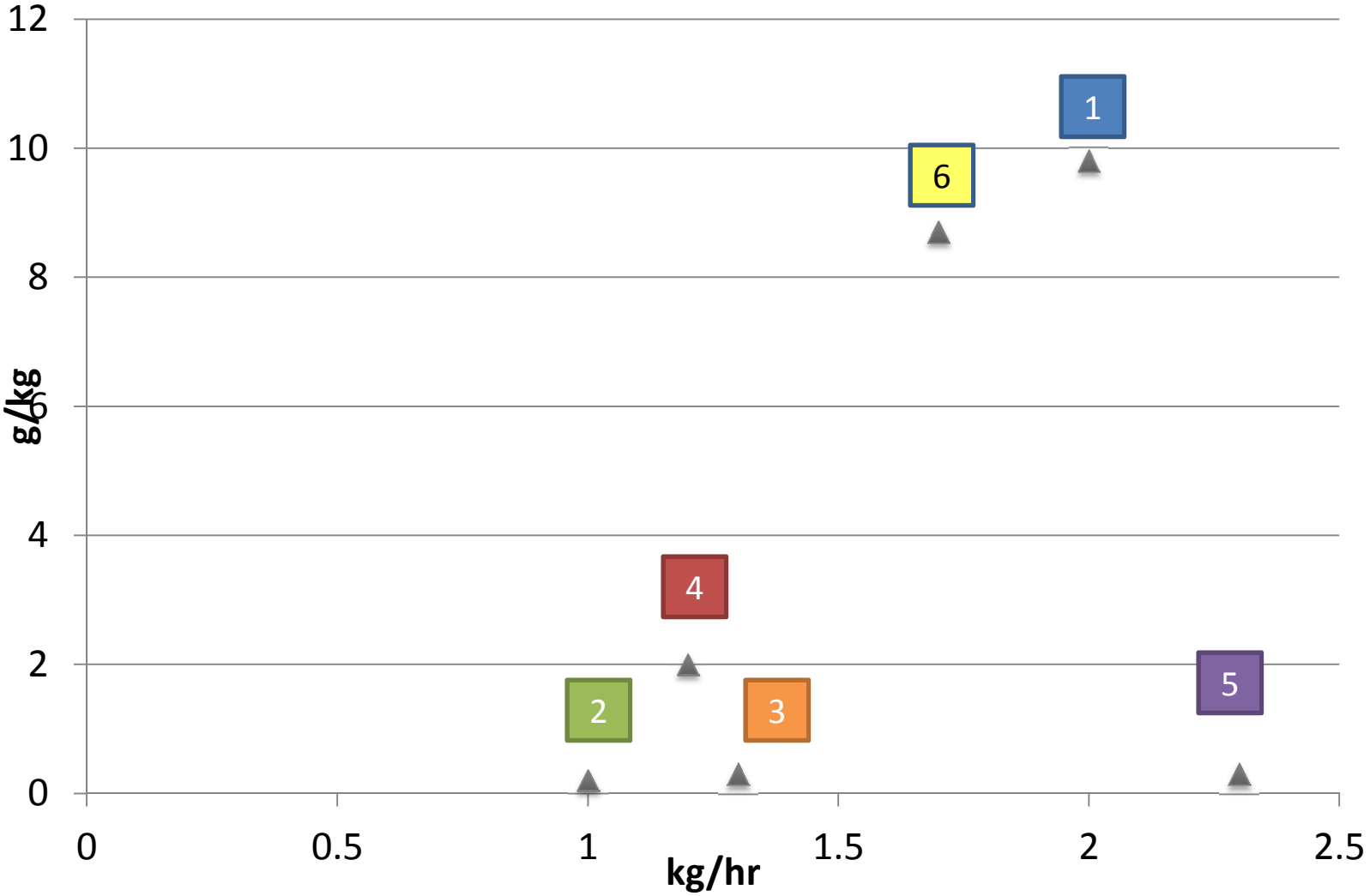
High Fire Phase – IDC Runs



Medium Air Phase – IDC Runs



Low Air Phase – IDC Runs



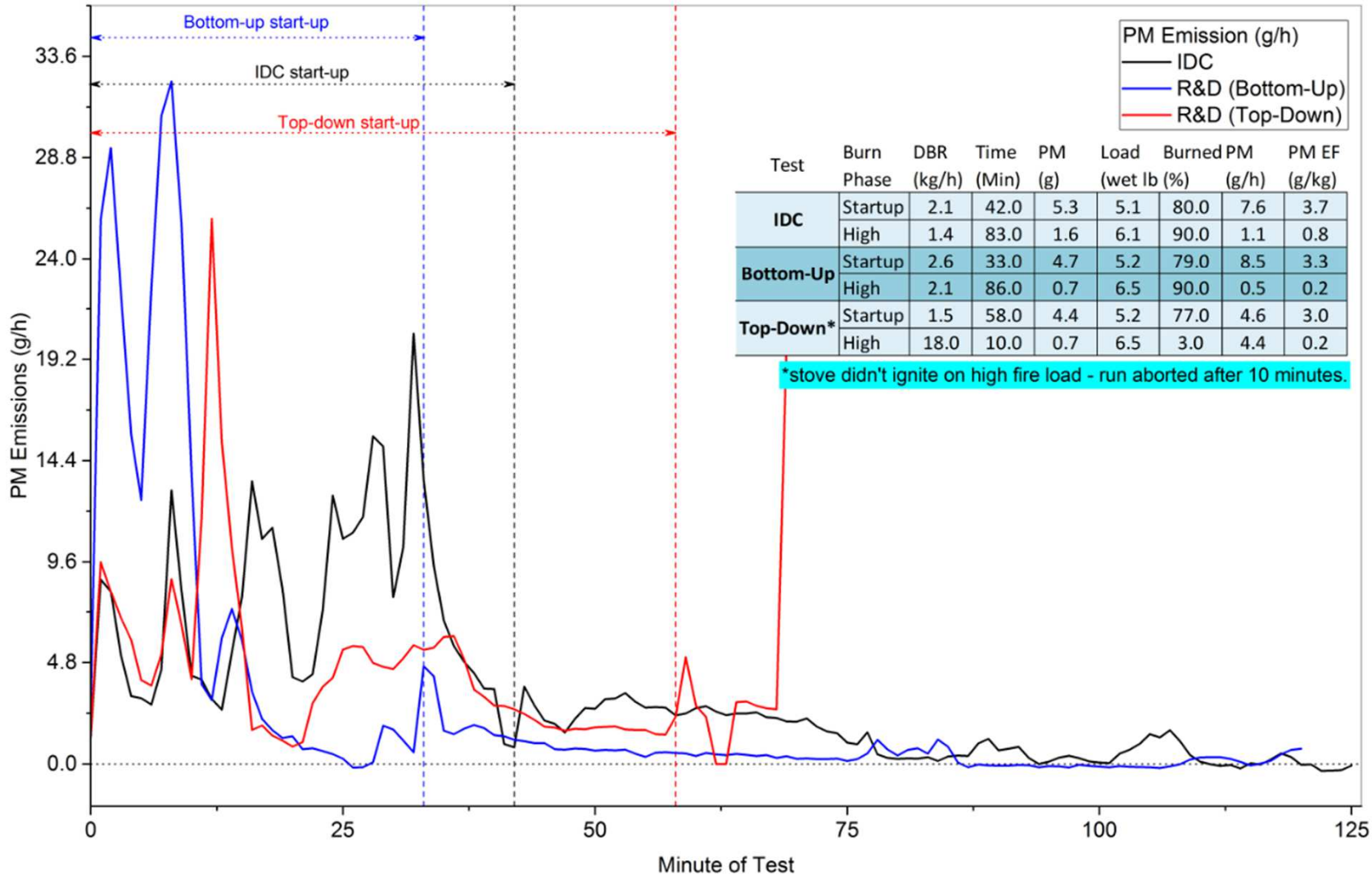
3/3/18

START-UP ANALYSIS

Bottom Up Start-up Load
March 1, 2018

Stove 2 – Top Down
start-up Load 2/27

Stove 2: PM Emissions - IDC (1/24/18) vs Bottom-Up (2/27/18) vs Top-Down* (2/28/18)

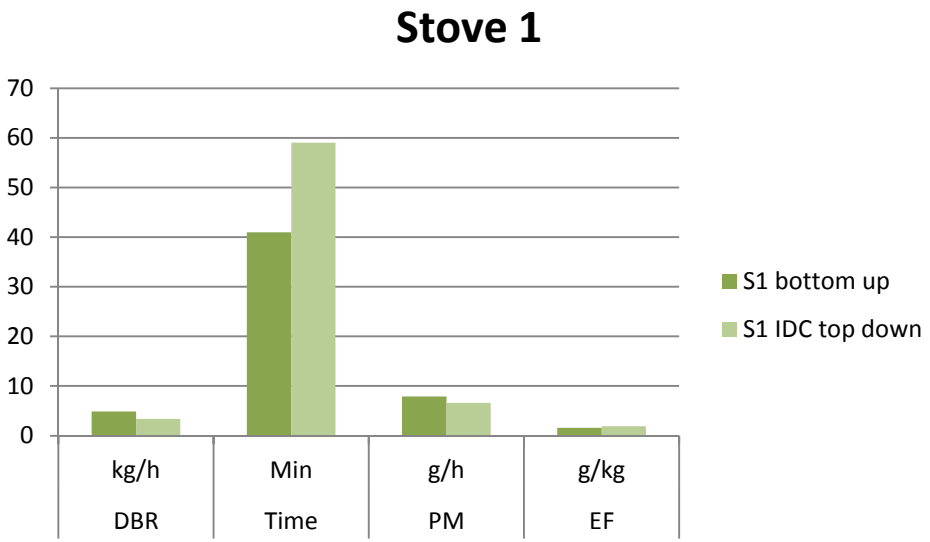


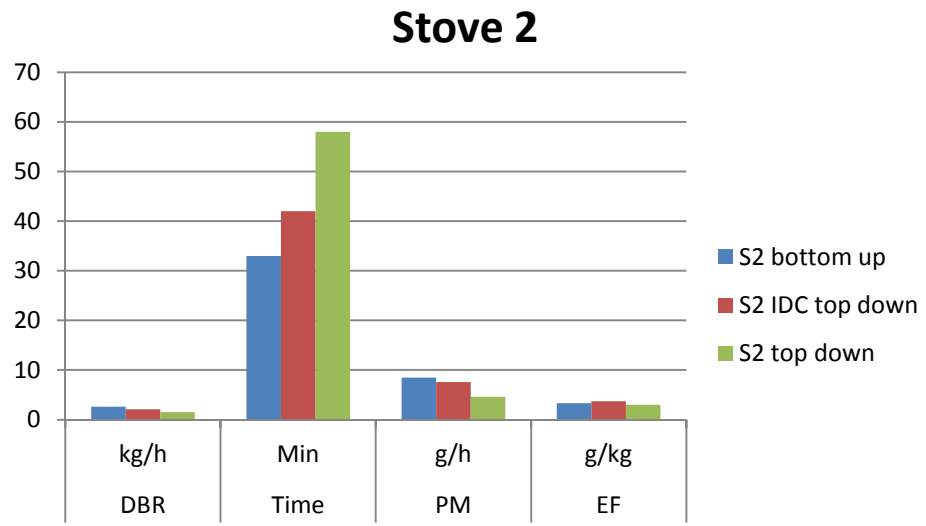
Test	Burn Phase	DBR (kg/h)	Time (Min)	PM (g)	Load (wet lb	Burned (%)	PM (g/h)	PM EF (g/kg)
IDC	Startup	2.1	42.0	5.3	5.1	80.0	7.6	3.7
	High	1.4	83.0	1.6	6.1	90.0	1.1	0.8
Bottom-Up	Startup	2.6	33.0	4.7	5.2	79.0	8.5	3.3
	High	2.1	86.0	0.7	6.5	90.0	0.5	0.2
Top-Down*	Startup	1.5	58.0	4.4	5.2	77.0	4.6	3.0
	High	18.0	10.0	0.7	6.5	3.0	4.4	0.2

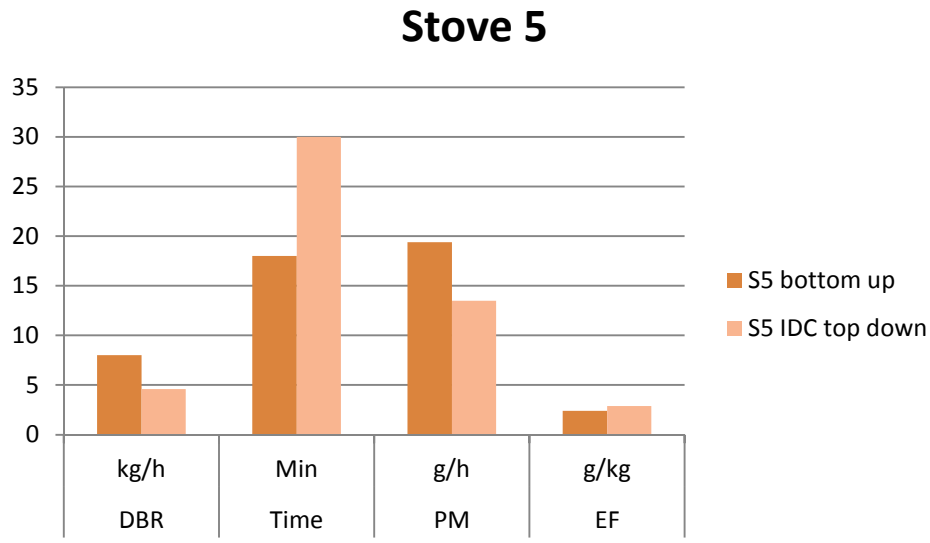
*stove didn't ignite on high fire load - run aborted after 10 minutes.

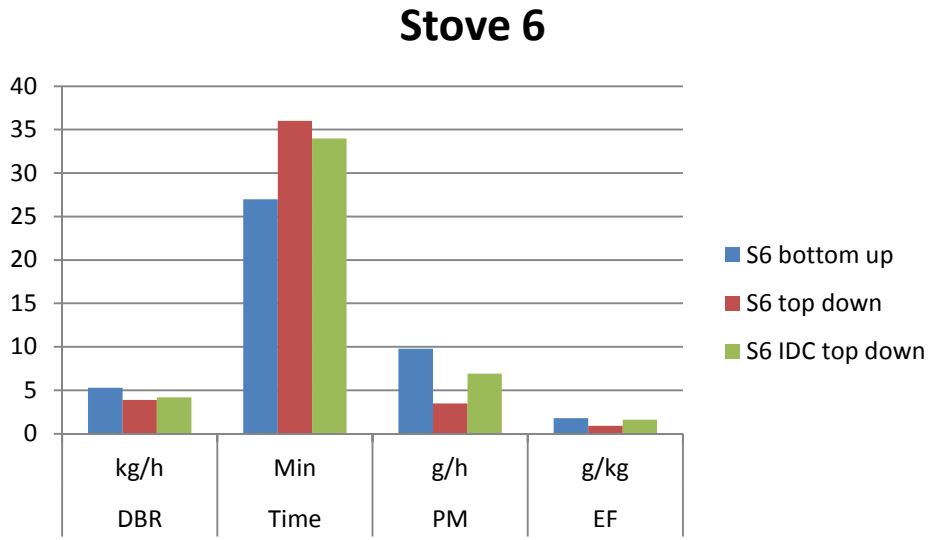
* Real-time PM Measurements obtained with Teom. On average Teom measurements are 10% less than filter measurements.

Comparison of SU Test Runs

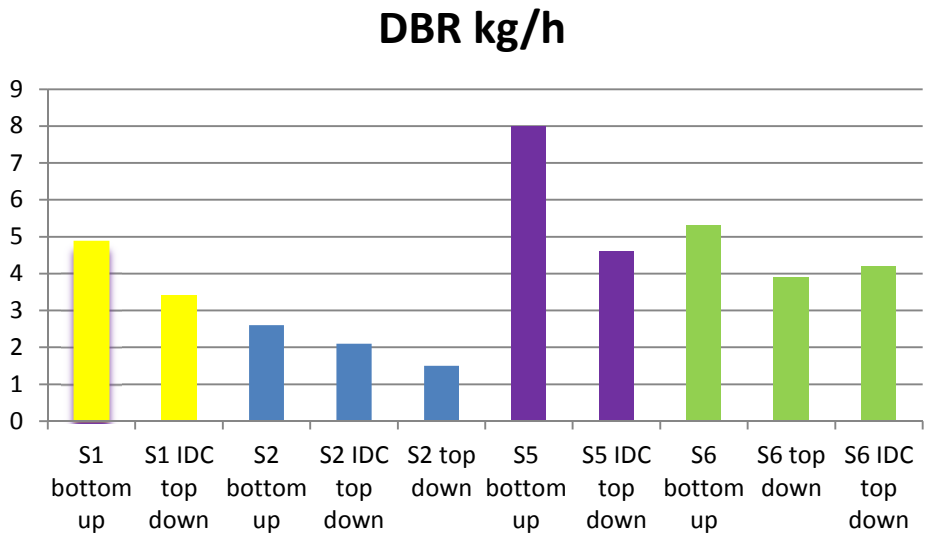


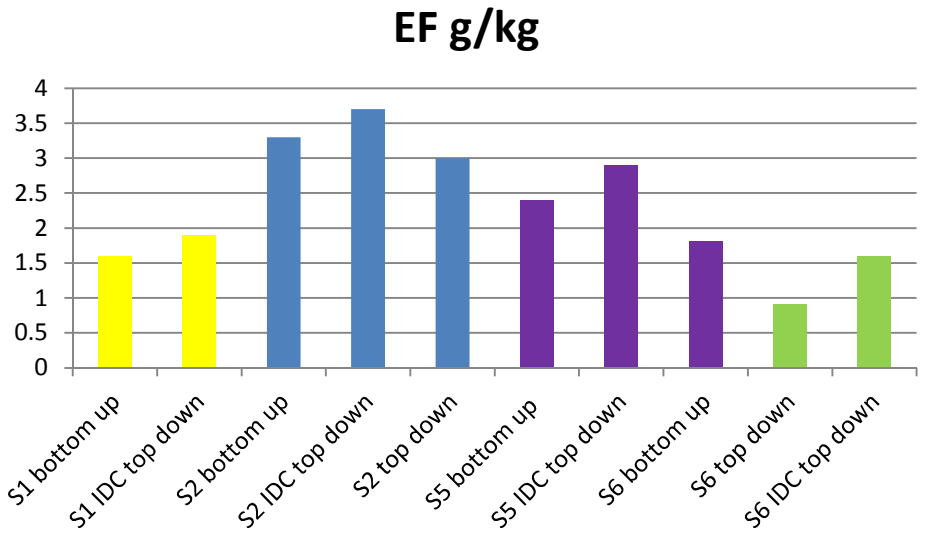


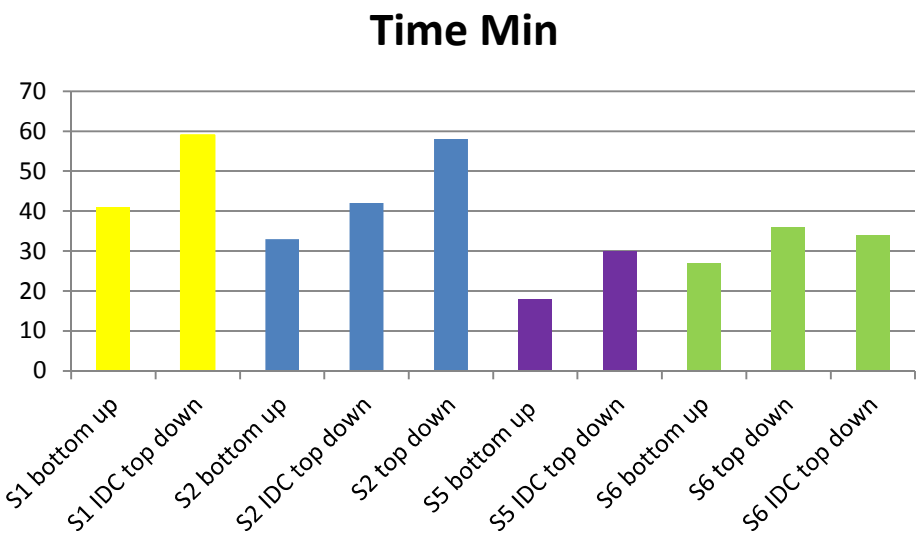


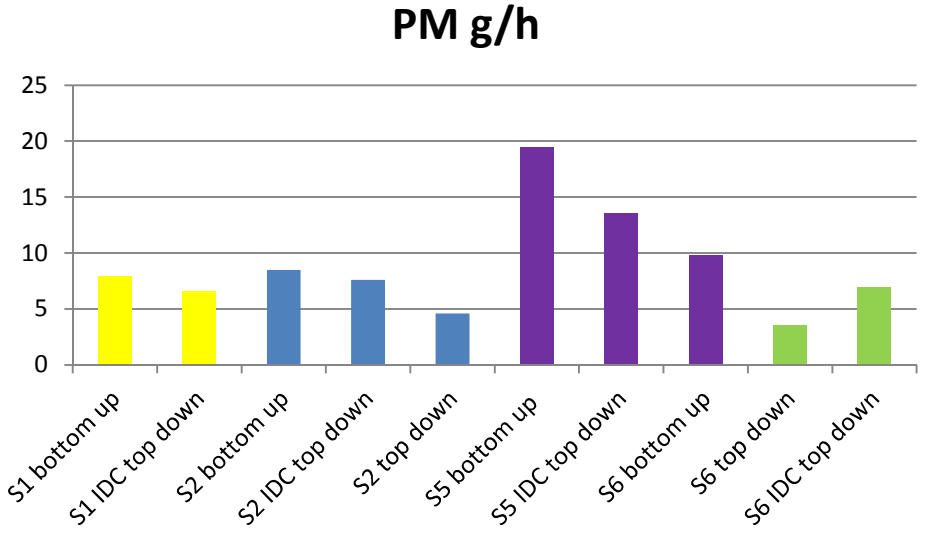


Comparison of SU Test Runs









3/3/2018

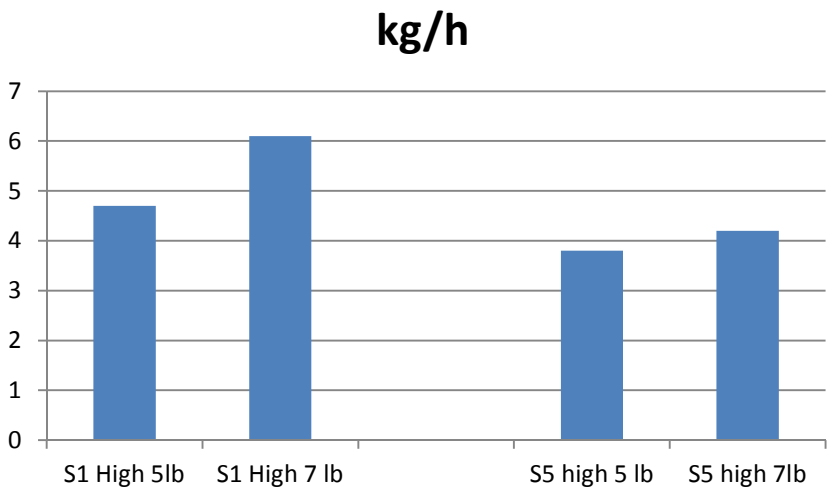
IMPACT OF INCREASING HIGH FIRE LOAD

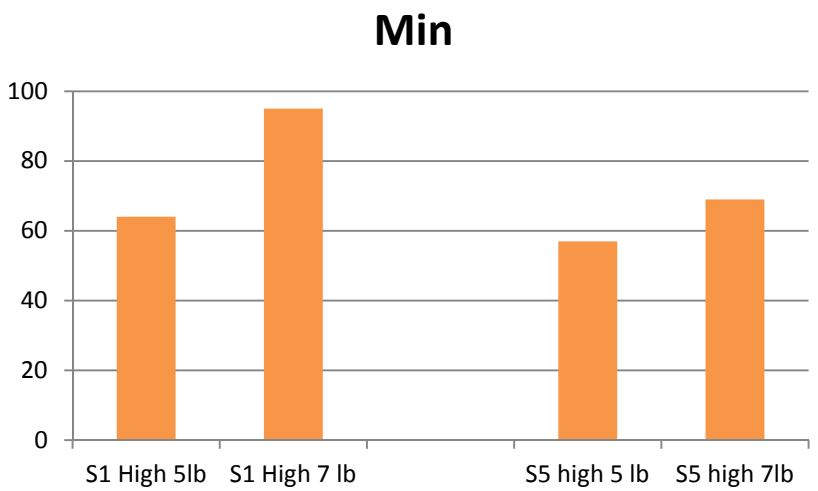
Changing High Fire Fuel Load

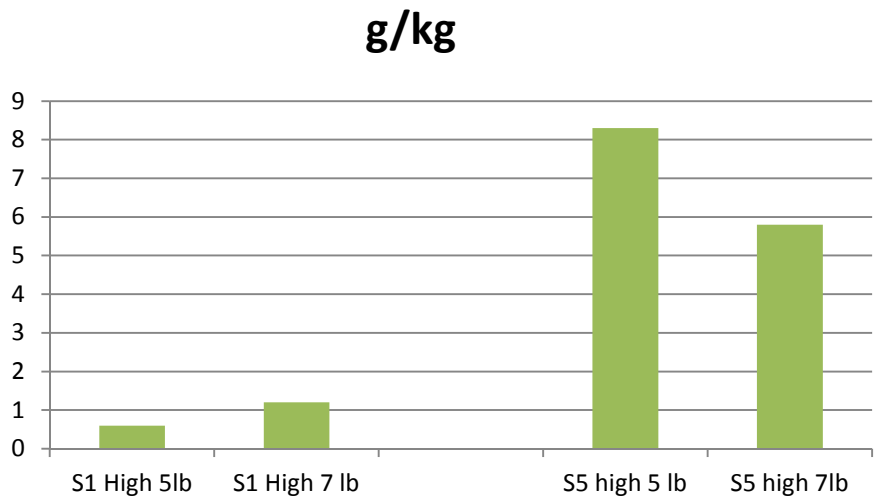
Full IDC load – HF at 5lbs/ft^3

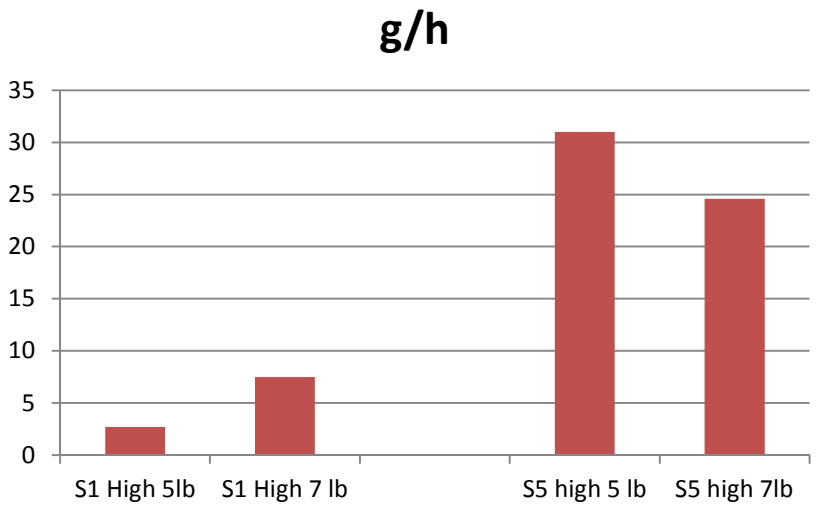
Start-up and HF load at 7lbs/ft^3

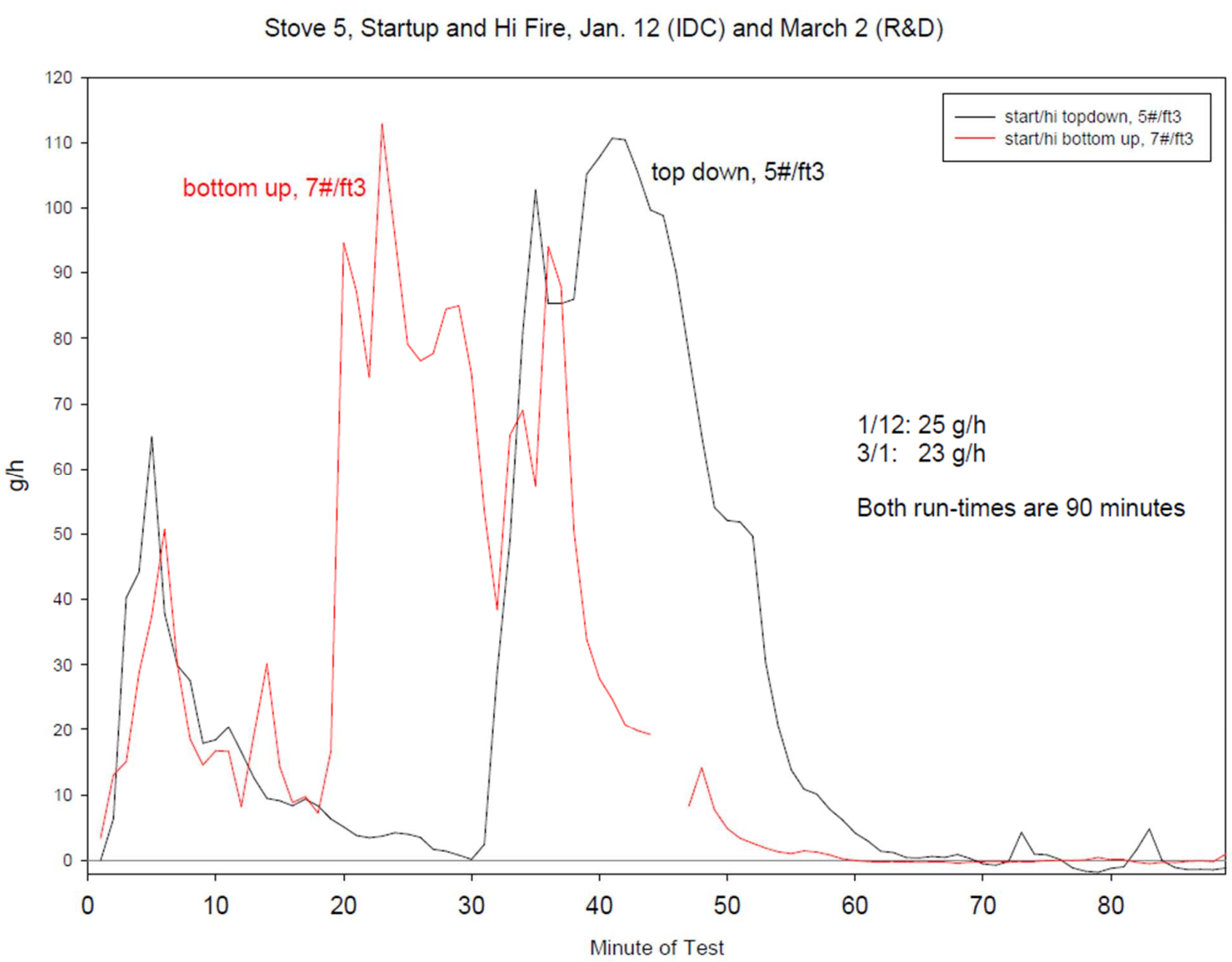
Impact of Increasing High Fire Load










Stove 5, Startup and Hi Fire, Jan. 12 (IDC) and March 2 (R&D)
start/hi topdown, 5#/ft3
start/hi bottom up, 7#/ft3
bottom up, 7#/ft3
top down, 5#/ft3
1/12: 25 g/h
3/1: 23 g/h
Both run-times are 90 minutes
g/h
Minute of Test
0
10
20
30
40
50
60
70
80
90
100
110
120

Discussion/Next Steps

ClearStak, LLC

Cold-Start Variable Testing

Presented by:
Kelli O'Brien
Laboratory Manager

NEW YORK STATE OF OPPORTUNITY. | NYSERDA Supported

ClearStak

12 July 2017

NYSERDA – Cold Start Variable Testing

- **Plan and Objectives**
  - Perform replicate cold-start tests, changing only one variable per series and determine what variables effect the boiler's performance
    - Cold-to-cold test = no established coal bed in firebox and boiler water temperatures at a minimum 120˚F and maximum 130˚F at start of test
  - Determine whether the variable effects only start-up or is consistent throughout the entire burn
- **Constants**
  - Use of a non-catalytic down-draft two-stage combustion residential boiler with sight hole for observing secondary combustion
    - 50 lbs. fuel charge weight based on 5 ft^3 firebox volume with additional 5 lbs. of kindling or 10% of fuel charge weight
    - 400 gallons external storage
  - Red oak cordwood from same supplier
  - Moisture content range between 18-21%
  - Fuel charge parameters were determined using CSA B415
  - Use of TEOMs in dilution tunnel for PM determination and burn profiling (real time emissions)

NYSERDA Agreement No. 63025

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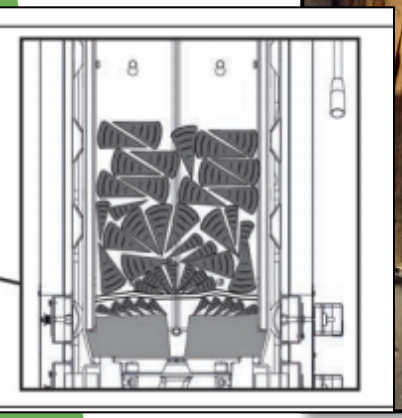
Cold - Start Variables

1. Test Fuel Configuration – The placement of kindling and fuel in the firebox
2. Test Fuel Piece Size – Reducing individual piece sizes (i.e. smaller weight & cross-sectional diameters)
3. Increased Kindling Quantity – Doubling the weight of kindling from 10% to 20% of the total test fuel charge
4. Startup Fuel – The use of up to an additional 10% “Startup fuel” defined as fuel pieces greater in size (i.e. weight and cross-sectional diameter) than the kindling, but smaller than the test fuel charge.

1. Test Fuel Configuration

- **Objective**
  - Observe the effect of three different kindling load configurations on the performance of Advanced Cordwood Boiler A. These three configurations are, or once were, part of the operating instructions.
  - Fuel charge load consisted of 6-7 fuel pieces of 6.7 to 11 lb. each and 10% (5lbs.) kindling of 1 to 2 in. diameter pieces.



New Manual (2016)

Old Manual (2014)

Original Configuration

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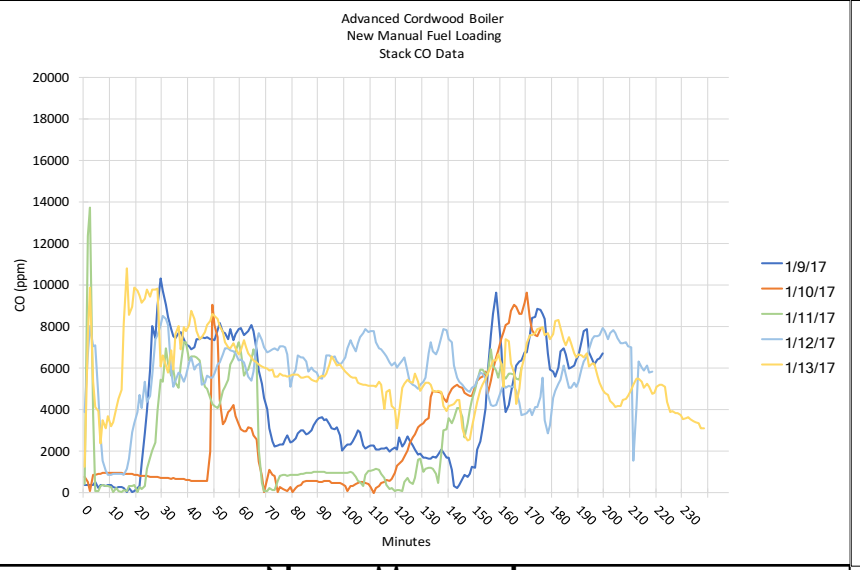
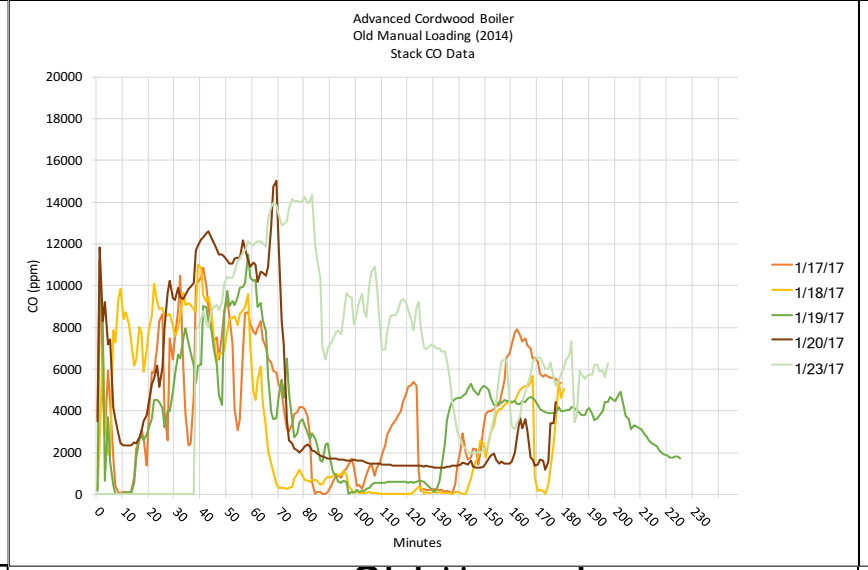
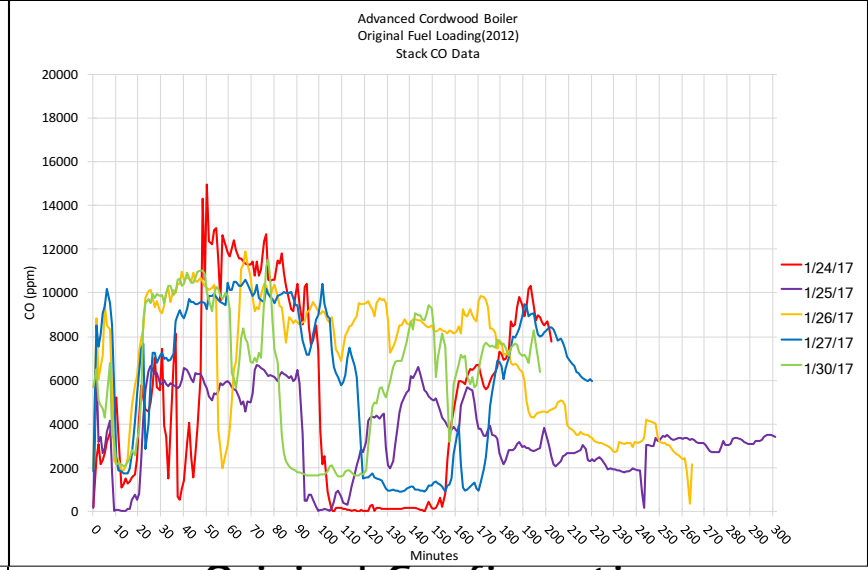
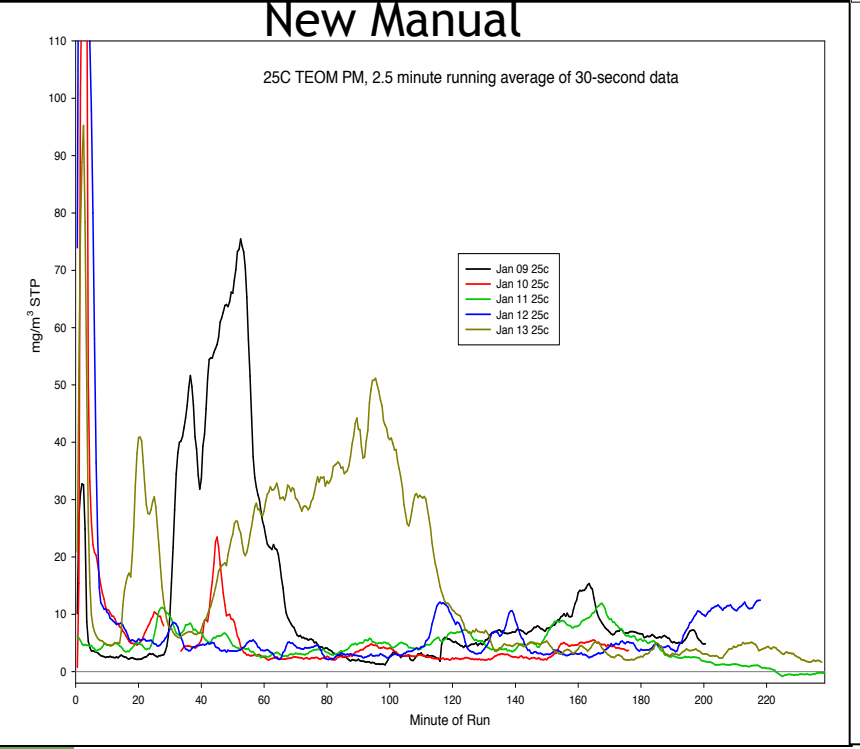


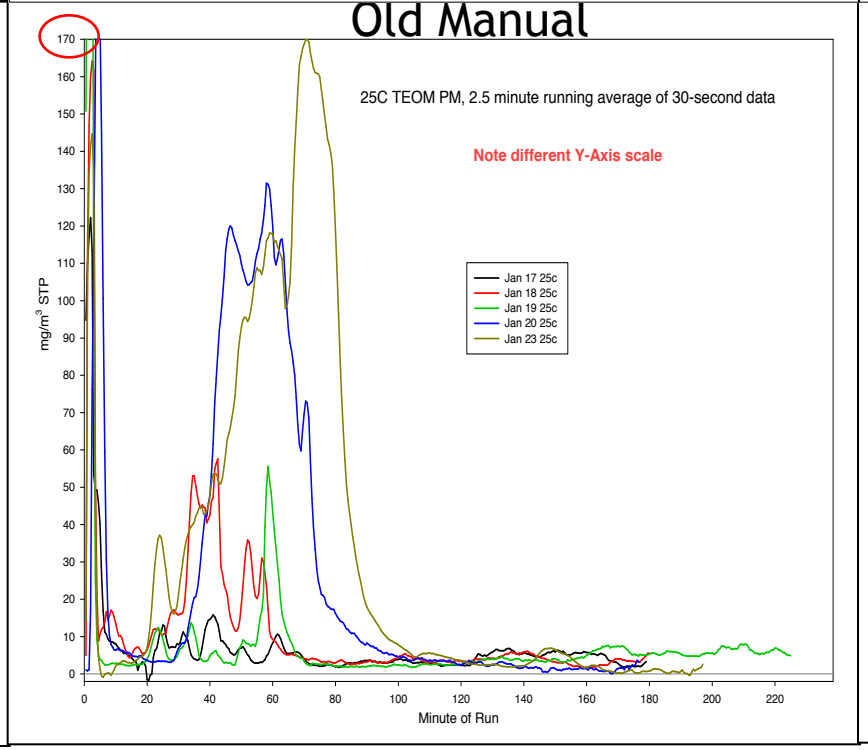




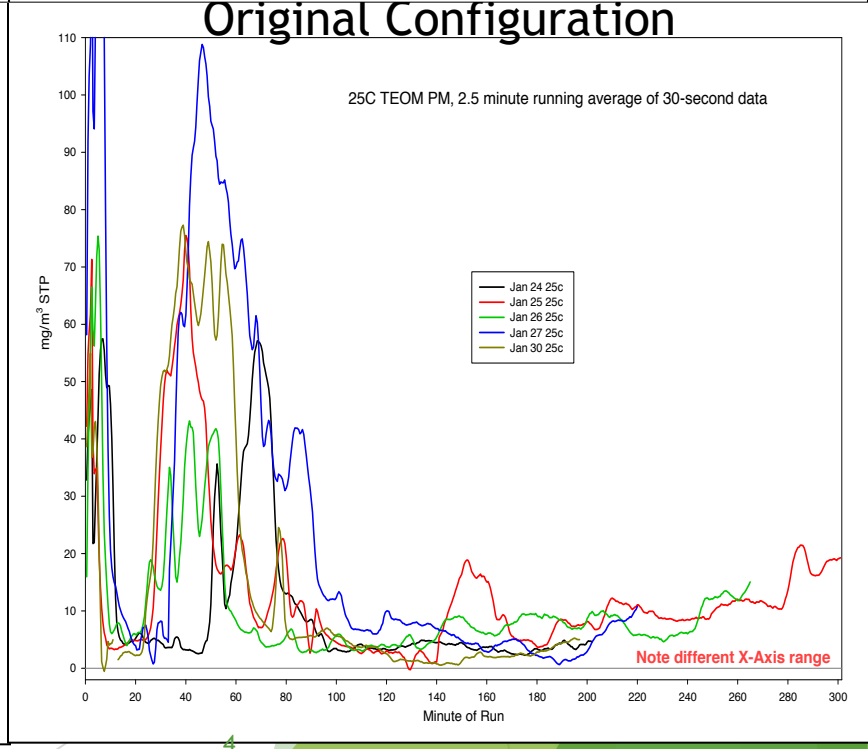
New Manual



Old Manual



Original Configuration

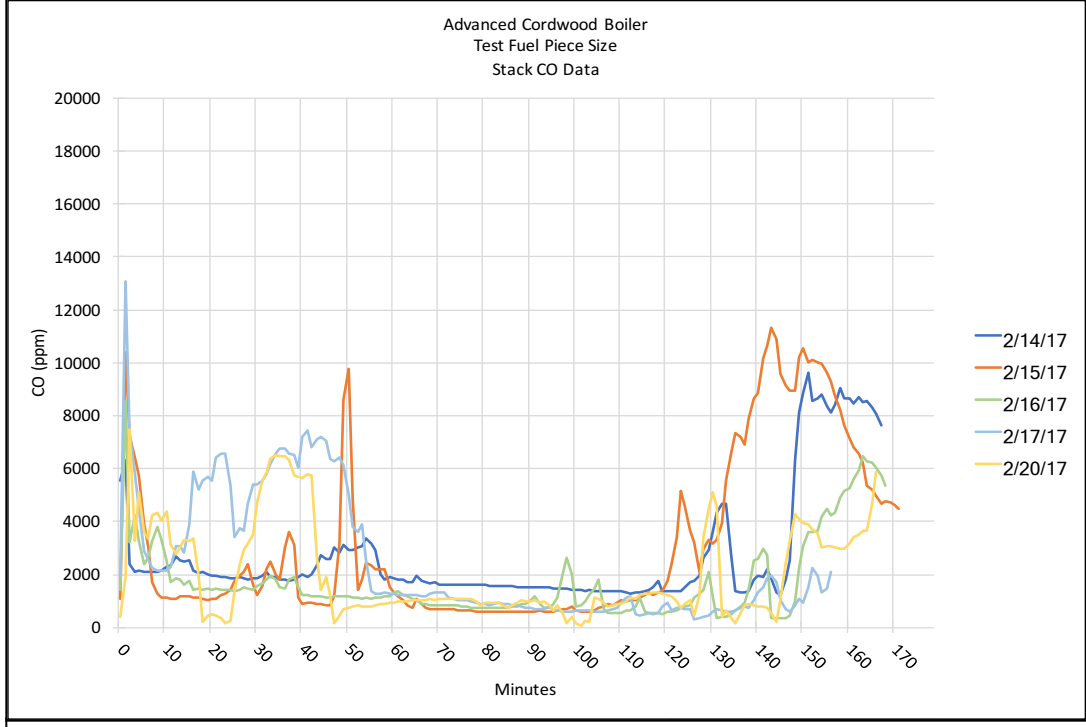


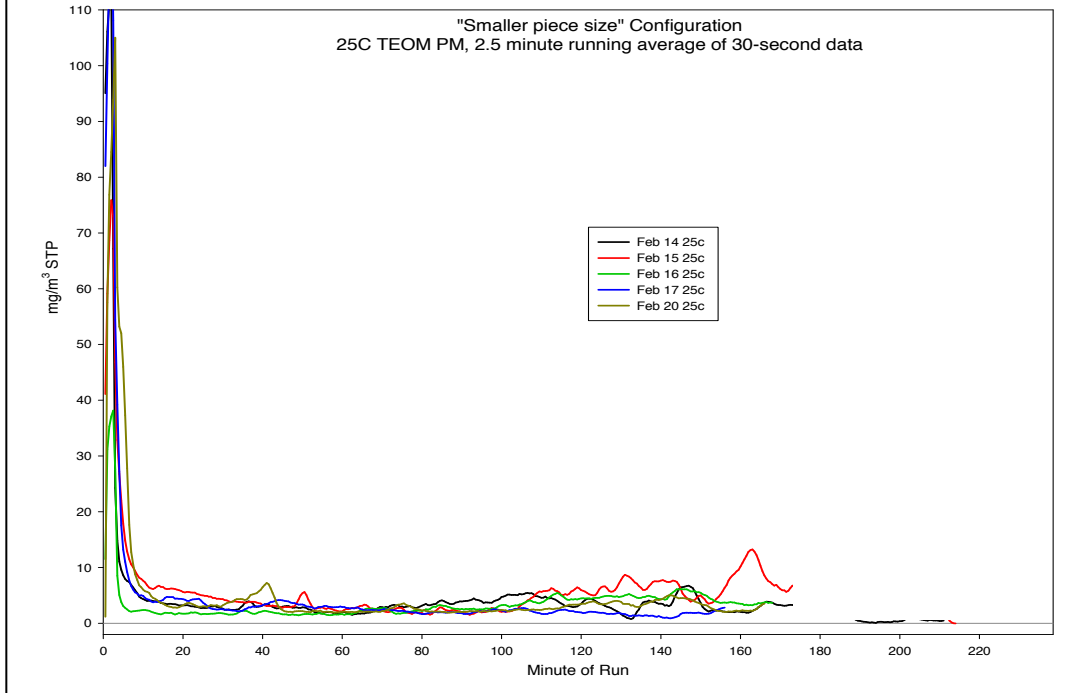
Conclusion - Overall, the results were too erratic to conclude if one configuration was significantly better than another. Realized that secondary combustion quality played larger factor in performance than fuel placement

2. Test Fuel Piece Size

- **Objective**
  - Observe the effect of Advanced Cordwood boiler A's operation by reducing the cross-section diameter and individual piece weight requirements of the test fuel charge. (following similar parameters to firebox volume < 4ft^3 instead of 5^3)
  - More pieces were used to get to desired fuel charge weight (8-10 pieces instead of 6-7 pieces)
- **Results and Conclusions**
  - By using smaller test fuel, but more of them, Advanced Cordwood Boiler A could maintain secondary combustion throughout the burn and thus better overall performance
  - Smaller pieces ignite easier and gasify quicker than larger pieces
  - Average PM was below 10 mg/m^3 for all 5 burns

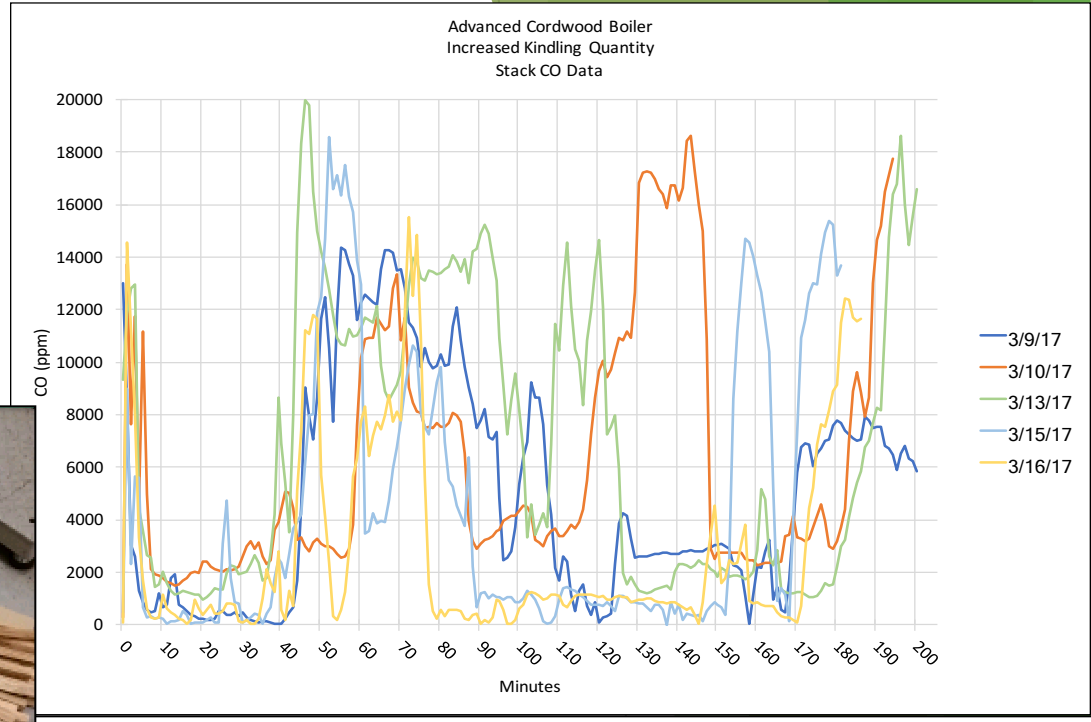
	Firebox volume, ft^3	Cross-section of piece, in.		Minimum weight of piece, lb.	Maximum weight of piece, lb.	80% piece weight range, lb.	Number of pieces
		Minimum	Maximum				
CSA B415.5 Table 4	< 4	2	6	2.2	13.2	3-11	4-7
	>/= 4 & </= 10	2.5	8.0	4.4	17.6	6.7-15.5	5-10

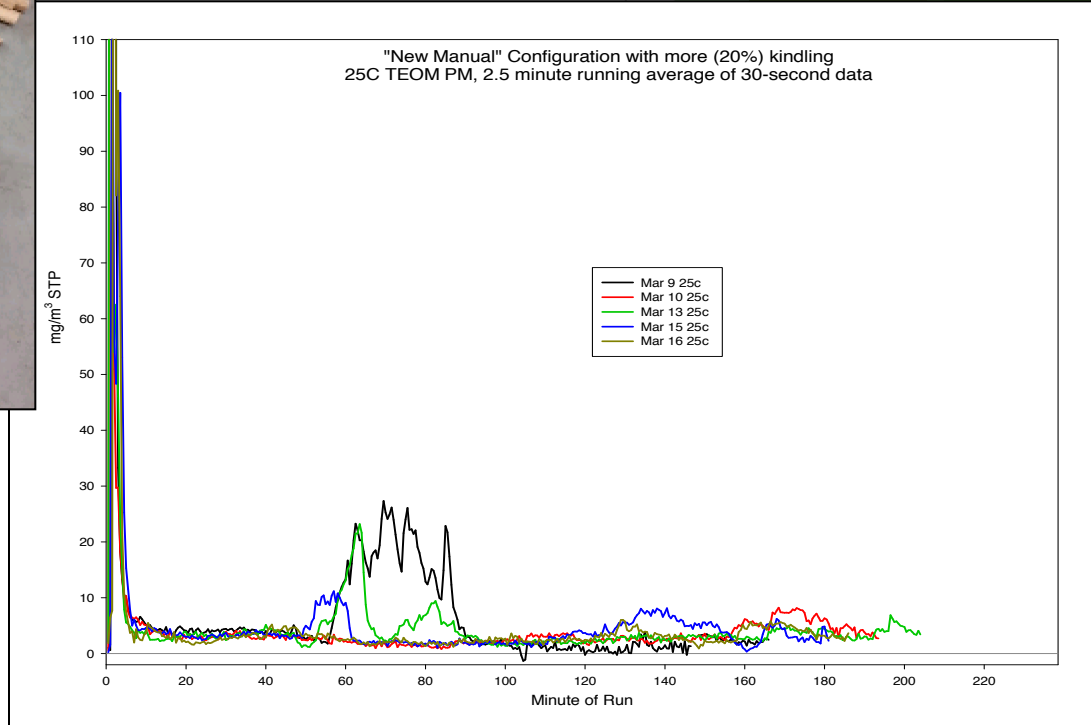




3. Test Fuel Kindling Quantity

- **Objective**
  - Analyze the effect of boiler operation by increasing the kindling weight from 10% (~ 5lbs.) of test fuel charge weight to 20% (~10 lbs.) for 50 lb. fuel charge
- **Results**
  - System performed almost as well as Test Fuel Piece Size series for PM, not necessary CO – sometimes double the average of CO from Test Fuel Piece Size series
    - PM was below10 mg/m3 for majority of burns, other than the 30-40 minute high concentration of PM in the mid 20s on March 9th with peak of 27.5 mg/m^3 (black)
  - The quality of secondary combustion varied throughout the tests
    - Lower quality during periods of high CO concentrations



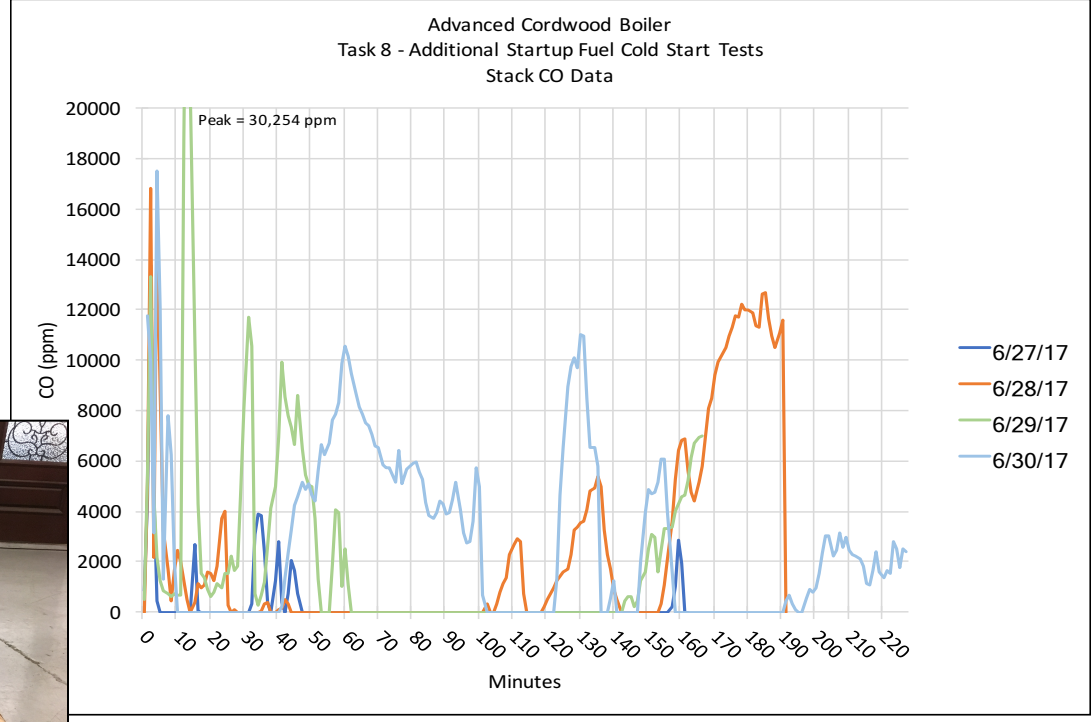


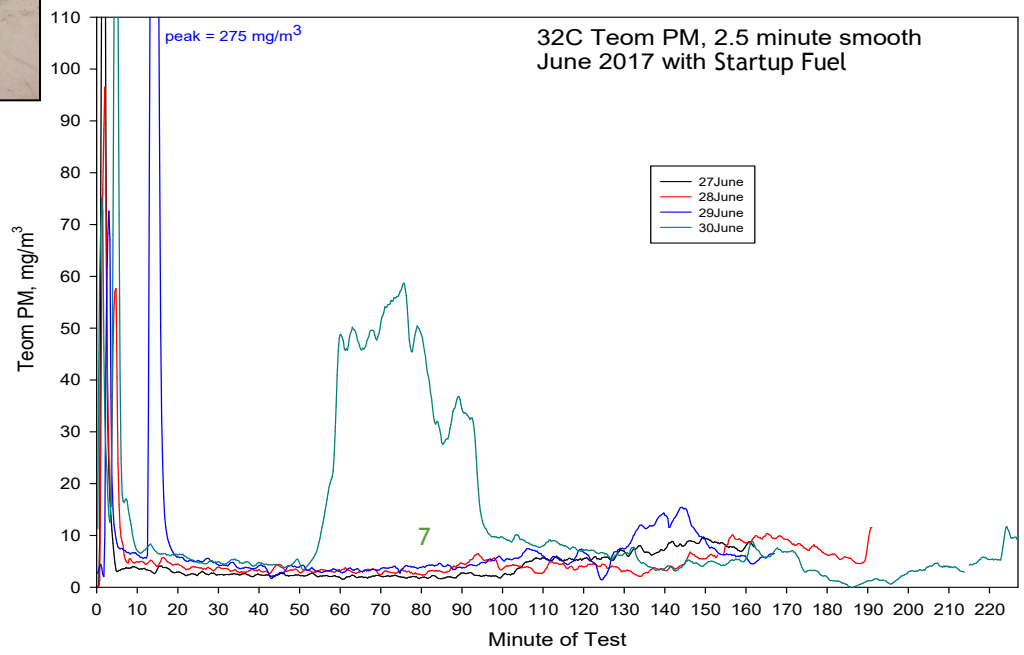
NYSERDA Agreement No. 63025

4. Startup Fuel

- **Objective**
  - Observe the effect of adding ‘startup fuel’ to the test fuel charge load.
- **Startup Fuel**
  - Consisted of 2-3 pieces at about 10% MC between 2.5 in. and 3.5 in. in cross-sectional diameter and together weighed ~5 lbs. (10%)

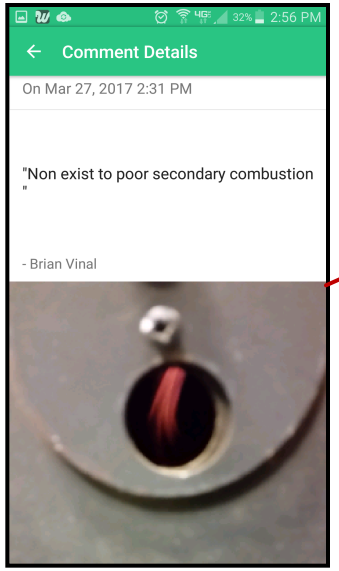
- **Results and Conclusions**
  - System performed consistently clean throughout the test series in both PM and CO emissions
  - Hit some periods of poor secondary combustion, but system was able to clean itself up (60 minutes, June 30th)
  - Smaller pieces helped light and gasify the larger fuel pieces falling from the top down in the primary combustion chamber

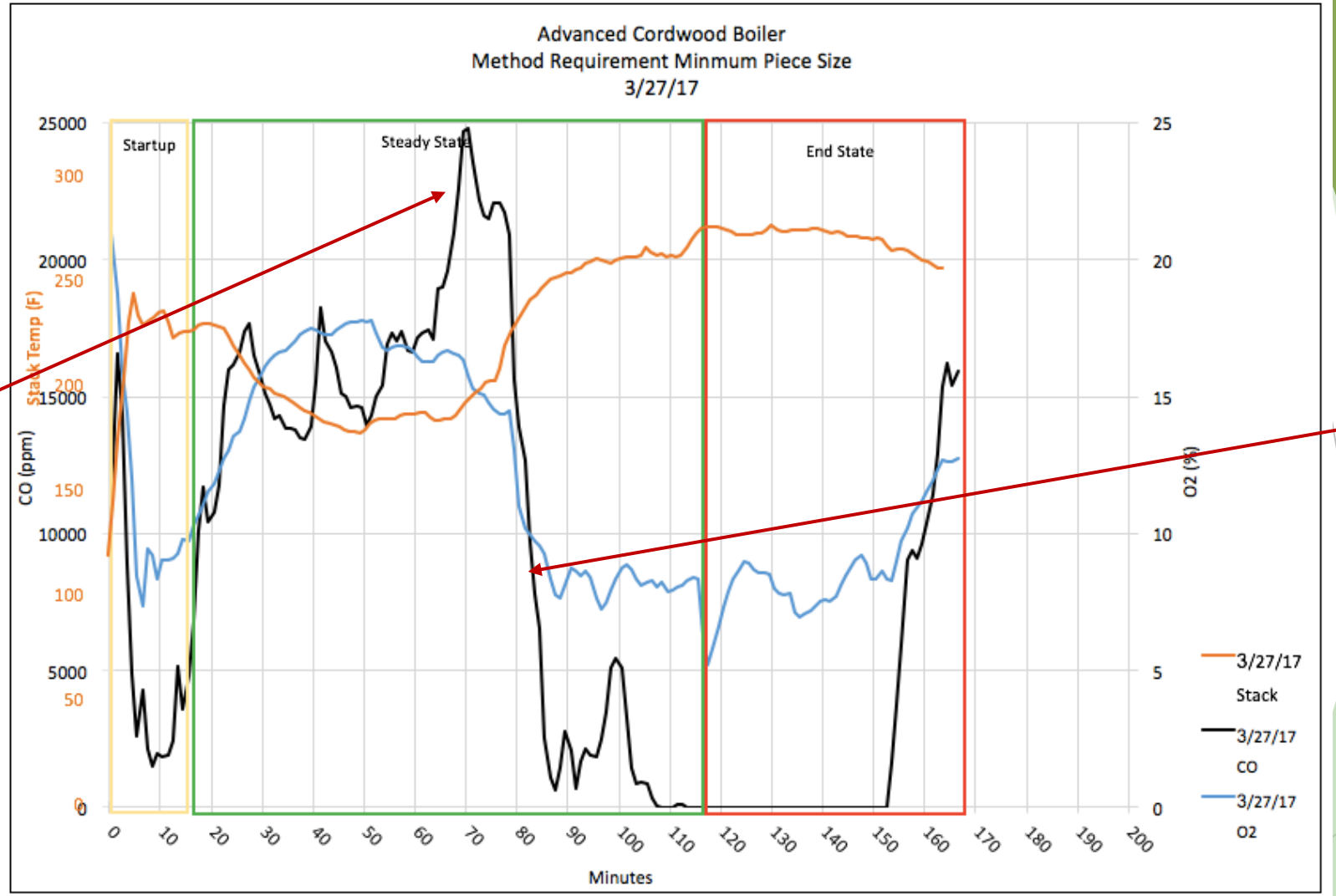


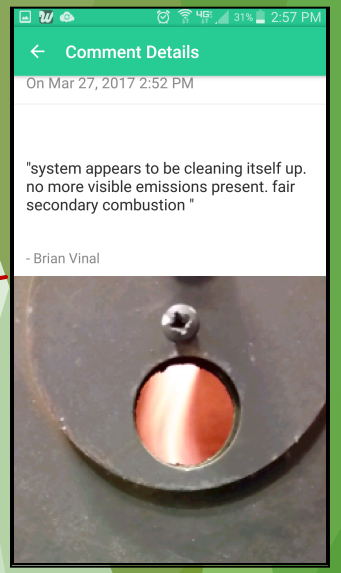


Overall Testing Conclusions:

1. Individual fuel weights and the quantity of smaller fuel pieces had greater impact over the boiler's emissions and repeatability than the configuration of the fuel in the firebox
   - Fuel charges consisting of smaller fuel pieces have greater total surface area and are easier to ignite and gasify
   - Fuel charges consisting of larger pieces have less surface area and take longer to ignite and gasify
     - Falling down in firebox as smaller pieces are consumed and blocking the outlet to the secondary combustion causing high PM and CO emissions
2. System could burn clean with larger fuel pieces and 10% kindling alone, but was not always repeatable (Test Fuel Configuration Series)
3. All burns had a high peak of both CO and PM at the start of the burn regardless of the variable tested
4. The observation of secondary combustion gave us invaluable insight to the boiler performance and emissions.







- Examples of correlation between quality of secondary combustion and combustion gas profile

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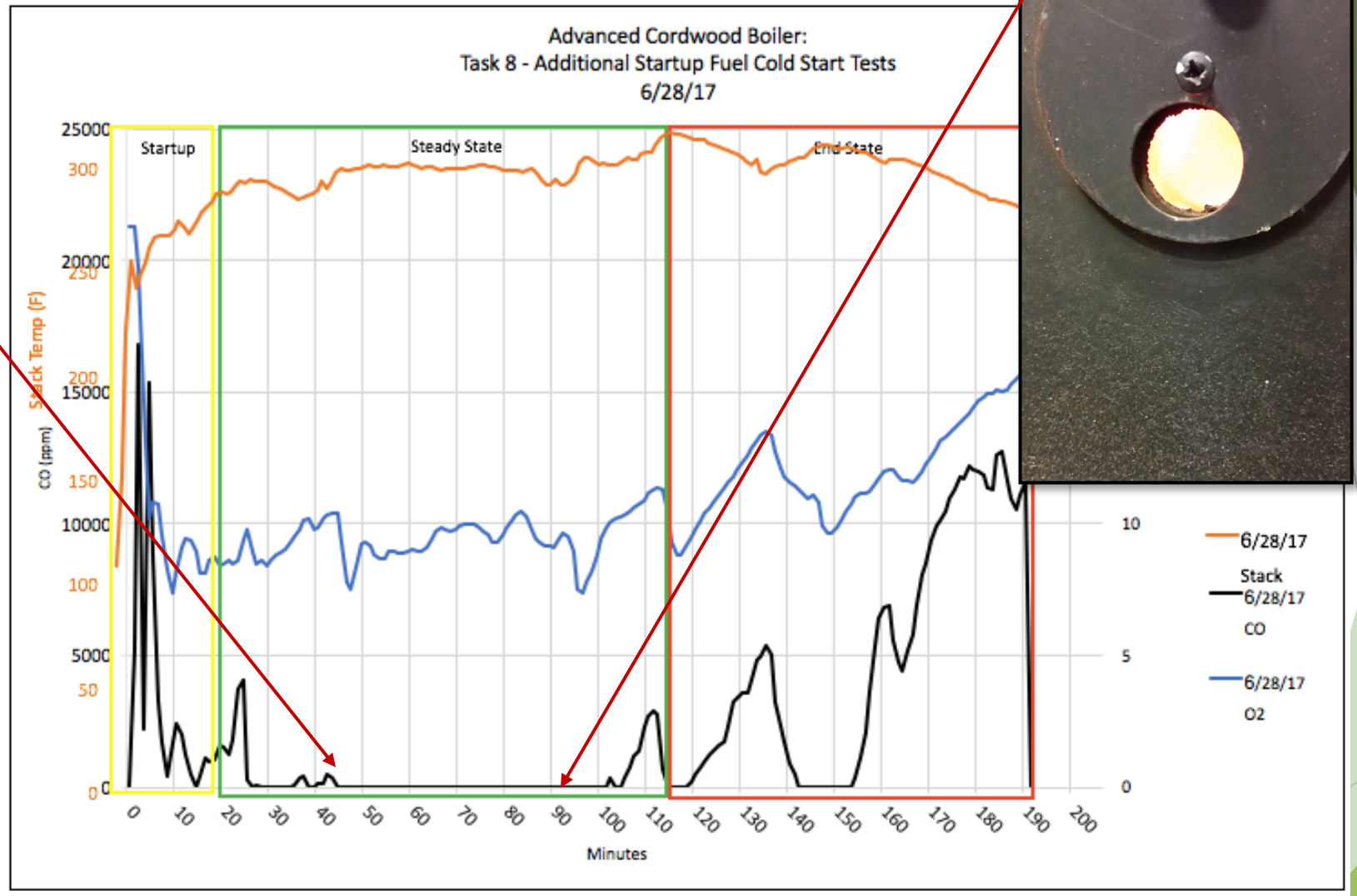

- Examples of consistently good to excellent secondary combustion throughout burn

Questions?

Thank you everyone for your time and support!

Special thanks to NYSERDA,NESCAUM, and BNL

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