MEASUREMENT OF BLACK CARBON IN A WOOD STOVE METHOD 5G DILUTION TUNNEL

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Disclaimer:

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Acknowledgments:

This project was carried out by SC&A, Inc. under the direction of EPA. Primary technical work was performed by Northeast States for Coordinated Air Use Management (NESCAUM), a subcontractor to SC&A, with assistance from Hearthlab Solutions (HLS) also a subcontractor to SC&A, that operated the black carbon (BC) instrument for this project. BC data was collected during wood stove testing performed by HLS under a separate subcontract to the New York State Energy Research and Development Authority (NYSERDA) under the direction of NESCAUM. Technical team members from the EPA Office of Air Quality and Standards provided review and consultation during development of the Quality Assurance Project Plan (QAPP) for this project, and the EPA Office of Research and Development provided a Standard Operating Procedure (SOP) for the handling of quartz filters.

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1. Introduction

Black carbon is carbonaceous particulate matter that appears black, is produced by high temperature incomplete combustion of fuels, and is closely related to and highly correlated with thermal-optical measurements of elemental carbon (EC, or graphitic carbon). It is a short-term climate-forcing pollutant, with an atmospheric lifetime on the order of days to weeks, and can be transported in the atmosphere for thousands of kilometers. Black carbon can also enhance melting of snow or ice when it is deposited on the surface by wet or dry deposition mechanisms. Limited black carbon emissions testing has been performed on wood burning residential stoves. The primary purpose of this project was to provide data on black carbon emissions from several different 2015 NSPS Step 1 and Step 2 wood stoves.

Under this project, NESCAUM measured black carbon (BC) from wood stoves using an optical transmission method. A modified Magee Scientific AE-22-ER Aethalometer BC analyzer was run in a manual tape advance mode to make 5-second BC measurements in a Method 5G dilution tunnel with a flow of 200 cubic feet per minute (CFM) at the Hearthlab Solutions (HLS) facility in Bethel, VT. The Aethalometer filter spot loading artifact was corrected using the Virkkula approach (JAWMA, 2007).

HLS ran eighteen tests burns on seven different 2015 NSPS Step1 and Step 2 certified stoves fueled with Red Maple cordwood, using a multi-mode cordwood test method protocol with burn durations of ~ 6 to 12 hours. This effort leveraged ongoing work at HLS funded by the New York State Energy Research and Development Authority (NYSERDA, Albany NY). The EPA-funded work (this project) added the Aethalometer BC measurements. Continuous PM and related stove test measurements were made by HLS under the NYSERDA stove testing contract, and those results will be available at the end of the NYSERDA project.

A Quality Assurance Project Plan (QAPP) and Aethalometer Standard Operating Protocol (SOP) were developed for the BC measurements prior to the start of measurements and are included with this report as appendices.

2. Project Management

This project, "Measurement of black carbon in a wood stove Method 5g dilution tunnel", was performed by NESCAUM as a subcontractor to SC&A Incorporated under EPA contract No. EP-D-12-001, Work Assignment (WA) No. 4-08, Support Development of Test Methods for Residential Cordwood and Coal. The specific work covered by this project was the measurement of black carbon from wood stoves using an Aethalometer in a Method 5G dilution tunnel, and was part of a test program to evaluate black carbon emissions from wood stoves, described as Subtask 6.2 in SC&A's approved work plan for the WA.

Technical direction was provided to prime contractor SC&A by the EPA Work Assignment Contracting Officer's Representative (WACOR). The EPA Work Assignment Contracting Officer's Representative (WACOR) at the start of the project was Larry Brockman, later changed by EPA to Ms. Rochelle Boyd, with David Nash serving as the Alternate WACOR. The SC&A Project Leader was Graham Fitzsimons. Consultation and review on quality assurance (QA) and other technical issues was provided by technical team members from the EPA Office of Air Quality Planning and Standards (OAQPS) and the Office of Research and Development.

SC&A provided project management and direction to subcontractor NESCAUM. All BC measurements and data processing were overseen by the NESCAUM Project Manager, George Allen. Reneé Landgrebe was the NESCAUM QA Manager. Under a separate subcontract, SC&A obtained HLS technical assistance specifically for operation of the black carbon (BC) instrument for this project during test burns conducted at HLS. The test burns were funded by the New York State Energy Research and Development Authority (NYSERDA, Albany NY) as part of a separate research and development effort. The EPA-funded work (this project) added the Aethalometer BC measurements.

3. Overview of Test Program

Eighteen black carbon test runs on seven different woodstoves were completed between January 9 and August 10, 2018 at HLS in Bethel, VT. A brief description of the stoves is provided in Table 1. All test runs used Red Maple cordwood with moisture content of 19% to 25% moisture content (dry basis). Different cordwood operation and fueling protocols were used, as the NYSERDA project required modifications to the fueling and operational protocol during the test program. Details of the protocols will be available at completion of that project.

Table 1. Description of stoves used

Stove #	Construction Type	Firebox Size	Emission Controls	EPA 2015 NSPS Certification Value
Stove 1	High mass	Large	Non-catalytic	Step 1 cert value <3.0 g/hr
Stove 2	High mass	Small	Catalytic	Step 2 cert value <2.0 g/hr
Stove 3	Steel	Large	Catalytic	Step 1 cert value <2.0 g/hr
Stove 4	Cast iron	Small	Non-catalytic	Step 1 cert value <4.0 g/hr
Stove 5	Cast	Medium	Non-catalytic	Step 1 cert value <2.0 g/hr
Stove 6	Steel	Medium	Non-catalytic	Step 1 cert value <4.0 g/hr
Stove 7	High mass	Medium	Hybrid - catalytic and non-catalytic	Step 2 cert value <2.0 g/hr

Integrated Duty Cycle (IDC) protocol V1 was used for the six runs in January, 2018 on Stoves 1, 2, 3, 4, 5, and 6. A revised final IDC protocol V2 was used for the remaining twelve test runs in July and August, 2018 on Stoves 1, 5, 6, and 7 (3 runs on each stove). Both protocols included startup (from match light) followed by three loads of cordwood at different stove air settings. These loads are identified as "Startup" and L1, L2, and L3. Wood load weights and stove air settings were changed between V1 and V2 protocols. The test run ended when 90% of the third test load weight was burned. Stoves 2, 3, and 4 were tested once, during January on the V1 protocol. Stoves 1, 5, and 6 were tested 4 times, once using the V1protocol and three times on the V2 protocol. Stove 7 was tested three times, only with the V2 protocol. The BC measurement method was the same for all eighteen runs.

NESCAUM measured black carbon (BC) from wood stoves in the HLS dilution tunnel using an optical transmission method. A modified Magee Scientific AE-22-ER Aethalometer BC analyzer was run in a manual tape advance mode to make 5-second BC measurements in a Method 5G dilution tunnel running at 200 CFM at the Hearthlab Solutions (HLS) facility in Bethel, VT. The Aethalometer filter spot loading artifact was corrected using the Virkkula approach (JAWMA, 2007). This method corrects the data for loading artifacts based on a best match in BC before and after a tape advance. A single "K" factor (loading correction as a function of filter attenuation) was used for each burn, using the Virkkula calculation to determine a K value that gave a reasonable before and after BC match across an entire burn run. While there are uncertainties in the value of K across an individual burn, the magnitude of the correction is not large (on the order of 20 to 25% on average), and thus modest errors or uncertainties for the value of K used do not result in substantial errors in BC measurements that are related to spot loading effects.

4. Sampling Procedure and Equipment

Sampling procedures and equipment are described in the Standard Operating Protocol (SOP) that is included in the Quality Assurance Project plan (QAPP) developed for this project, and included as an Appendix to this report. Briefly, a Magee Scientific (Berkeley, CA) model AE22-ER Aethalometer was used in a manual tape advance mode to minimize data loss during tape advances to 5 seconds. The Aethalometer flow was calibrated to sample at approximately 0.65 EPA SLPM (25 C and 1 Atm). Data were corrected during post-processing to account for the difference between actual and Aethalometer reported flow. The Aethalometer tape was manually advanced when attenuation (a measure of BC loading on the filter spot) reached a value of 75. For the first three runs (January 9, 12, and 16, while the operating procedure was being fine-tuned), the maximum attenuation used for a tape advance trigger was 120, and thus the uncertainty from the filter loading correction is somewhat larger. Five-second data were averaged up to 1-minute intervals for use in data analysis for this report.

5. Quality Assurance

A Quality Assurance Project Plan (QAPP) was developed specifically for this project and met EPA's Category III requirements. The QAPP was based on the guidance and requirements for quality assurance project plans, as specified by the EPA, and by the quality management plan (QMP) of EPA's Office of Air Quality Planning and Standards (OAQPS). The QAPP described project organization, responsibilities, laboratory procedures, documentation and reporting. Approval signatures on the final QAPP were received from EPA on February 1, 2018. All procedures, sampling, analysis and data handling in this study adhered to the QAPP's requirements. The QAPP is included as an Appendix to this report.

6. Results

Data capture across all runs was 97%. Of the 72 burn phases (4 per run, 18 runs), data are available for 70. There were two periods with missing data due to instrument problems. The test run on January 24 (V1 protocol) is missing load 2 data, and the test run on July 18 (V2 protocol) is missing startup data. All BC data reported here were collected at EPA standard temperature (25 C) and pressure (1 atmosphere).

A summary table of BC emission rates across all eighteen burns is shown in Table 2. The overall average BC emission rate was 0.27 g/h. BC emission rates parsed by fuel load and stove range from a minimum of 0.03 g/h to a maximum of 2.04 g/h. The startup burn phase had the highest BC emission rate on average, but the duration of the startup phase was less than the other fuel loads. Fuel load #2 had lower BC emission rates and total BC emitted compared to other burn phases. Load #3 had the highest BC emitted of all burn phases. The average full run BC emitted across all stoves and all burns was 2.46 grams, with a range of 1.2 to 4.0 grams. BC emission factors (g BC emitted per kg of dry wood burned) for different burn phases ranged from 0.017 to 0.721 g/kg, with a mean value of 0.128 g/kg across all burns. The Startup phase had the highest average BC emission factor (0.355 g/kg).

Table 2. BC emission rates (g/h), total BC emitted (grams), and BC emission factors (g/kg)

Fuel Load	g/h Avg	g/h Std	g/h Median	g/h Max	g/h Min	Duration minutes	grams Avg	grams Std	grams Median	grams Max	grams Min	EF g/kg Avg	EF g/kg Std	EF g/kg Median	EF g/kg Max	EF g/kg Min
Startup	1.08	0.42	1.00	2.04	0.41	47	0.84	0.21	0.79	1.18	0.33	0.355	0.120	0.330	0.670	0.161
L 1	0.42	0.37	0.30	1.72	0.11	95	0.67	0.21	0.47	1.00	0.15	0.133	0.110	0.100	0.535	0.049
L 2	0.15	0.11	0.10	0.53	0.05	138	0.34	0.13	0.24	0.55	0.13	0.076	0.034	0.069	0.153	0.017
L 3	0.18	0.08	0.20	0.33	0.03	276	0.83	0.41	0.78	1.95	0.16	0.101	0.047	0.100	0.200	0.026
FullRun	0.27	0.09	0.28	0.40	0.09	556	2.46	0.69	2.39	4.04	1.21	0.128	0.040	0.118	0.240	0.047

Wood loads for each stove were based on firebox capacity, which ranged from 0.7 to 3.5 cubic feet volume. Thus, full run wood load weights varied across stoves in absolute value, with small stoves having smaller wood loads by weight. Individual burn phase wood loads (wet and dry) and the fuel calculator used to determine those loads will be available at the end of the NYSERDA project. Table 3 shows the distribution of full run wet wood loads and the National Emissions Inventory (NEI) metric of grams BC per wet # of wood burned. This number is an estimate since the three fuel loads were only burned down to 90%, not 100% and thus the actual wet weight of wood burned is somewhat smaller than the weight of all the wood loaded.

Table 3. Full run wood loads (wet #), and grams BC per wet lb (#) of wood load

	Full Run wood loads, wet #	grams BC per wet #
Average	59.7	0.042
Std	16.7	0.015
Median	56.9	0.037
Max	89.6	0.084
Min	22.3	0.015

BC emission rate (g/h), total BC emitted (g), and BC emission factor (g/kg dry fuel) by burn phase for each of the eighteen stove test runs are shown in Table 4. Durations of each burn phase in minutes and the dry burn rates in kg/hour are also shown for each run. The total fuel load for the full run is reported in wet pounds. Fuel load wet and dry weights for each phase are not reported here, but will be available at the completion of the NYSERDA project.

Table 4. BC emission rate, total BC emitted by burn phase, and BC emission factor (g/kg)

Note: DBR is dry burn rate, kg/h. # is pounds. ET is elapsed test time. Duration is minutes.

S6 1/9/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:53	Startup	4.2	34	1.46	0.83	0.346
34	10:27	L 1	4.3	50	0.54	0.45	0.127
84	11:17	L 2	2.1	139	0.09	0.21	0.044
223	13:36	L 3	1.7	247	0.21	0.86	0.122
470	17:43	Full Run	2.3	470	0.30	2.37	0.133
	Dry wood burned, kg:			17.82			
	Full Run, wet wood # load:			55.0	grams BC/#:	0.043	
S5 1/12/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:14	Startup	4.8	29	2.04	0.99	0.428
29	9:43	L 1	3.6	59	0.91	0.90	0.251
88	10:42	L 2	2.2	145	0.10	0.24	0.046
233	13:07	L 3	2.2	227	0.23	0.86	0.105
460	16:54	Full Run	2.5	460	0.39	3.02	0.156
	Dry wood burned, kg:			19.37			
	Full Run wood load, wet #:			58.4	grams bc/#:	0.052	
S4 1/16/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	8:37	Startup	1.5	34	1.03	0.58	0.670
34	9:11	L 1	3.2	25	1.72	0.72	0.535
59	9:36	L 2	3.5	33	0.53	0.29	0.153
92	10:09	L 3	1.2	191	0.09	0.30	0.080
283	13:20	Full Run	1.7	283	0.40	1.88	0.240
	Dry wood burned, kg:			7.83			
	Full Run wood load, wet #:			22.3	grams bc/#:	0.084	
S1 1/19/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	8:32	Startup	3.4	59	1.20	1.18	0.351
59	9:31	L 1	4.7	64	0.47	0.50	0.100
123	10:35	L 2	2.8	149	0.17	0.41	0.060
272	13:04	L3	2.0	365	0.32	1.95	0.161
637	19:09	Full Run	2.6	637	0.38	4.04	0.148
	Dry wood burned, kg:			27.37			
	Full Run wood load, wet #:			85.4	grams bc/#:	0.047	

S2 1/24/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:01	Startup	2.1	42	1.00	0.70	0.479
42	9:43	L 1	1.4	84	0.11	0.15	0.077
126	11:07	L 2	1.2	142	n/a		
268	13:29	L 3	1.0	291	0.03	0.16	0.031
559	18:20	Full Run	1.2	559	0.13	1.21	0.107
	Dry wood burned, kg:			11.37			
	Full Run wood load, wet #:			35.3	grams bc/#:	0.034	
S3 1/26/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	8:57	Startup	2.8	62	0.56	0.58	0.200
62	9:59	L 1	4.8	67	0.28	0.31	0.058
129	11:06	L 2	3.2	142	0.05	0.13	0.017
271	13:28	L 3	1.3	586	0.03	0.34	0.026
857	23:14	Full Run	2.0	857	0.09	1.35	0.047
	Dry wood burned, kg:			28.51			
	Full Run wood load, wet #:			89.6	grams bc/#:	0.015	
S6 7/18/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:41	Startup	3.0	47	n/a		
47	10:28	L 1	3.4	88	0.34	0.50	0.100
135	11:56	L 2	1.5	140	0.13	0.30	0.086
275	14:16	L 3	1.4	260	0.22	0.94	0.152
535	18:36	Full Run	1.9	535	0.21	1.91	0.112
	Dry wood burned, kg:			17.01			
	Full Run wood load, wet #:			53.2	grams bc/#:	0.036	
S6 7/19/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:47	Startup	3.8	36	1.52	0.91	0.400
36	10:23	L 1	3.5	86	0.28	0.39	0.080
122	11:49	L 2	1.5	138	0.19	0.43	0.120
260	14:07	L3	1.6	250	0.33	1.37	0.200
510	18:17	Full Run	2.1	510	0.37	3.11	0.176
	Dry wood burned, kg:			17.64			
	Full Run wood load, wet #:			55.2	grams bc/#:	0.056	
S6 7/20/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:24	Startup	2.9	46	0.92	0.71	0.318
46	10:10	L 1	3.4	88	0.48	0.70	0.142
134	11:38	L 2	1.3	161	0.16	0.42	0.122
295	14:19	L3	1.6	263	0.18	0.79	0.112
558	18:42	Full Run	1.9	558	0.28	2.63	0.148
	Dry wood burned, kg:			17.75			
	Full Run wood load, wet #:			55.6	grams bc/#:	0.047	

S7 7/25/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:22	Startup	2.2	57	0.67	0.64	0.312
57	10:19	L 1	1.9	143	0.18	0.43	0.096
200	12:42	L 2	1.2	158	0.09	0.22	0.073
358	15:20	L3	1.4	314	0.15	0.76	0.103
672	20:34	Full Run	1.5	672	0.18	2.05	0.121
	Dry wood burned, kg:			17.02			
	Full Run wood load, wet #:			52.8			
S7 7/26/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:24	Startup	2.7	45	0.86	0.64	0.317
45	10:09	L 1	1.9	141	0.20	0.46	0.104
186	12:30	L 2	1.1	178	0.07	0.22	0.069
364	15:28	L3	1.4	283	0.24	1.11	0.171
647	20:11	Full Run	1.5	647	0.23	2.43	0.151
	Dry wood burned, kg:			16.08			
	Full Run wood load, wet #:			49.8	grams bc/#:	0.049	
S7 7/27/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:10	Startup	2.6	47	0.41	0.33	0.161
47	9:57	L 1	1.8	153	0.19	0.48	0.107
200	12:30	L 2	1.4	139	0.08	0.20	0.060
339	14:56	L3	1.2	315	0.14	0.72	0.112
654	20:11	Full Run	1.5	654	0.16	1.72	0.106
	Dry wood burned, kg:			16.23			
	Full Run wood load, wet #:			49.9	grams bc/#:	0.034	
S5 8/1/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:12	Startup	3.3	39	1.76	1.14	0.536
39	9:51	L 1	3.1	93	0.65	1.00	0.207
132	11:24	L 2	1.6	131	0.06	0.14	0.039
263	13:39	L 3	2.4	208	0.23	0.80	0.096
471	17:07	Full Run	2.4	471	0.36	2.83	0.151
	Dry wood burned, kg:			18.81			
	Full Run wood load, wet #:			58.7	grams bc/#:	0.048	
S5 8/2/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:12	Startup	3.6	35	1.39	0.81	0.383
35	9:47	L 1	2.6	111	0.13	0.24	0.049
146	11:38	L 2	1.5	135	0.09	0.19	0.056
281	13:59	L 3	1.7	291	0.06	0.28	0.034
572	18:50	Full Run	1.9	572	0.16	1.49	0.080
	Dry wood burned, kg:			18.53			
	Full Run wood load, wet #:			58.3	grams bc/#:	0.026	

S5 8/3/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:10	Startup	2.5	54	0.82	0.74	0.330
54	10:04	L 1	2.7	103	0.42	0.72	0.152
157	11:47	L 2	1.6	133	0.08	0.19	0.054
290	14:05	L 3	2.3	212	0.14	0.49	0.060
502	17:37	Full Run	2.2	502	0.25	2.12	0.114
	Dry wood burned, kg:			18.55			
	Full Run wood load, wet #:			58.4	grams bc/#:	0.036	
S1 8/8/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:09	Startup	3.4	57	0.88	0.84	0.259
57	10:06	L 1	3.7	118	0.33	0.64	0.089
175	12:04	L 2	2.4	128	0.21	0.44	0.087
303	14:18	L 3	2.7	222	0.19	0.71	0.071
525	18:00	Full Run	2.9	525	0.30	2.62	0.102
	Dry wood burned, kg:			25.56			
	Full Run wood load, wet #:			80.1	grams bc/#:	0.033	
S1 8/9/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:19	Startup	3.3	59	0.80	0.79	0.245
59	10:18	L 1	3.3	131	0.21	0.46	0.064
190	12:29	L 2	2.1	140	0.20	0.47	0.094
330	14:49	L 3	2.8	193	0.22	0.70	0.077
523	18:02	Full Run	2.8	523	0.28	2.42	0.099
	Dry wood burned, kg:			24.47			
	Full Run wood load, wet #:			76.9	grams bc/#:	0.031	
S1 8/10/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:26	Startup	3.4	59	1.01	0.99	0.301
59	10:25	L 1	3.9	108	0.21	0.38	0.054
167	12:13	L 2	2.0	154	0.22	0.55	0.109
321	14:47	L 3	2.5	248	0.24	1.00	0.098
569	18:55	Full Run	2.7	569	0.31	2.94	0.115
	Dry wood burned, kg:			25.68			
	Full Run wood load, wet #:			80.1	grams bc/#:	0.037	

Dry BC emission factors in the context of stove emission control type, construction, and size are shown in Table 5. Stoves with only one test (S2, S3, and S4) used only the V1 IDC protocol. The sample size in this project is too small to be able to say if any of these stove design parameters are related to BC EF. Stove 4, the small non-catalytic cast iron stove, appears to have distinctly higher BC EF than the other stoves, but that is based on a single test run. Table 6 shows individual test run BC EF by IDC version.

Table 5. Stove descriptions, PM certification values, and average dry BC EF

Stove #	# of test runs	Construction Type	Firebox Size	Emission Controls	EPA 2015 NSPS Certification Value	Dry BC EF, g/kg
Stove 1	4	High mass	Large	Non-catalytic	Step 1 cert value <3.0 g/hr	0.116
Stove 2	1	High mass	Small	Catalytic	Step 2 cert value <2.0 g/hr	0.107*
Stove 3	1	Steel	Large	Catalytic	Step 1 cert value <2.0 g/hr	0.047*
Stove 4	1	Cast iron	Small	Non-catalytic	Step 1 cert value <4.0 g/hr	0.240*
Stove 5	4	Cast iron	Medium	Non-catalytic, non-tube	Step 1 cert value <2.0 g/hr	0.125
Stove 6	4	Steel	Medium	Non-catalytic	Step 1 cert value <4.0 g/hr	0.142
Stove 7	3	High mass	Medium	Hybrid - catalytic and non-catalytic	Step 2 cert value <2.0 g/hr	0.126

* Stoves with a single run may not be representative of typical performance, and BC from IDC protocol V1 may not be comparable to V2. Project resources did not allow for additional BC testing of stoves 2, 3, and 4 on IDC protocol V2.

Table 6. Detail of BC EF by IDC version

Stove #	V1	V2	V2	V2	Range	avg EF	Notes
1	0.148	0.102	0.099	0.115	0.049	0.116	
2	0.107					0.107	missing L2
3	0.047					0.047	
4	0.240					0.240	
5	0.156	0.151	0.080	0.114	0.075	0.125	
6	0.133	0.112	0.176	0.148	0.064	0.142	missing startup on 2nd run
7		0.121	0.151	0.106	0.046	0.126	

Additional detail on each test run are presented as time series plots and box plots of BC emission rate (g/h) data for each run. These are included as an appendix to this report.

7. Conclusions

BC emissions are highly variable both within a single test burn and across different test burns. Emission rate (grams/hour), total grams emitted, and emission factors (EF, in g/kg) are reported, but the metric of most interest is the BC emission factor, both as a function of burn phase and for the full burn. Of the four burn phases (startup and three fuel loads), startup had the highest average EF (0.355 g/kg). For total grams of BC emitted, the third (final) fuel load had the largest average BC (1.21), in part because it was the longest burn phase duration (276 minutes on average).

Startup had the highest average emission rate (1.08 g/h) of the four burn phases. For total grams of BC emitted, the third (final) fuel load had the largest average BC (1.21), in part because it was the longest burn phase duration (276 minutes on average).

For the entire burn (all four phases), the BC emitted varied by somewhat less than a factor of four (from 1.21 to 4.04 grams). The BC EF for full runs ranged from 0.047 to 0.240 g/kg. For an inventory (NEI) EF perspective, an estimate of grams BC emitted per pound of wet wood loaded (not burned) is reported but only for the full run. The average EF was 0.042/wet #, with a range of 0.015 to 0.084 (a factor of 5.6 times). As noted above, this NEI EF metric is an estimate since the three fuel loads were only burned down to 90% (not 100%) and thus the actual wet weight of wood burned is slightly smaller than the weight of all the wood loaded.

These results reflect a "real-world" stove use scenario where the stove is run in a way that is a reasonable reflection of everyday in-home use. No attempt was made to analyze the data from the two different IDC operation and fueling protocols separately since the sample size was too limited. Details on the IDC protocol will be available at the end of the NYSERDA project.

8. Variability, Precision and Potential Limitations

Variability.
Burning wood in a woodstove is an inherently highly variable process. The natural variability of cordwood combustion adds a large amount of variability to the measured BC within a given stove that has multiple runs, as well as across different stoves. To the extent possible, the test runs controlled parameters such as pre-test conditions, consistent wood moisture and consistent stove operation. Batch combustion of wood includes many variables that may not be controlled such as settling of pieces during the combustion cycle, the way air flows around one set of logs versus another, spacing between the fuel pieces, and sap pockets within the fuel, to name a few. Such variables cannot be controlled and add variability to the overall measurement and make comparisons of BC emissions between stoves uncertain. A much larger data set would help quantify differences in BC across different stoves.

Precision.
It is not possible to assess the precision of the BC measurement since no replicate measurements were made. Sample flows were measured continuously by the Aethalometer. External flow

checks with a calibrated mass flow meter were made at the start and end of each measurement run. Flow uncertainties were typically less than 5%, and other Aethalometer measurement uncertainties (spot dimensions, tape spot to spot variations in optical properties, etc.) are estimated to be less than 5%. The uncertainty and variability of the filter loading correction factor ("K") contributes approximately 10% uncertainty and precision. Accuracy of the BC measurement is affected by the parameters described above, as well as the operational definition of optical BC. The relationship between AE22 Aethalometer BC and filter-based EC measurements varies substantially, depending on the method used to measure BC (TOR, TOT, NIOSH5040, etc.), since there can be up to a factor of two difference between these EC measurement methods. Various direct comparisons of Aethalometer BC and EC generally show agreement within 20 to 25%.

Potential Limitations.

BC emissions are based on generic tunnel flows, not actual 1 minute tunnel flow data, since HLS tunnel flow data are not currently available for use in this report. Those data will be available upon completion of the NYSERDA project. The uncertainty introduced by this is minimal, since HLS tunnel flows are automatically controlled and are typically within 10% of the 200 CFM target flow.

Since the data for wet weight of individual fuel loads will not be available until the end of the NYSERDA project, the NEI EF metric of grams BC emitted per wet # of wood burned for individual burn phases is not available. The full run g/wet # data EF data is an estimate, since the three fuel loads were each burned to 90% (not 100%), and thus the actual wet weight of wood burned is slightly smaller than the weight of all the wood loaded.

Stoves 2, 3, and 4 were only tested once, only on IDC protocol V1. Stoves with a single run may not be representative of typical performance, and BC EF data from IDC protocol V1 may not be comparable to V2. Thus, the usefulness of BC EF data from Stoves 2, 3, and 4 may be limited. Project resources did not allow for additional BC testing of these stoves on IDC protocol V2. In general, the sample size in this project is too small to be able to say if any of the stove design parameters are related to BC EF.

Appendix A: Stove Descriptions and Run Dates

The seven stoves are described as follows. All stoves are at least Step 1 2015 NSPS compliant.

#1. High mass construction, large firebox, tube/non-catalytic 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-catalytic emission controls
#5. Cast iron construction, medium firebox, non-catalytic/non-tube emission controls, top loading
#6. Steel construction, medium firebox, tube/non-catalytic emission controls
#7. High mass construction, medium firebox, hybrid combination of catalytic and tube technologies

Run Dates for stove and the protocols used are shown below.

V1 IDC protocol

18-01-09	S6
18-01-12	S5
18-01-16	S4
18-01-19	S1
18-01-24	S2
18-01-26	S3

V2 IDC protocol

18-07-18	S6
18-07-19	S6
18-07-19	S6
18-07-25	S7
18-07-26	S7
18-07-27	S7
18-07-28	S7
18-08-01	S5
18-08-02	S5
18-08-03	S5
18-08-08	S1
18-08-09	S1
18-08-10	S1

Appendix B: QA Project Plan and Standard Operating Procedures for BC Measurements.

NESCAUM

Standard Operating Procedure for measuring black carbon in a Method 5G wood stove dilution tunnel with a Magee Scientific model AE22-ER Aethalometer®

Prepared by
NESCAUM

December 28, 2017

George Allen
Project Manager, NESCAUM

Charla Rudisill
Quality Assurance Manager, NESCAUM

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1.0 PURPOSE

This Standard Operating Procedure (SOP) for the model AE22-ER Magee Science Aethalometer® Black Carbon Monitor describes the continuous measurement of concentrations of Black Carbon (BC) particulate from wood stoves in an EPA Method 5G wood stove dilution tunnel. The purpose of this SOP is to describe operating procedures and supplement the manufacturer's procedures in the instrument's manual.

2.0 SUMMARY OF METHOD

The principle of the Aethalometer® is to measure the attenuation of a beam of light transmitted through a filter while the filter is continuously collecting an aerosol sample. The measurement is made at successive regular intervals of a time base period. By using a value of the specific attenuation for the particular combination of filter and optical components, the BC content of an aerosol deposit can be determined at each measurement time. The increase in optical attenuation from one period to the next is due to the increment of aerosol BC collected from the airstream during the period. Dividing this increment by the volume of air sampled during that time determines the mean BC concentration in the sampled airstream during the period.

The configuration of the Aethalometer includes a filtration and analysis chamber with Teflon coated glass fiber tape, sample aspiration pump, air mass flow controller, and temperature-stabilized optics and electronics. The instrument is operated by an embedded computer that controls all instrument functions and records data internally; RS-232 outputs are available for use with data acquisition.

BC concentrations in the wood stove dilution tunnel range from less than 100 µg/m3 to more than 20 mg/m3. The AE22-ER was designed for sampling BC in ambient air and has been used in a wide range of research studies and routine ongoing measurement networks over the last 25 years. For this application, the operation of the instrument is modified by performing manual tape advances instead of the normal operating mode with automatic tape advances to minimize data loss during an automatic tape advance sequence. A measuring interval ("Time Base") of 5 seconds is used to avoid filter overload and triggering of an automatic tape advance sequence.

The AE22 is no longer in production, but it is the only model of Aethalometer that can be used for the high BC concentrations present in the dilution tunnel without additional dilution of the sample air. Older versions of the Aethalometer (AE16, 21, 31, 42) can not report 5-second data, and the current version (AE33) can not be used for manual tape advances.

For this application, the operation of the instrument is modified to allow sampling of BC up to 20 mg/m^3 concentration, approximately 1,000 times higher than ambient BC. Sample tape advances are done manually while watching the optical attenuation of the instrument on a real-time laptop data display. Using this technique, a tape advance can be performed with only 5 seconds of data loss, instead of the usual 2 to3 minutes of data loss. At the high end of the BC range of interest, the spot may only last 20 to 30 seconds, but even with 2 tape advances in a single minute more than 75% of the data (9 5-second data points) for the minute is valid. Additional dynamic range is obtained by mis-calibrating the instrument's flow meter to allow sample flow lower than ~ 1.2 lpm and correcting the flow during data processing using actual and reported instrument flows.

Additional information and user manuals are available at the NESCAUM Aethalometer training google drive collection at http://tinyurl.com/aethtraining and at the Magee Scientific web site at http://mageesci.com/

3.0 DEFINITIONS

NESCAUM	Northeast States for Coordinated Air Use Management
EPA	Environmental Solutions Agency
BC	Black Carbon
CFM	Cubic Feet per Minute
EC	Elemental or graphitic carbon
SOP	Standard Operating Procedure
OC	Organic carbon
Aerosol	A system of colloidal particles dispersed in a gas.
Calibration	The process of comparing a standard or instrument with one of greater accuracy (small uncertainty) to obtain quantitative estimates of the actual values of the standard being calibrated, the deviation of the actual value from a nominal value, or the difference between the value indicated by an instrument and the actual value.
Flowmeter	An instrument for measuring the rate of flow of a fluid moving through a pipe or duct system. The instrument is calibrated to give volume or mass rate of flow.
Mass Flowmeter	Device that measures the mass flow rate of air passing a point, usually using the rate of cooling or heat transfer from a heated probe.
Matter	The substance of which a physical object is composed.
Particle	A small discrete mass of solid or liquid matter
Particulate	Solids of liquids existing in the form of separate particles
Precision	The degree of mutual agreement between individual measurements, namely repeatability and reproducibility.
Sampling	A process consisting of the withdrawal or isolation of a fractional part of a whole. In air or gas analysis, the separation of a portion of an ambient atmosphere with or without the simultaneous isolation of selected components.
Standard	A concept that has been established by authority, custom, or agreement to serve as a model or rule in the measurement of quantity of the establishment of a practice or procedure.
Traceability to NIST	Documented procedure by which a standard is related to a more

	reliable standard verified by the National Institute of Standards Technology (NIST).
Woodsmoke	Aerosol from the combustion of wood.
Wood Smoke	See above
Wood Stove	A stove that burns wood, usually for space heating

4.0 HEALTH AND SAFETY WARNINGS

Installation, operation, maintenance, repair or calibration of the Aethalometer Black Carbon monitor should only be performed by properly trained personnel. All repairs shall be conducted in accordance with this SOP and manufacturer's documents

To prevent personal injury, please heed these warnings concerning the Aethalometer:
• Electric Shock: Disconnect power when servicing or replacing parts;
High voltages may be present inside the monitor enclosure. Avoid electrical contact with jewelry. Remove rings, watches, bracelets, and necklaces to prevent electrical burns. CHECK the main power supply cord ANNUALLY. If the supply cable is DAMAGED, stop using the equipment and contact your authorized representative.
• Fire and explosion: NEVER install the instrument in explosion-risk areas and never use the equipment near flammable substances.
• Instrument overheating: ALWAYS assure the instrument operates under proper operating ambient conditions. NEVER install the instrument in spaces with limited air circulation.
• UV radiation: The Aethalometer light source contains an ultraviolet (UV) light emitting diode (LED). The LED radiates UV and visible light during operation. Precautions must be taken to prevent looking directly at the UV light with unprotected eyes. NEVER touch or look directly into the Model Aethalometer light source!
• Moving parts: During tape advance procedure, the measurement chamber is lifted by a motorized chamber lift mechanism. To prevent any injuries to your fingers, NEVER squeeze your hands or fingers into ANY mechanical apertures, DURING the tape advance procedure.

5.0 CAUTIONS

To prevent damage to the Aethalometer Black Carbon monitor, the following precautions should be taken:
• The coated glass fiber tape is delicate and can be easily torn or gouged. Handle tape and tape roll carefully along the edges and avoid touching deposition surface. Keep the interior of the monitor clean.

6.0 INTERFERENCES AND LIMITATIONS

To avoid contamination of Aethalometer filter tape media, the following precautions should be taken:

- Keep the filter tape rolls in a secure, dry, contamination-free area. Avoid exposure of filter tape to any possible contamination.
- The Aethalometer interior surfaces surrounding the tape rolls must be cleaned periodically to avoid dust build up.

Limitations:
Aethalometer BC is a quantity defined by the method, and although is usually highly correlated with EC measurements, may be higher or lower than those measurements.

7.0 PERSONNEL QUALIFICATIONS AND RESPONSIBILITIES

Installation, operation, maintenance, repair or calibration of the monitor should only be performed by properly trained personnel. Personnel should meet NESCAUM requirements and qualifications for an Air Quality Instrument Operator.

8.0 EQUIPMENT AND SUPPLIES

Each Aethalometer is supplied and operated with the following equipment:

- Power supply cord
- Glass fiber tape.
- Black conductive sample line tubing
- 2 ea. - 3/8”-1/4” NPTF Reducer
- RS-232 cable
- RS-232 Null Modem adapter
- RS-232 to USB 2.0 adapter
- Laptop computer with USB port

The laptop computer is connected to the Aethalometer to allow operator access to the attenuation data in real time to inform the required manual tape advances.

For verification/calibration of the Aethalometer, the following equipment is required:

- NIST traceable, certified flow standard (BGI tetraCal, TSI 4100 mass flowmeter)

9.0 PROCEDURES

9.1 Instrument Setup and Configuration

Instrument Setup:
The Aethalometer is positioned near the dilution tunnel sampling port to minimize the length of the sample inlet tubing to no more than 3 meters. The laptop is connected to the Aethalometer's serial output data port. A terminal program (RealTerm) is used to display the Aethalometer data in real-time. Data are stored internally in the Aethalometer using a compact flash (CF) card.

Instrument Configuration:
Flow: 1.2 lpm (actual flow is ~ ½ this value)
Max ATN: 150
UV Channel: off
BC unit: micro-grams

9.2 Startup Procedures

At the start of each test day, the Aethalometer date and time (on the display) must be checked. If the time is more than 5 seconds different from laboratory time (on the Teom laptop) it should be set to be within 5 seconds.

The AE22-ER must be warmed up at least 15 minutes before use. During this time it should be sampling room air, not dilution tunnel air. An external flow check should be done prior to the start of each sampling day using the TSI 4100 mass flow meter. This measurement is entered into the Aethalometer operating log. The nominal flow is approximately 0.68 lpm, and should be between 0.60 and 0.75 lpm. All flows are at EPA SLPM (1 ATM and 25C).

The Aethalometer sample line is inserted into the dilution tunnel through a ¼" hole, and secured with metal stack tape. The sample line is 3 meters long and made of 3/8" OD (1/4" ID) conductive rubber tubing, with a short section of ¼" OD aluminum tubing at the end for insertion into the tunnel ~ 20 cm above the ports for the 5G filter samples.

9.3 Operation

The Aethalometer operation is automatic except for filter tape advances. The system laptop displays the output of the Aethalometer, updated every 5 seconds. This is used to determine when the filter tape needs to be manually advanced. The Aethalometer serial port output is connected to the laptop, and REALTERM is used to display the data in real-time.

The Aethalometer data output format is as follows:

18-Jul-17, 15:17:40,1627119, 1.2, 0.0221, 1.0634, 0.0224, 3.3428, 1, **52.326**
date, time, BC, flow, sz, sb, rz, rb, FF, **ATN**

where BC is in $\mu g/m^3$, and flow is in LPM.

The value of interest for operation is the last entry, "ATN". This is used to determine when the tape must be advanced. Tape advances are performed manually to minimize data loss. When ATN reaches the trigger value (see below), the tape is advanced by pulling up on the optical head, pulling the tape using the take up spool, and releasing the head. Advance the tape at least 1 spot's worth so spots do not overlap. The tape should be advanced immediately after the data display updates. This gives the instrument a few seconds to stabilize before the start of next 5-second data interval. The first reading after a tape advance is a large negative number; this is normal.

It is important to not let ATN exceed 145, since at 150 an automatic tape advance is triggered, resulting in ~ 3 minutes of lost data. When BC concentrations are high, ATN can jump as much as 20 units in a single 5-second interval. In this situation, the tape should be advanced when ATN exceeds 100 to 120. When BC is lower, ATN can get somewhat higher if needed, but in general should not exceed ~ 120.

If an automatic tape advance is triggered, remove the sample line from the instrument inlet to avoid filter overload during stabilization after the automatic tape advance. Once the instrument is reporting 5-second data again, connect the sample line back to the instrument.

Note: sometimes the value of ATN after a tape advance is negative. Small (< 10) negative ATN values are not a problem, but larger values mean that the reported ATN is too low, and the tape advance should be done at a lower reported ATN, corrected for the negative initial value so the net ATN value is less than ~ 120. Example: if the initial ATN after a tape advance is -60, the tape should be advanced when ATN reaches ~ 120-60, or 60.

9.4 Determining when to end BC measurements

Towards the end of the low-fire burn, PM and BC become very low, and BC measurements can be stopped before the actual end of the test. The criteria for end of test for BC is as follows.

1. At least 80% of the low-fire load mass has been burned (based on scale weight).
2. The pDR PM is less than 2 mg/m^3 (2000 $\mu g/m^3$)
3. The BC ATN value is increasing less than 2 units per minute.

Once all 3 of these criteria are met, BC measurements can be stopped. An exception to these criteria is when HLS staff are leaving the lab for the night while the low fire burn continues; in this case BC measurements are stopped at that time regardless of these criteria.

9.5 Shutdown

At the end of the run day, simply turn off the instrument and remove the sample line from the tunnel. Turn the Aethalometer off, and remove the CF data card from it (the instrument MUST be off to do this). Download the day's data onto the laptop using the CF card reader (copy all files with today's date). Do not erase any files on the CF card. Put the CF card back into the Aethalometer. Leave it off, and leave the laptop on.

9.6 NESCAUM point of contact

To minimize data loss, the instrument operator should contact Nescaum when any problems or questions arise. Call George Allen (gallen@nescaum.org) at 617-259-2035 (w) or 781-592-7756 (h) immediately.

10.0 DATA AND RECORDS MANAGEMENT

The following records shall be maintained for the BC Instrument:

- The instrument operator enters time and flow check information into the "NESCAUM Dilution Tunnel Aethalometer BC Operating Checklist" log sheet for each day of operation
- NESCAUM staff will reviewed data on a regular basis.
- Copies of all instrument log sheets are maintained by the instrument operator and forwarded to NESCAUM staff on a weekly basis.

11.0 QUALITY CONTROL AND QUALITY ASSURANCE

- Quality Control procedures include the completion of any required flow checks, external flow verifications, and any required maintenance.

The NESCAUM acceptance criteria for BC valid sample data are as follows:

ITEM	Frequency	Acceptance Criteria
Instrument date and time	Start of each run day	5 seconds of lab time
Flow check	Start of each run day	0.60 to 0.75 SLPM

12.0 AUTHORS

George Allen, NESCAUM

NESCAUM Dilution Tunnel Aethalometer BC Operating Checklist Version 1.0, December 28, 2017

Date:										
Operator initials:										

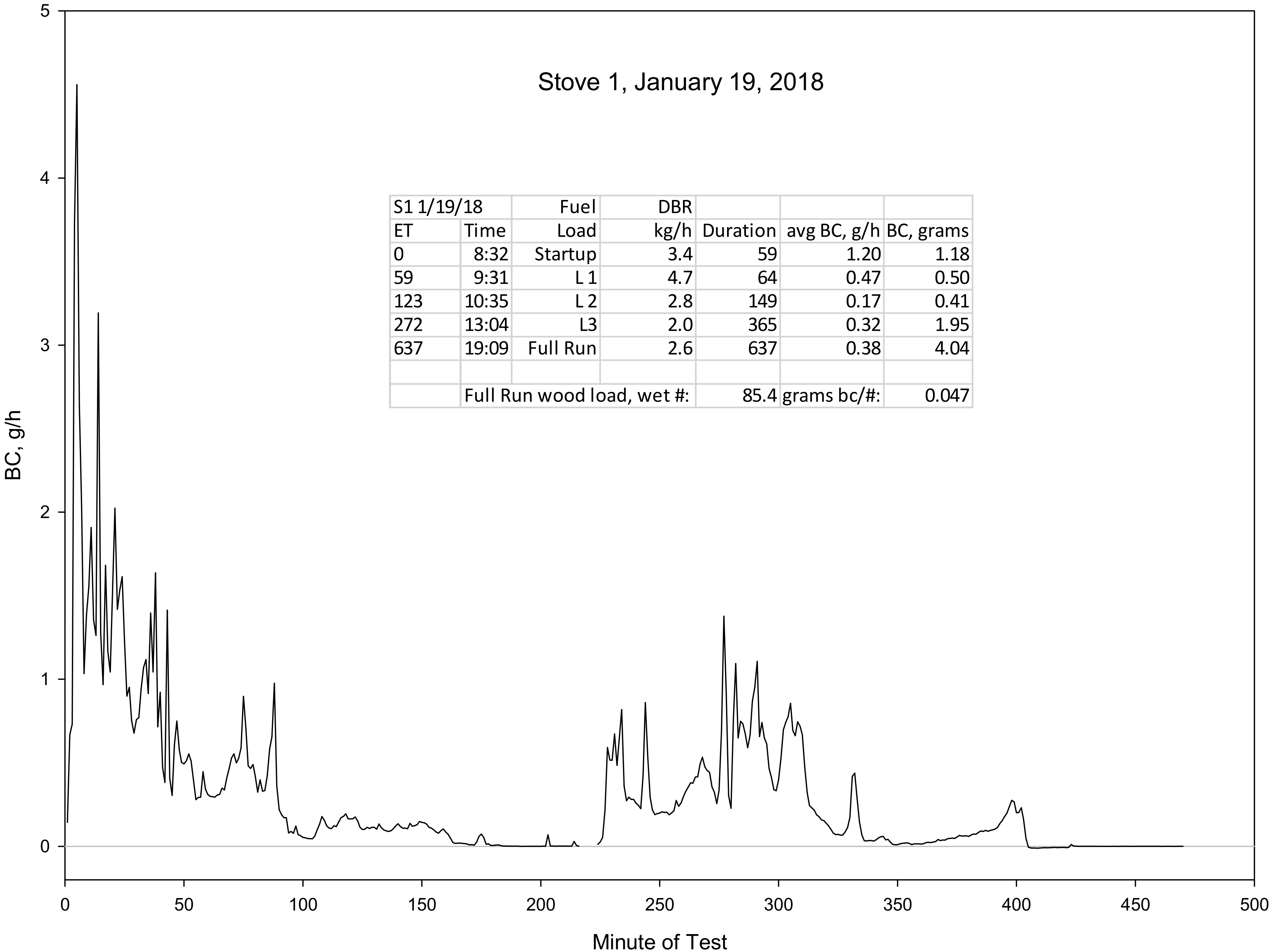
Aeth time set to lab time (✓)										
Flow check with TSI flowmeter:										
TSI Flow meter zero (slpm)										
Aeth inlet flow (slpm)										

Inlet removed from tunnel										
Copy CF card data to laptop										

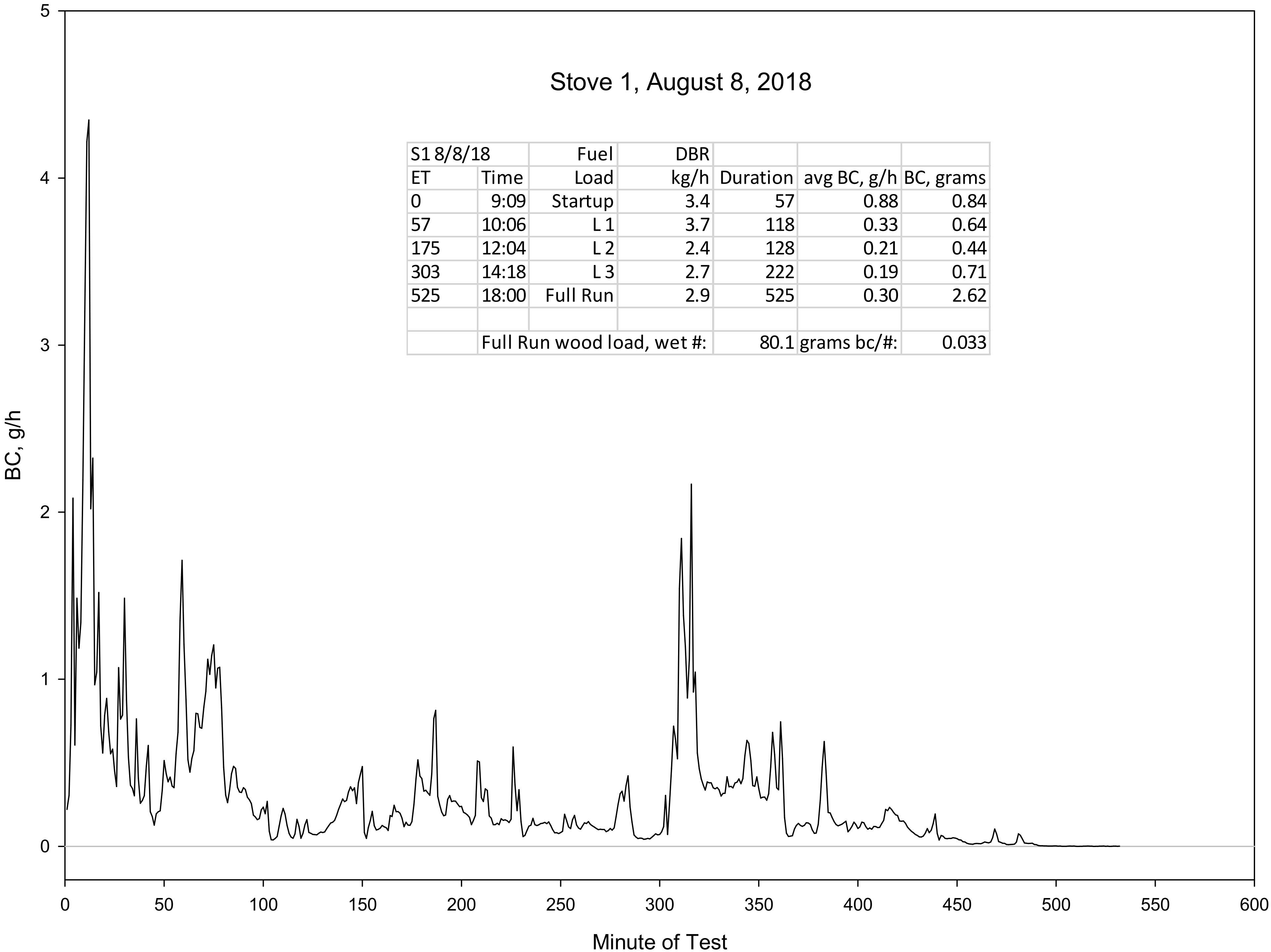
Notes:

Appendix C: Time series and box plots of BC. Each test run has an individual time series plot.

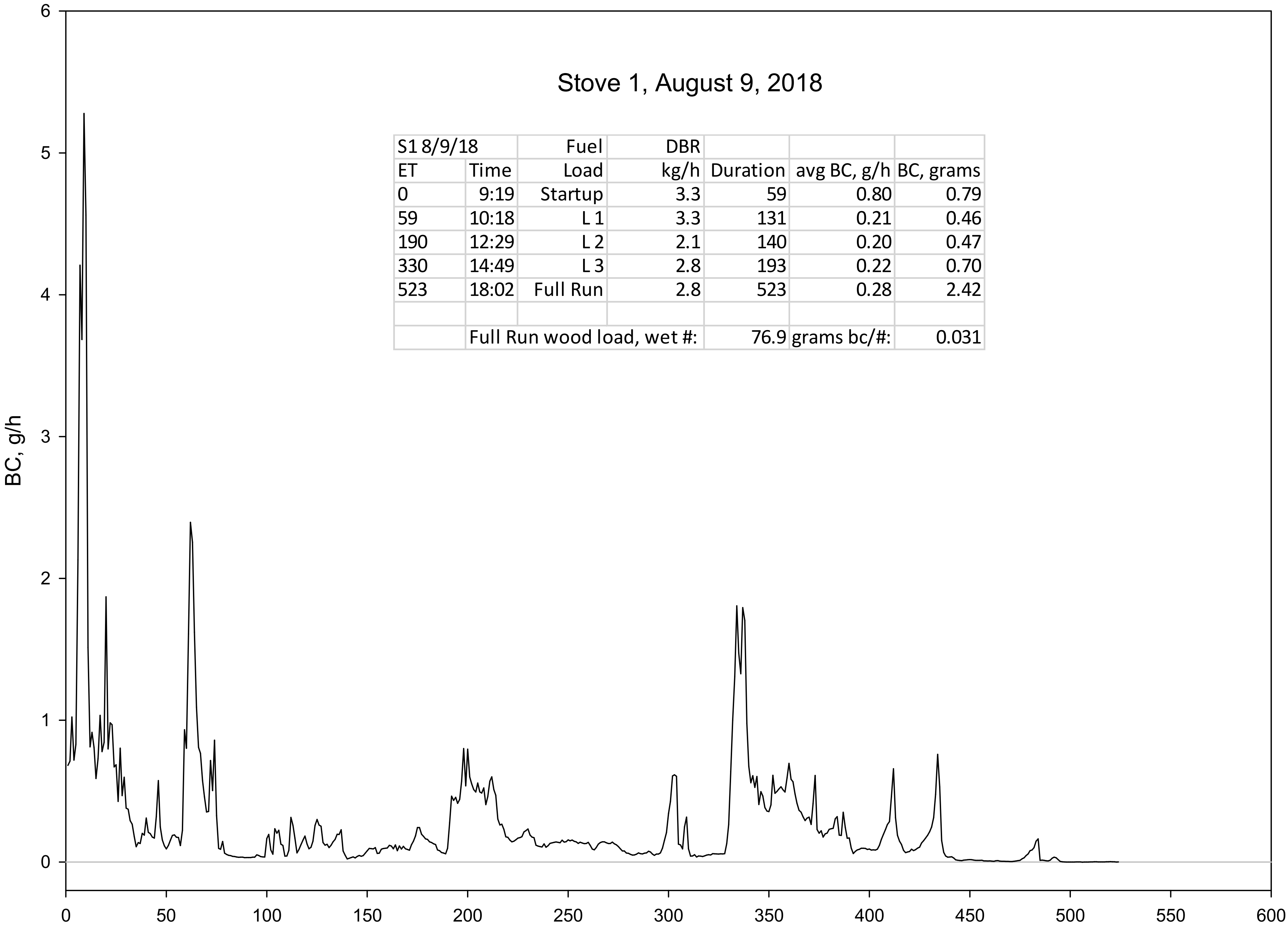
For stoves with multiple runs, time series plots are included that combine all runs from that stove. Box plots are shown comparing replicate runs for stoves with more than one run. Stoves with a single run are shown together on a single box plot.



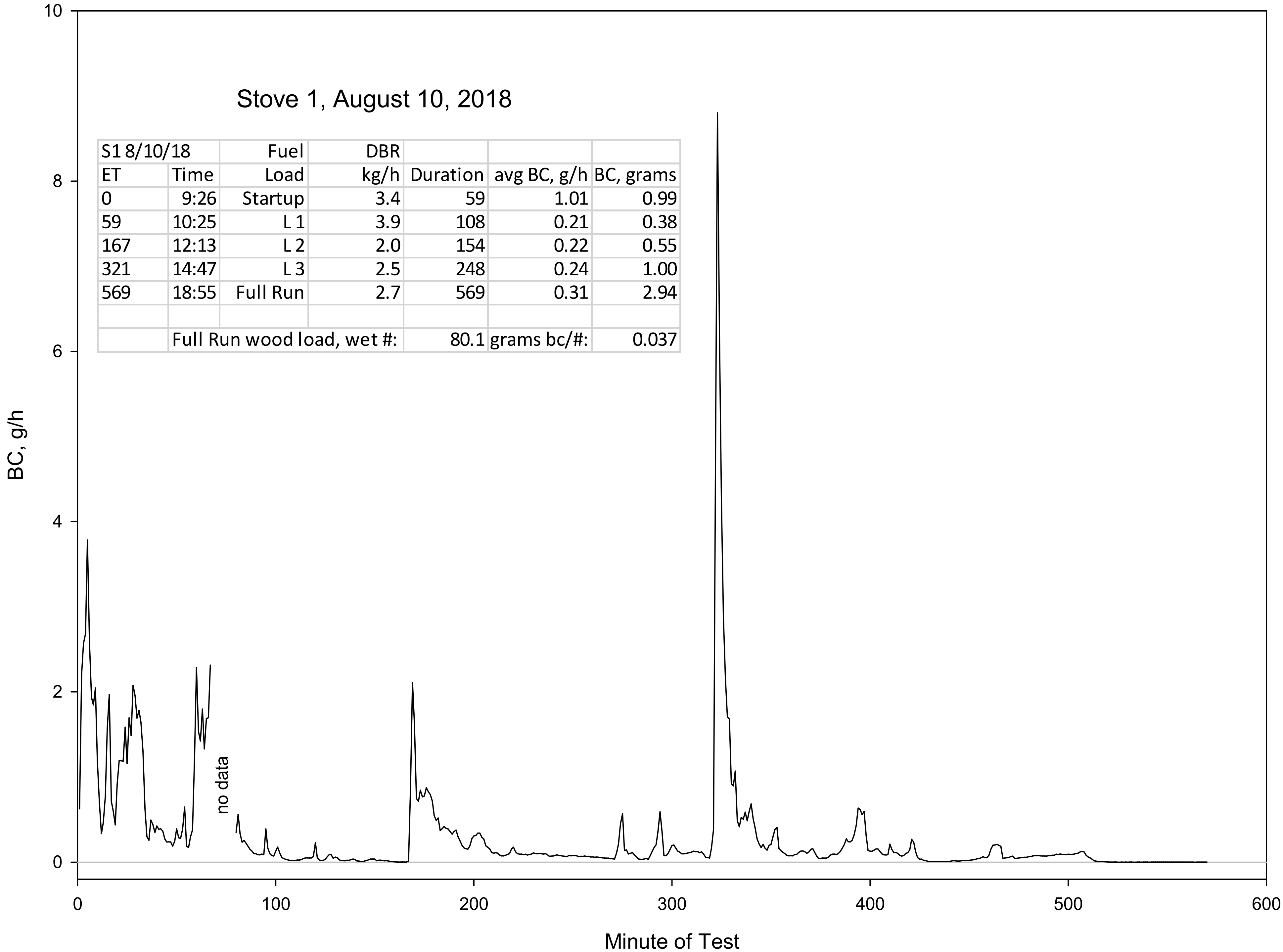
S1 1/19/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	8:32	Startup	3.4	59	1.20	1.18
59	9:31	L 1	4.7	64	0.47	0.50
123	10:35	L 2	2.8	149	0.17	0.41
272	13:04	L3	2.0	365	0.32	1.95
637	19:09	Full Run	2.6	637	0.38	4.04
	Full Run wood load, wet #:			85.4	grams bc/#:	0.047



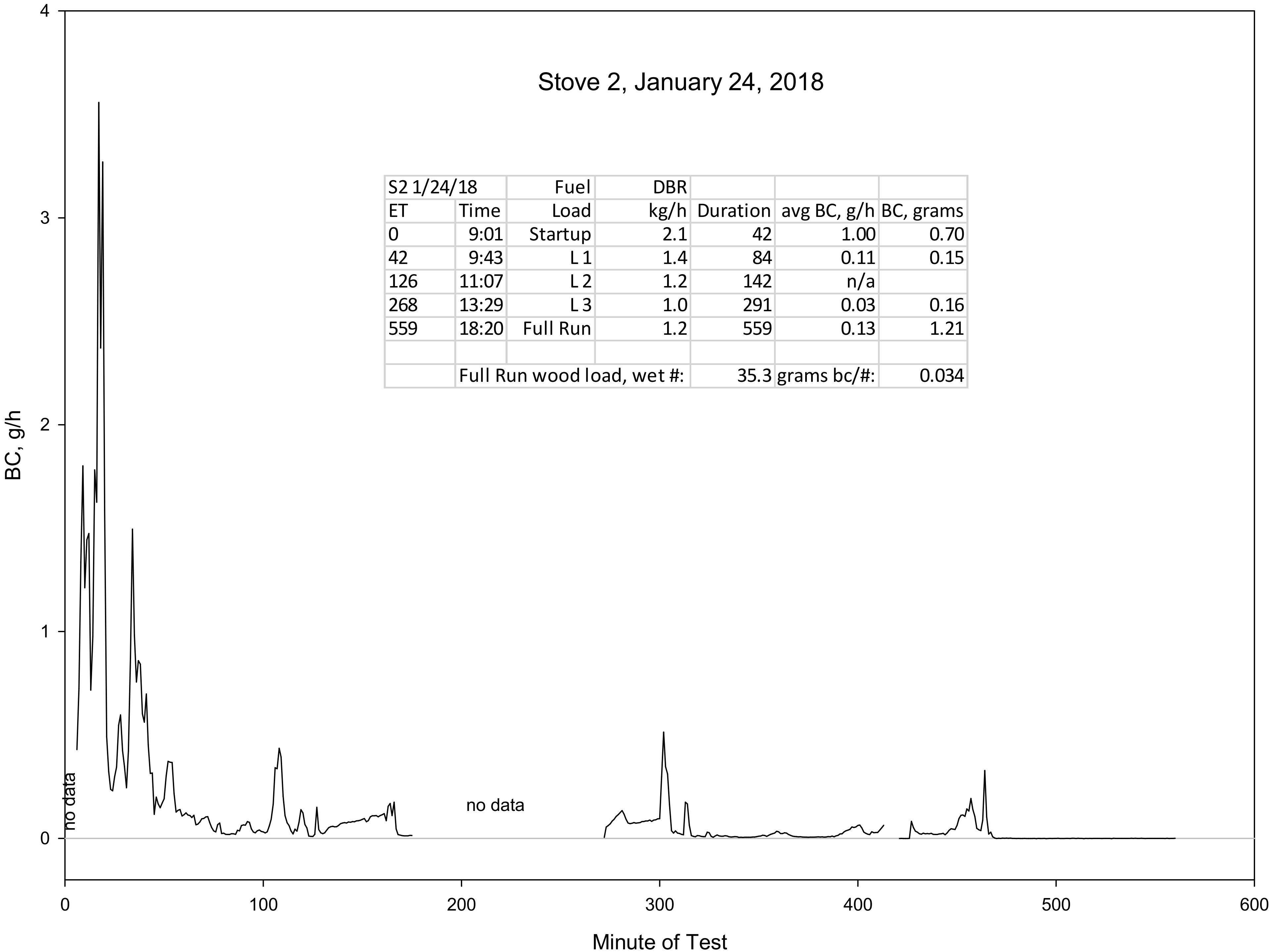
S1 8/8/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:09	Startup	3.4	57	0.88	0.84
57	10:06	L 1	3.7	118	0.33	0.64
175	12:04	L 2	2.4	128	0.21	0.44
303	14:18	L 3	2.7	222	0.19	0.71
525	18:00	Full Run	2.9	525	0.30	2.62
	Full Run wood load, wet #:			80.1	grams bc/#:	0.033



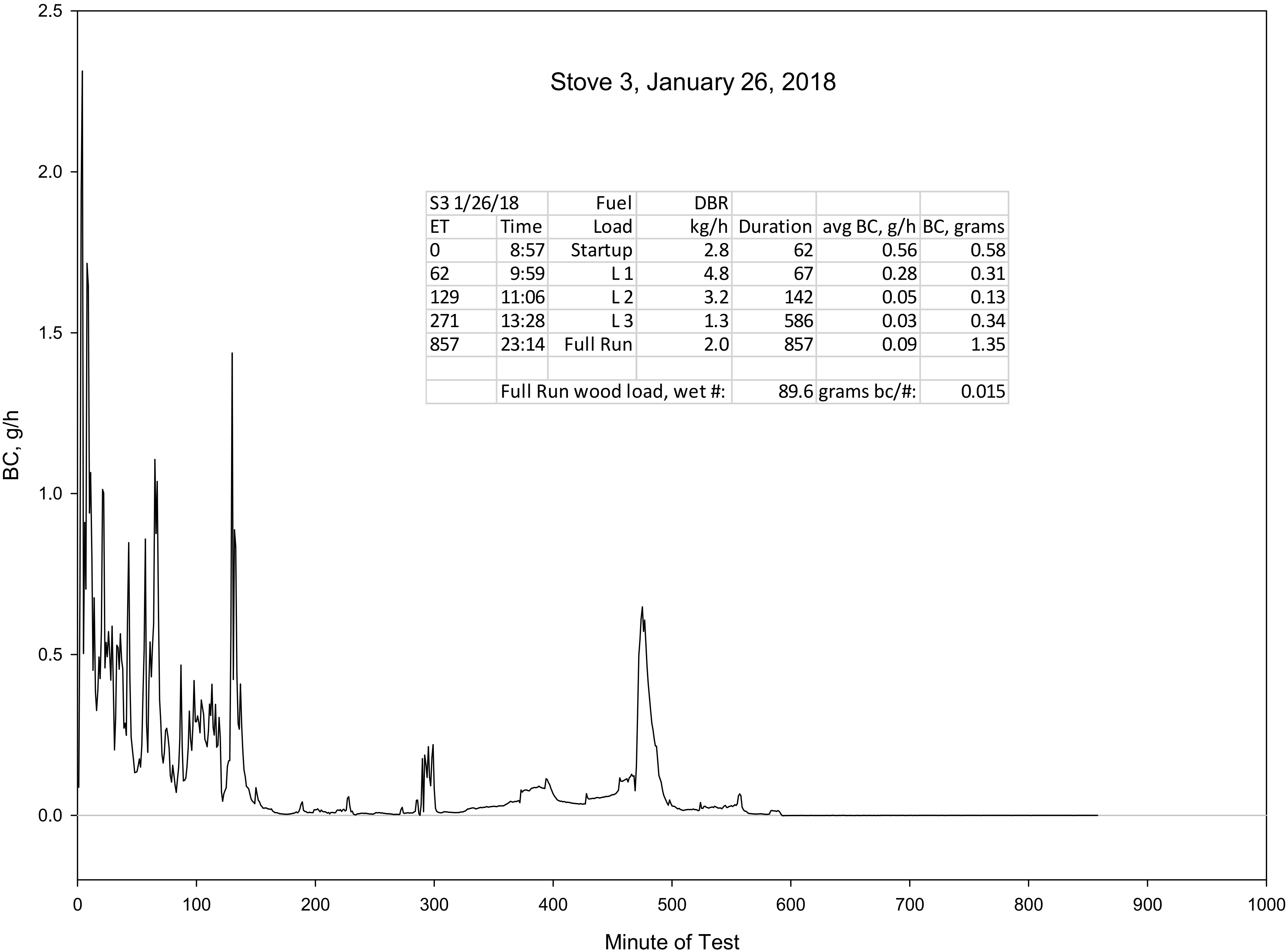
S1 8/9/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:19	Startup	3.3	59	0.80	0.79
59	10:18	L 1	3.3	131	0.21	0.46
190	12:29	L 2	2.1	140	0.20	0.47
330	14:49	L 3	2.8	193	0.22	0.70
523	18:02	Full Run	2.8	523	0.28	2.42
	Full Run wood load, wet #:			76.9	grams bc/#:	0.031



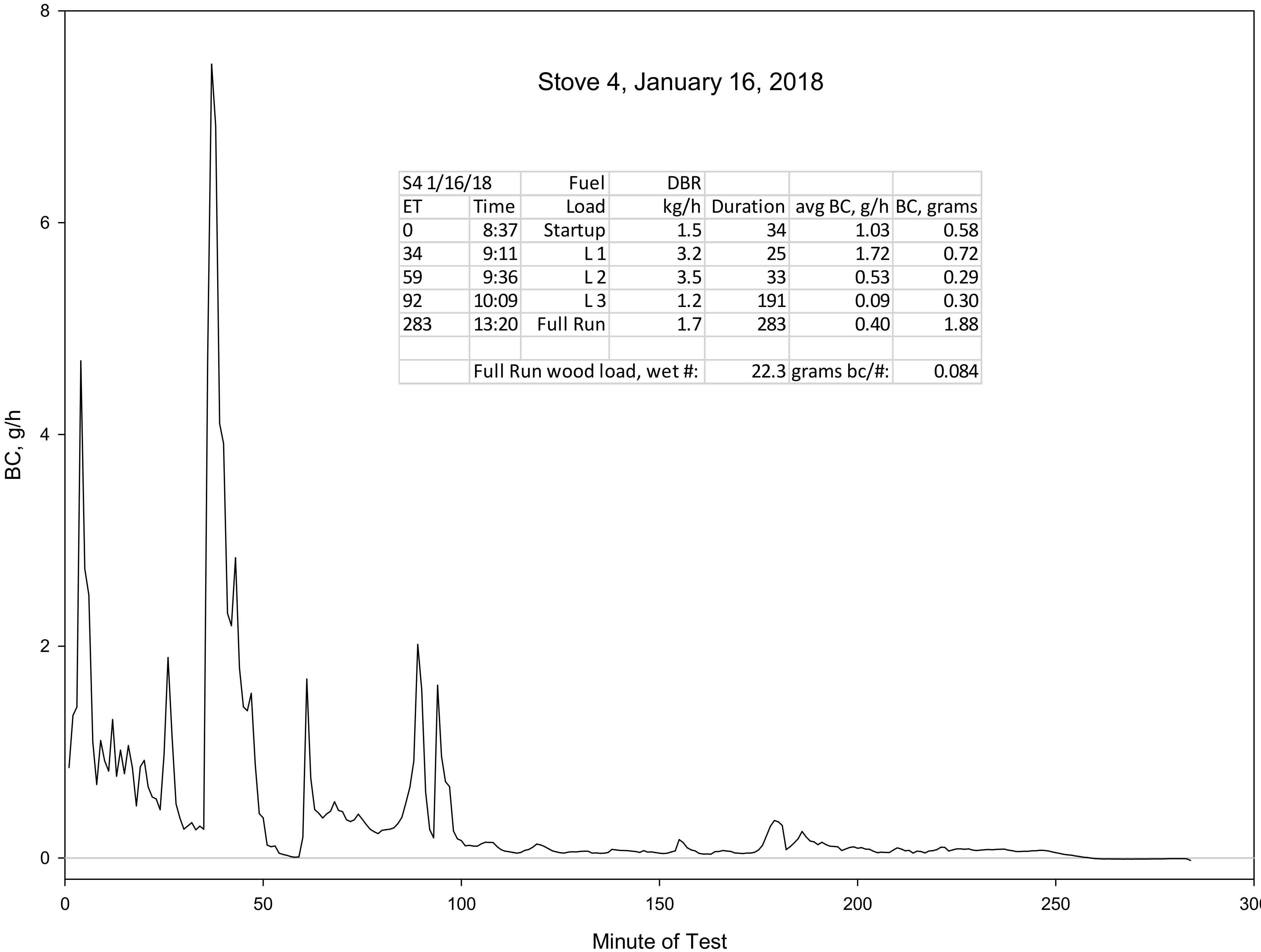
S1 8/10/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:26	Startup	3.4	59	1.01	0.99
59	10:25	L 1	3.9	108	0.21	0.38
167	12:13	L 2	2.0	154	0.22	0.55
321	14:47	L 3	2.5	248	0.24	1.00
569	18:55	Full Run	2.7	569	0.31	2.94
	Full Run wood load, wet #:			80.1	grams bc/#:	0.037



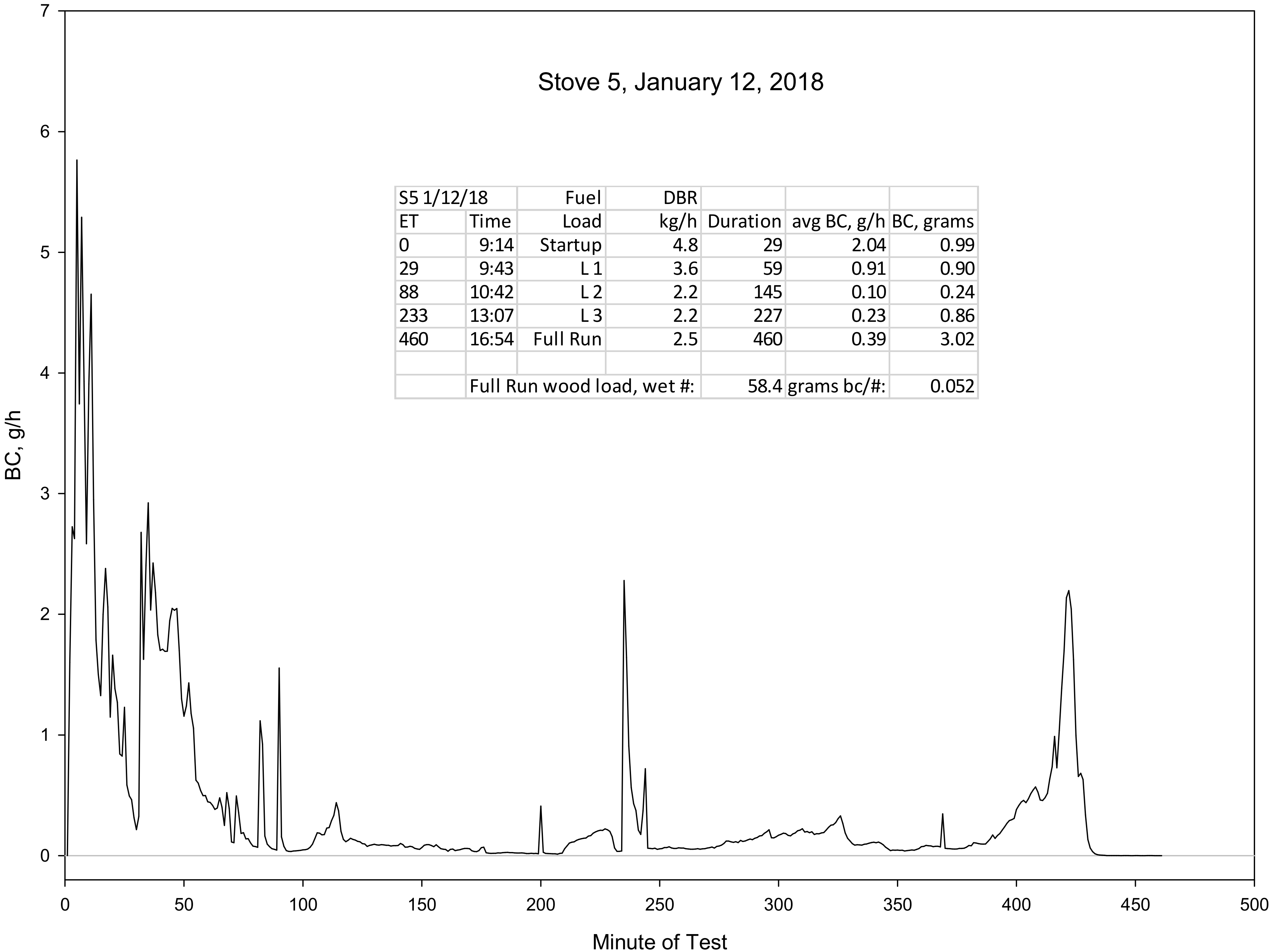
S2 1/24/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:01	Startup	2.1	42	1.00	0.70
42	9:43	L 1	1.4	84	0.11	0.15
126	11:07	L 2	1.2	142	n/a	
268	13:29	L 3	1.0	291	0.03	0.16
559	18:20	Full Run	1.2	559	0.13	1.21
	Full Run wood load, wet #:			35.3	grams bc/#:	0.034



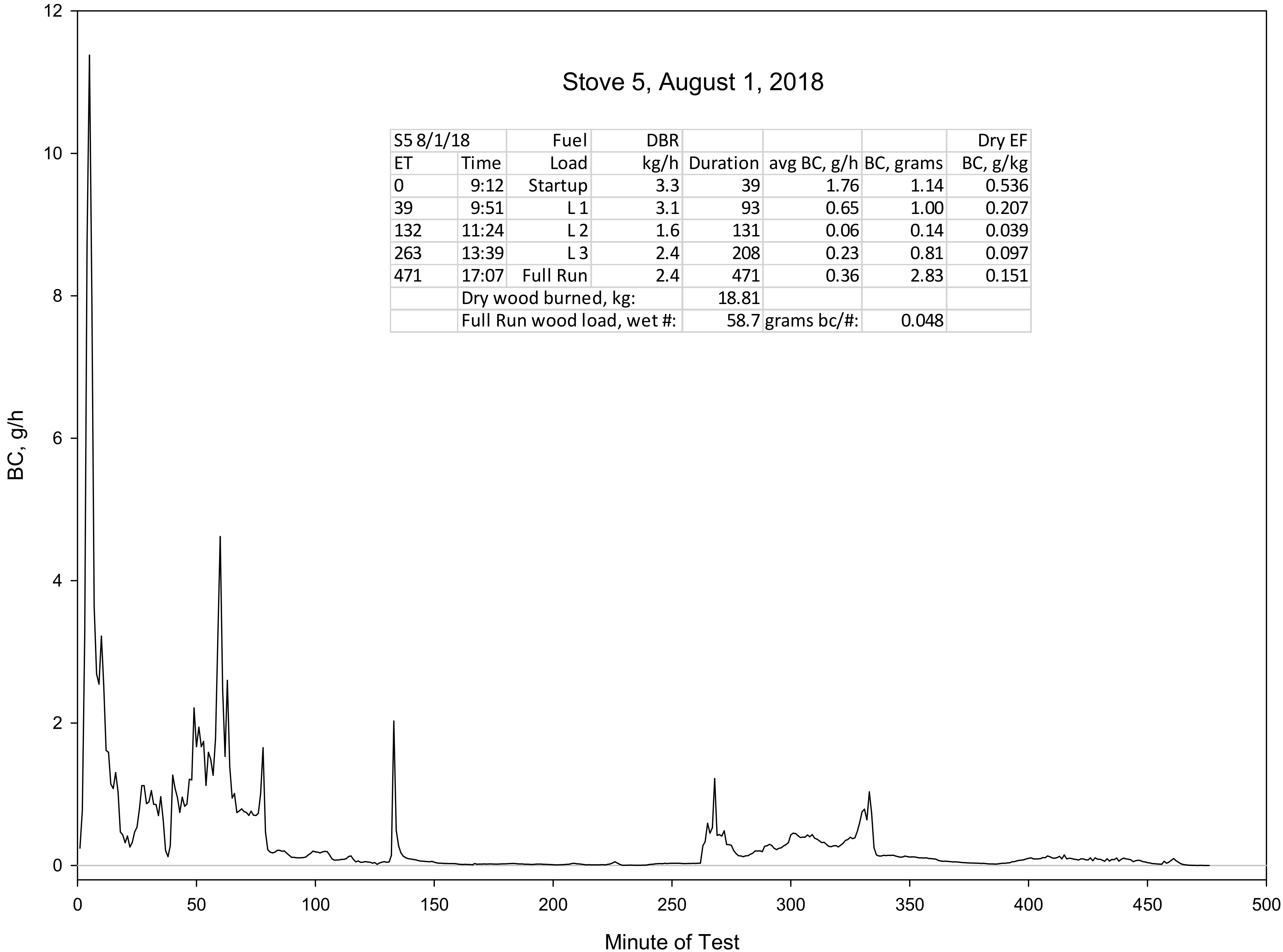
S3 1/26/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	8:57	Startup	2.8	62	0.56	0.58
62	9:59	L 1	4.8	67	0.28	0.31
129	11:06	L 2	3.2	142	0.05	0.13
271	13:28	L 3	1.3	586	0.03	0.34
857	23:14	Full Run	2.0	857	0.09	1.35
	Full Run wood load, wet #:			89.6	grams bc/#:	0.015



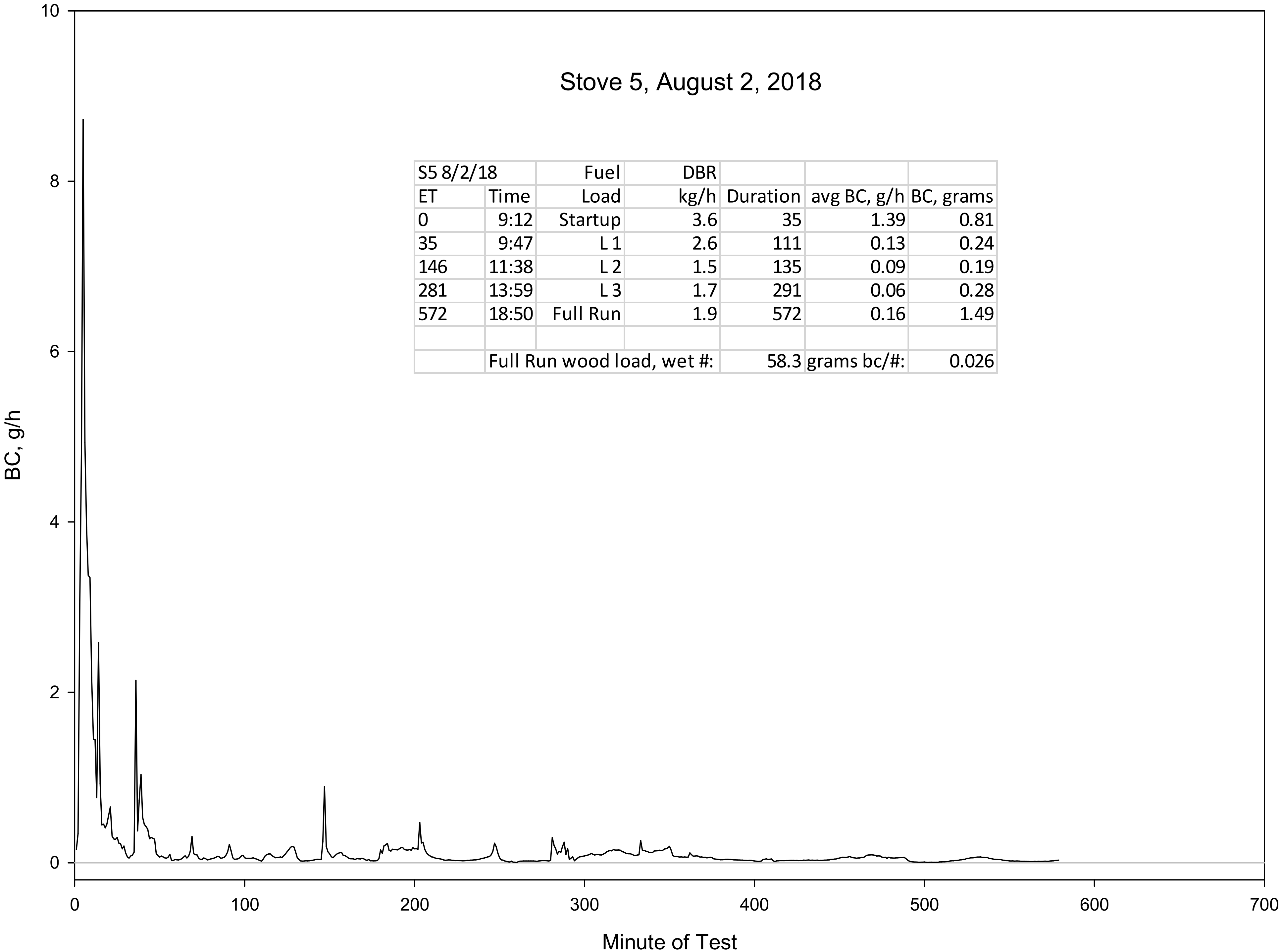
S4 1/16/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	8:37	Startup	1.5	34	1.03	0.58
34	9:11	L 1	3.2	25	1.72	0.72
59	9:36	L 2	3.5	33	0.53	0.29
92	10:09	L 3	1.2	191	0.09	0.30
283	13:20	Full Run	1.7	283	0.40	1.88
	Full Run wood load, wet #:			22.3	grams bc/#:	0.084



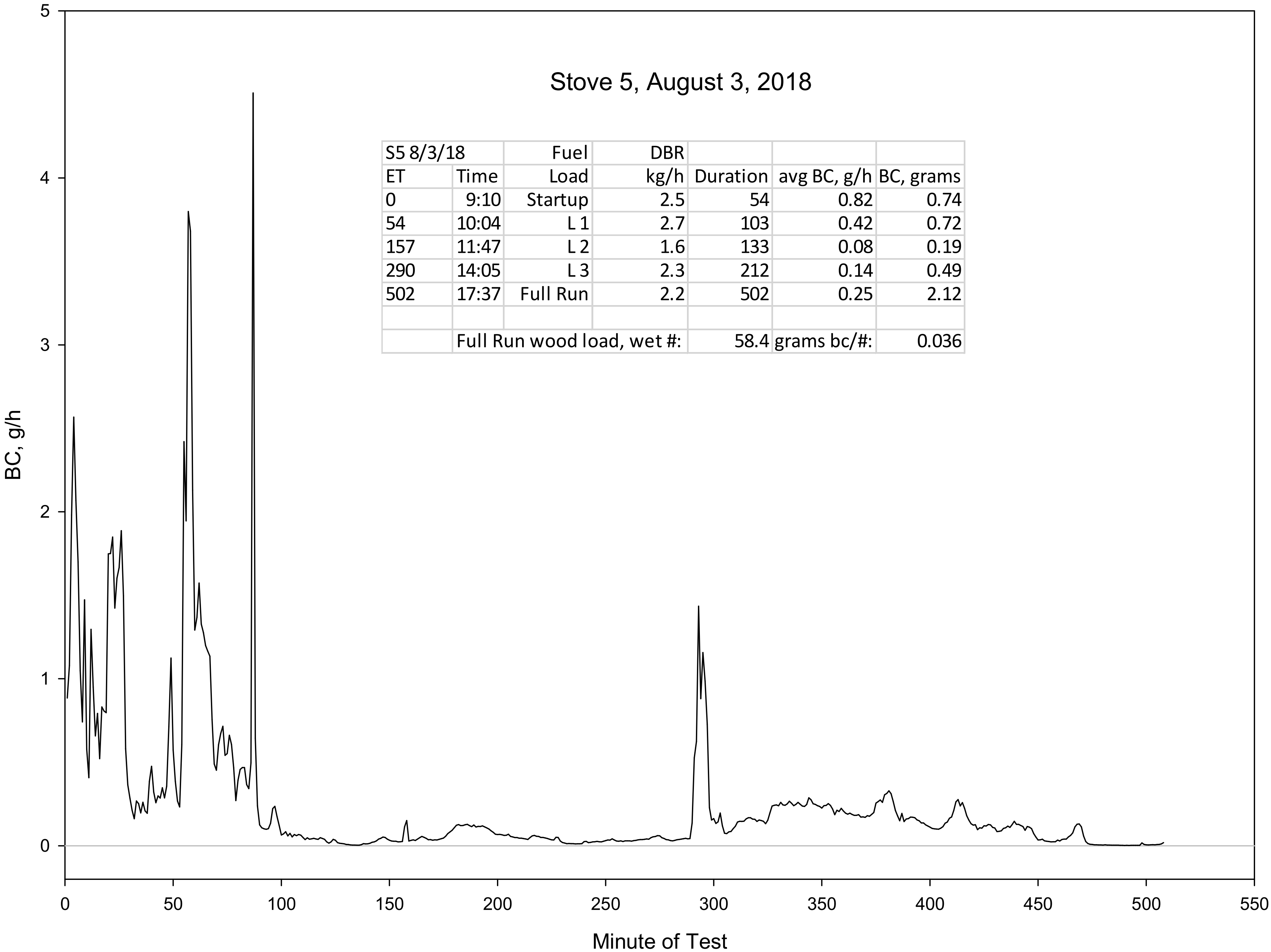
S5 1/12/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:14	Startup	4.8	29	2.04	0.99
29	9:43	L 1	3.6	59	0.91	0.90
88	10:42	L 2	2.2	145	0.10	0.24
233	13:07	L 3	2.2	227	0.23	0.86
460	16:54	Full Run	2.5	460	0.39	3.02
	Full Run wood load, wet #:			58.4	grams bc/#:	0.052



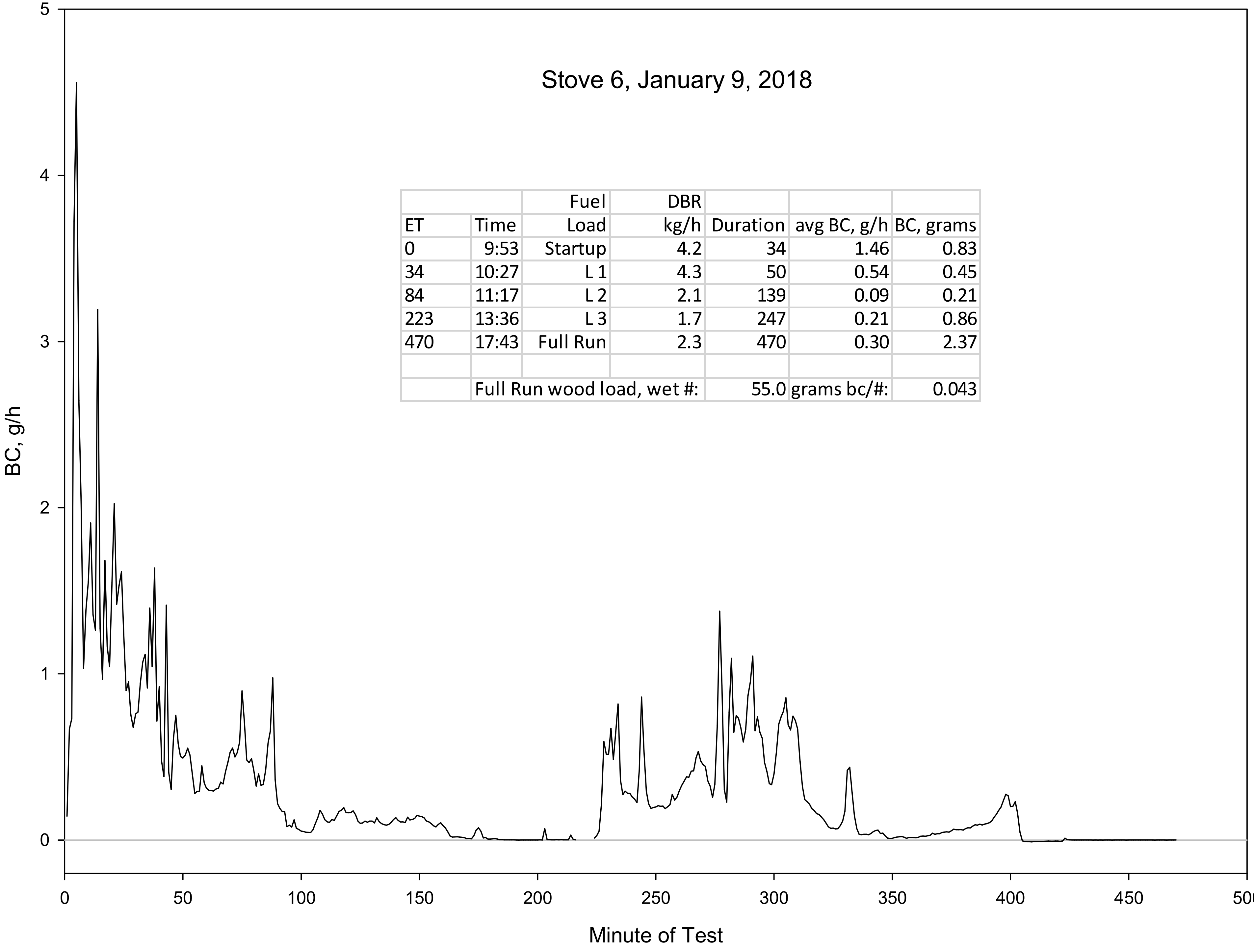
S5 8/1/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:12	Startup	3.3	39	1.76	1.14	0.536
39	9:51	L 1	3.1	93	0.65	1.00	0.207
132	11:24	L 2	1.6	131	0.06	0.14	0.039
263	13:39	L 3	2.4	208	0.23	0.81	0.097
471	17:07	Full Run	2.4	471	0.36	2.83	0.151
	Dry wood burned, kg:			18.81			
	Full Run wood load, wet #:			58.7	grams bc/#:	0.048	



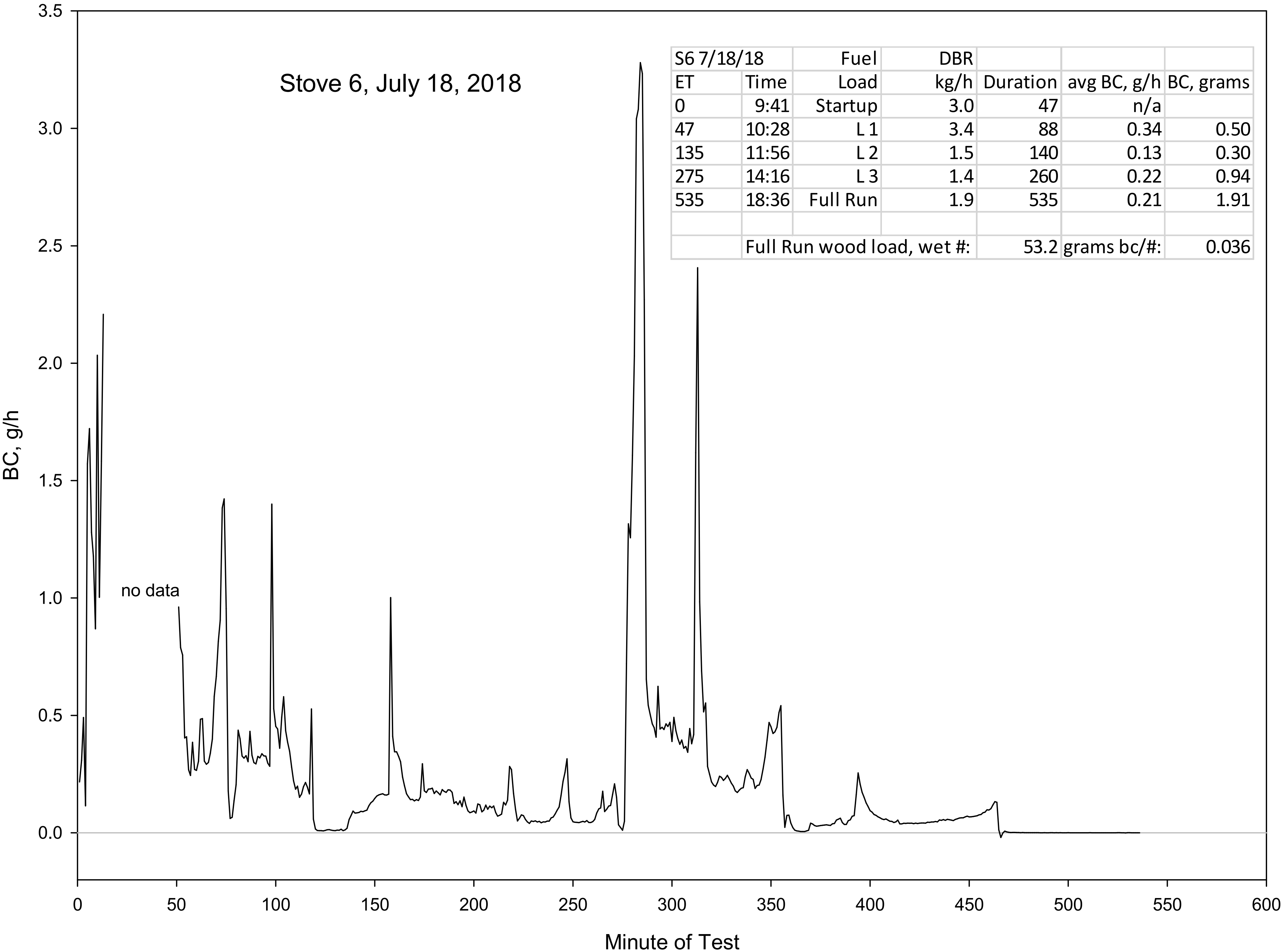
S5 8/2/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:12	Startup	3.6	35	1.39	0.81
35	9:47	L 1	2.6	111	0.13	0.24
146	11:38	L 2	1.5	135	0.09	0.19
281	13:59	L 3	1.7	291	0.06	0.28
572	18:50	Full Run	1.9	572	0.16	1.49
	Full Run wood load, wet #:			58.3	grams bc/#:	0.026



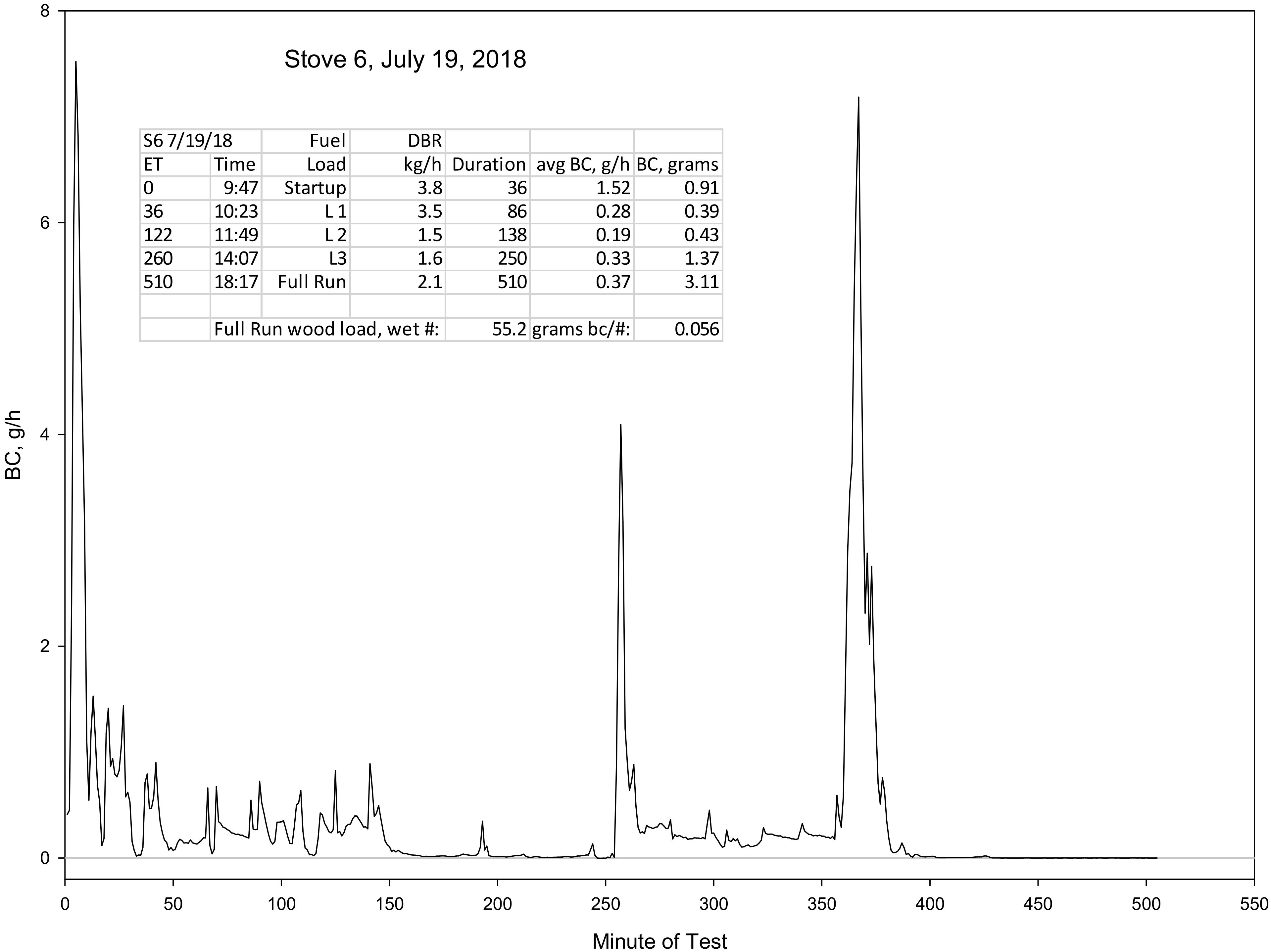
S5 8/3/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:10	Startup	2.5	54	0.82	0.74
54	10:04	L 1	2.7	103	0.42	0.72
157	11:47	L 2	1.6	133	0.08	0.19
290	14:05	L 3	2.3	212	0.14	0.49
502	17:37	Full Run	2.2	502	0.25	2.12
	Full Run wood load, wet #:			58.4	grams bc/#:	0.036



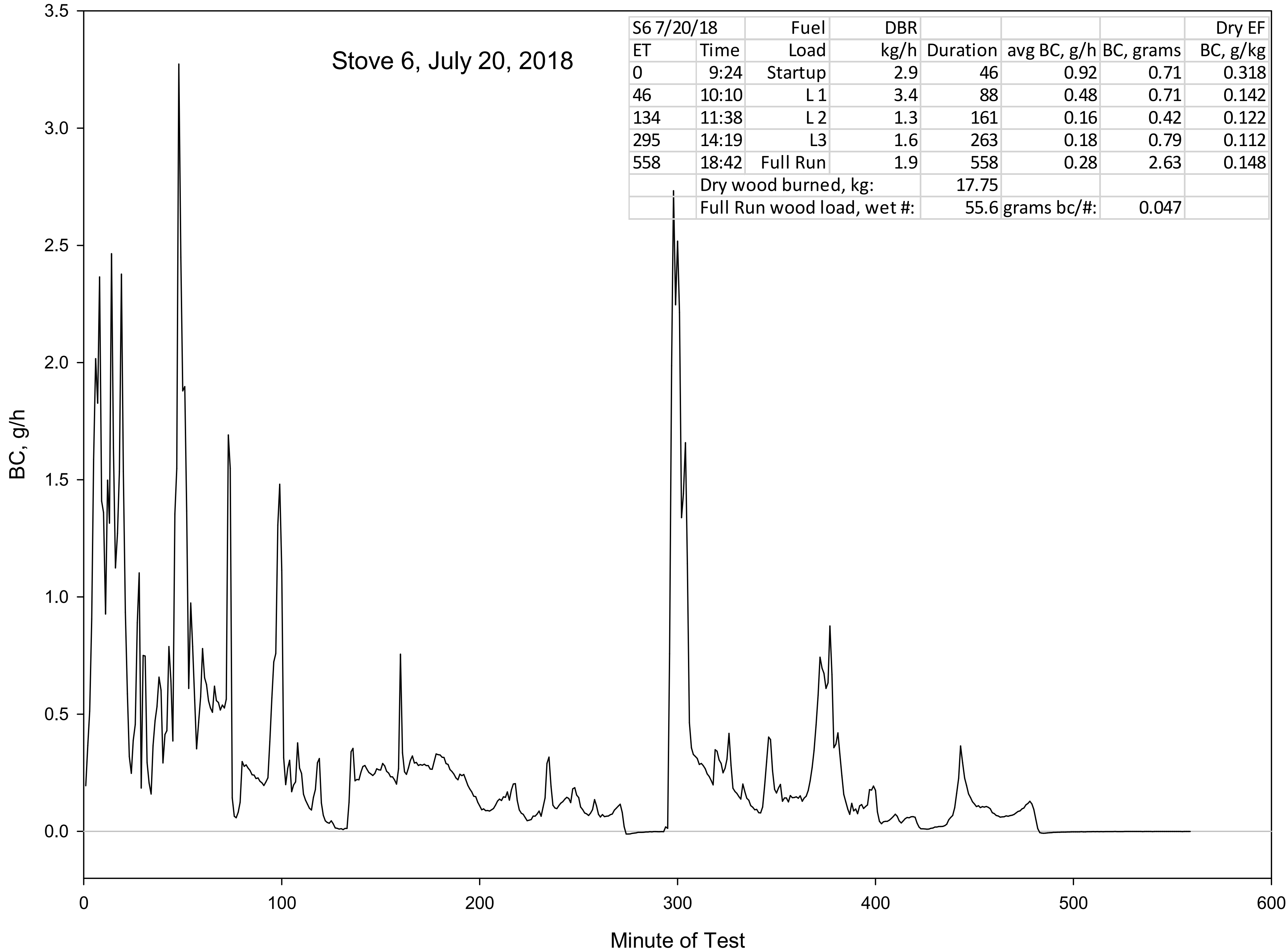
		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:53	Startup	4.2	34	1.46	0.83
34	10:27	L 1	4.3	50	0.54	0.45
84	11:17	L 2	2.1	139	0.09	0.21
223	13:36	L 3	1.7	247	0.21	0.86
470	17:43	Full Run	2.3	470	0.30	2.37
	Full Run wood load, wet #:			55.0	grams bc/#:	0.043



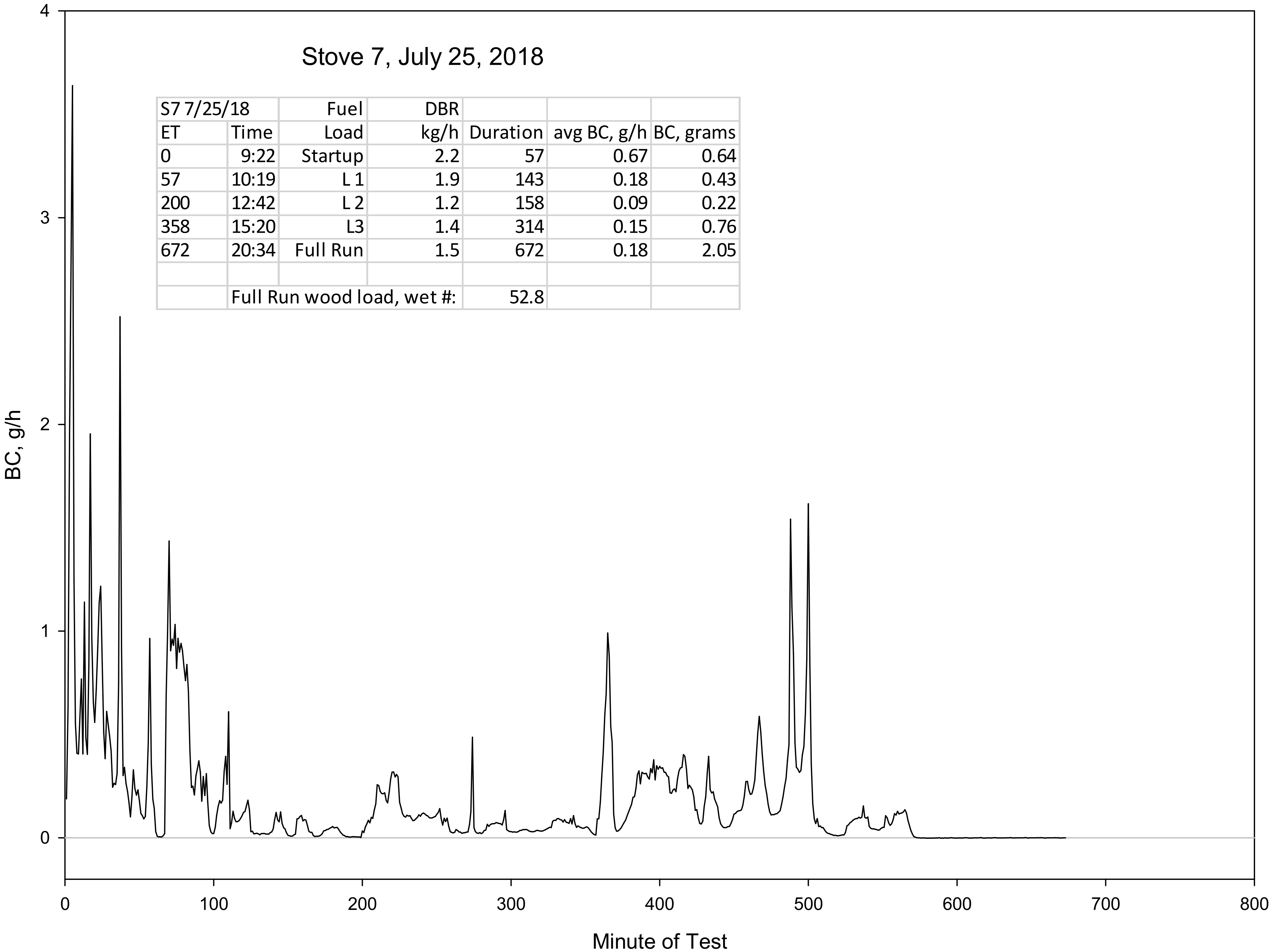
S6 7/18/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:41	Startup	3.0	47	n/a	
47	10:28	L 1	3.4	88	0.34	0.50
135	11:56	L 2	1.5	140	0.13	0.30
275	14:16	L 3	1.4	260	0.22	0.94
535	18:36	Full Run	1.9	535	0.21	1.91
	Full Run wood load, wet #:			53.2	grams bc/#:	0.036



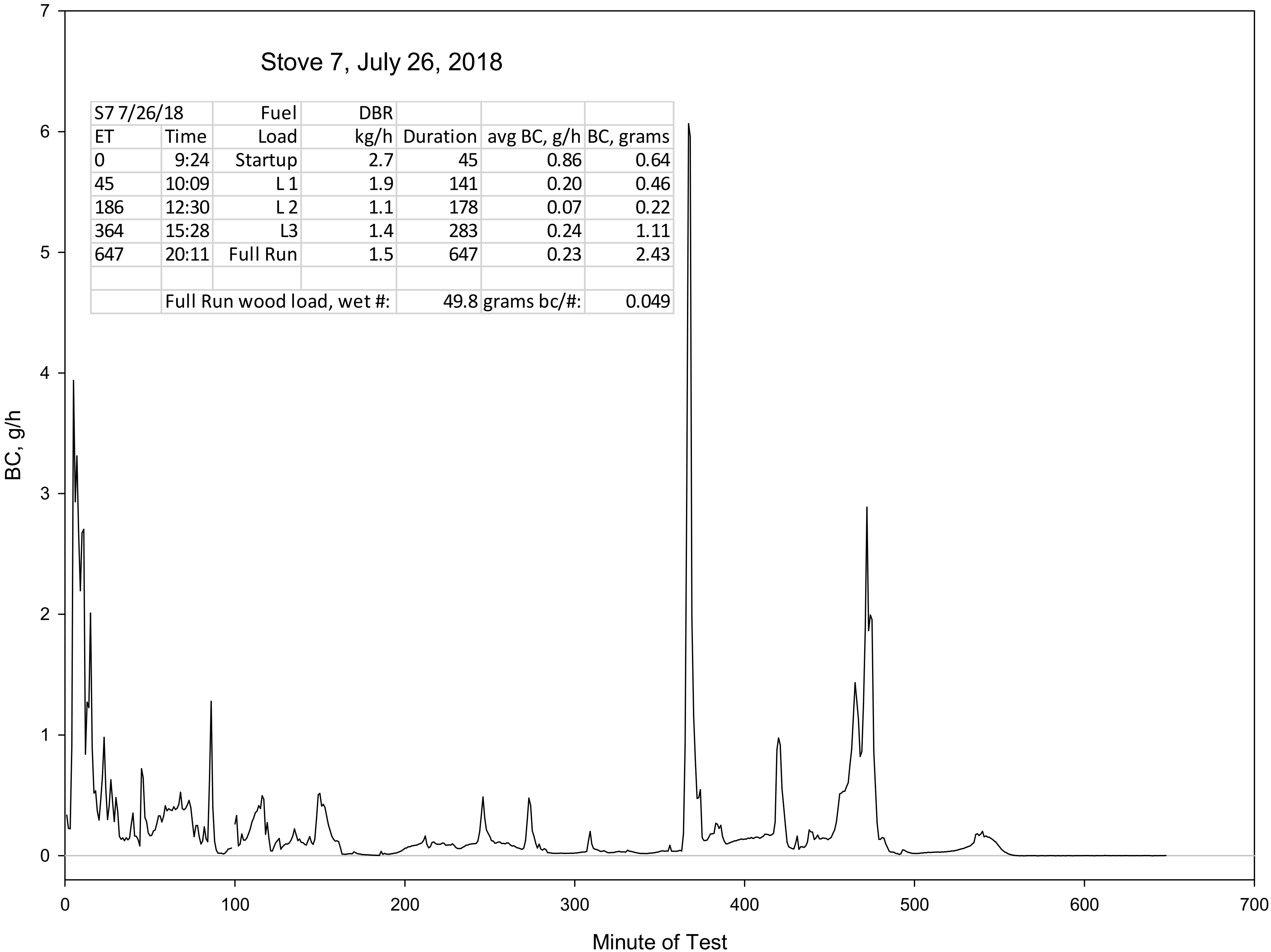
S6 7/19/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:47	Startup	3.8	36	1.52	0.91
36	10:23	L 1	3.5	86	0.28	0.39
122	11:49	L 2	1.5	138	0.19	0.43
260	14:07	L3	1.6	250	0.33	1.37
510	18:17	Full Run	2.1	510	0.37	3.11
	Full Run wood load, wet #:			55.2	grams bc/#:	0.056



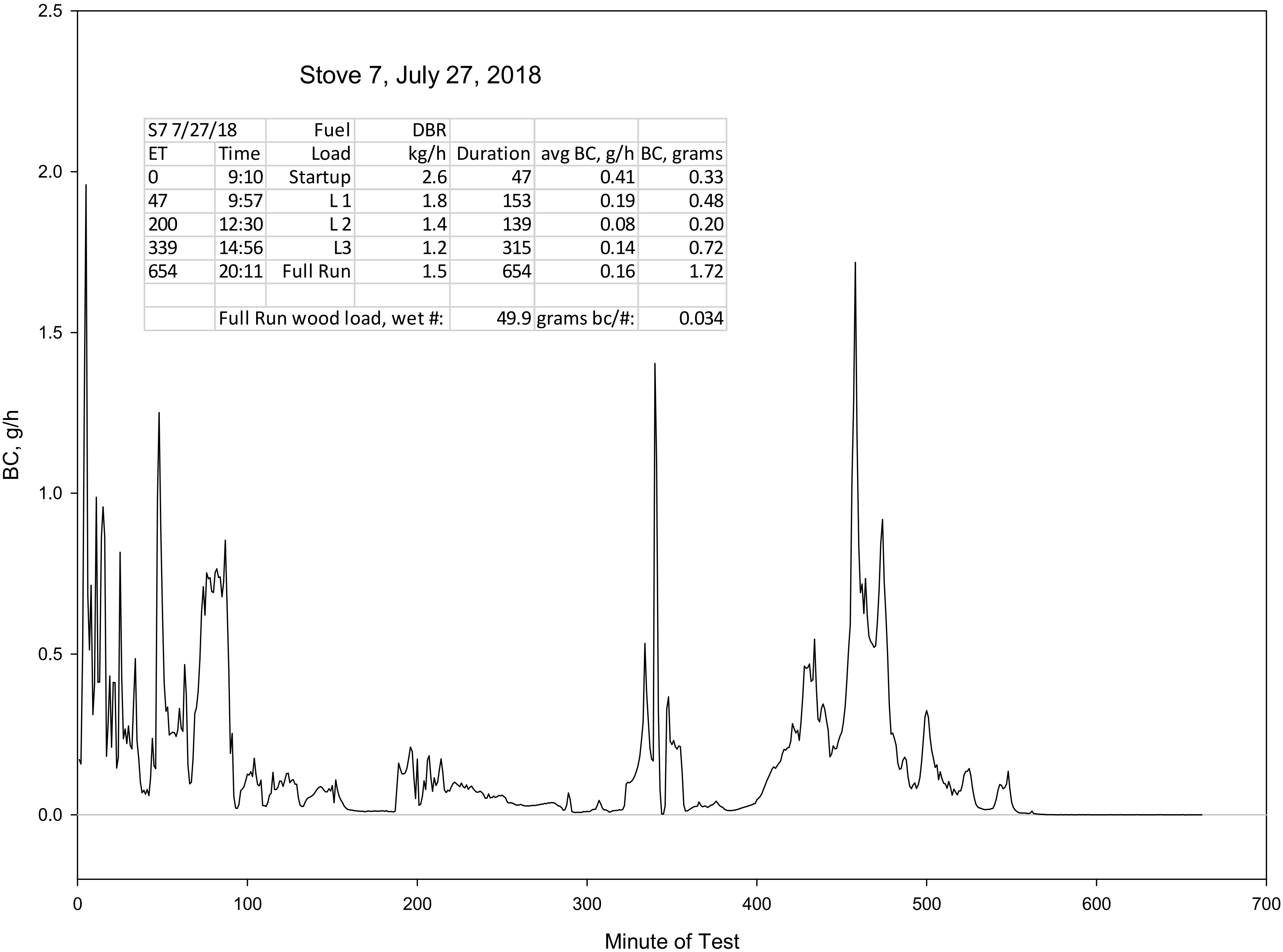
S6 7/20/18		Fuel	DBR				Dry EF
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams	BC, g/kg
0	9:24	Startup	2.9	46	0.92	0.71	0.318
46	10:10	L 1	3.4	88	0.48	0.71	0.142
134	11:38	L 2	1.3	161	0.16	0.42	0.122
295	14:19	L3	1.6	263	0.18	0.79	0.112
558	18:42	Full Run	1.9	558	0.28	2.63	0.148
	Dry wood burned, kg:			17.75			
	Full Run wood load, wet #:			55.6	grams bc/#:	0.047	



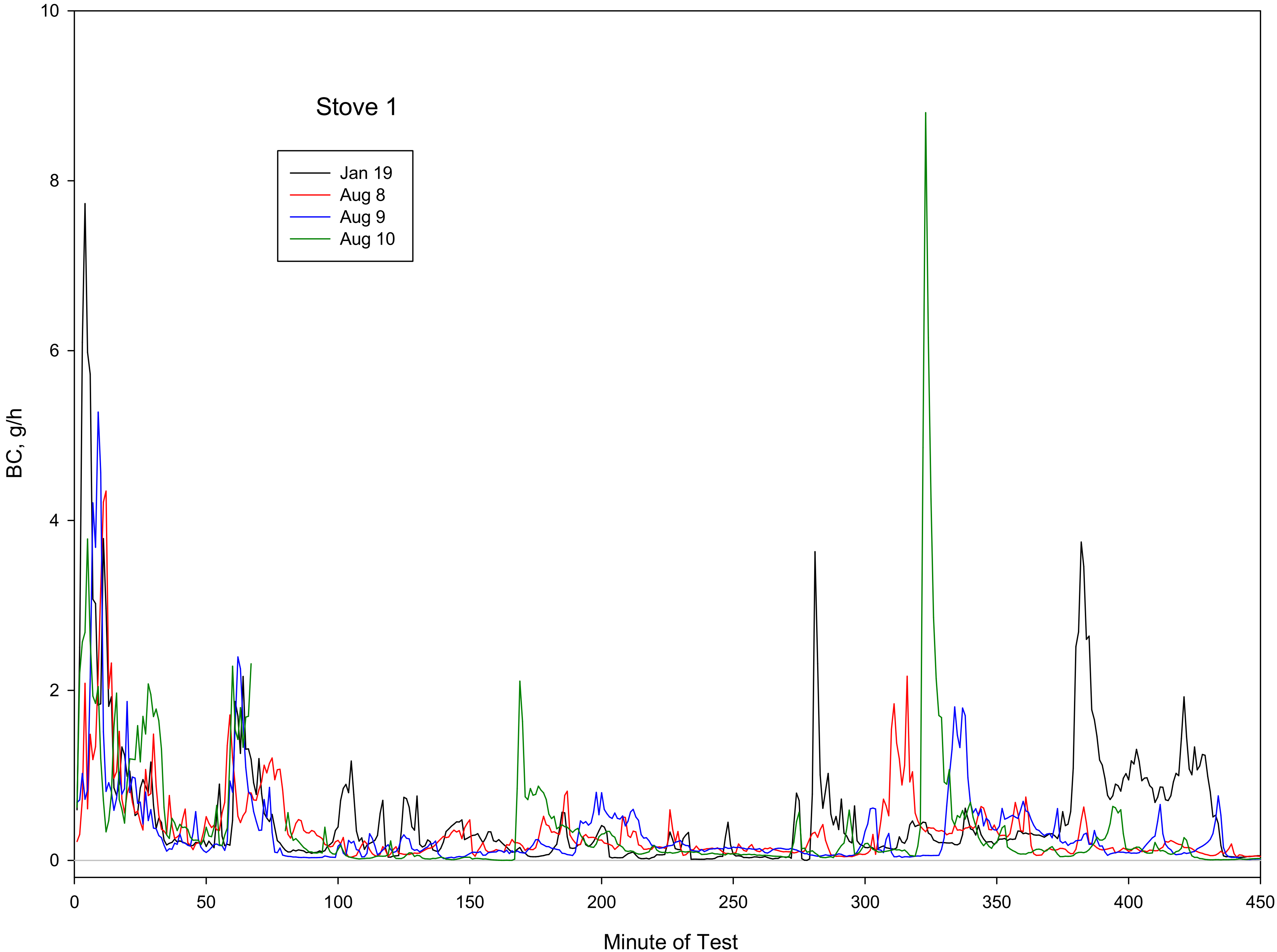
S7 7/25/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:22	Startup	2.2	57	0.67	0.64
57	10:19	L 1	1.9	143	0.18	0.43
200	12:42	L 2	1.2	158	0.09	0.22
358	15:20	L3	1.4	314	0.15	0.76
672	20:34	Full Run	1.5	672	0.18	2.05
	Full Run wood load, wet #:			52.8		

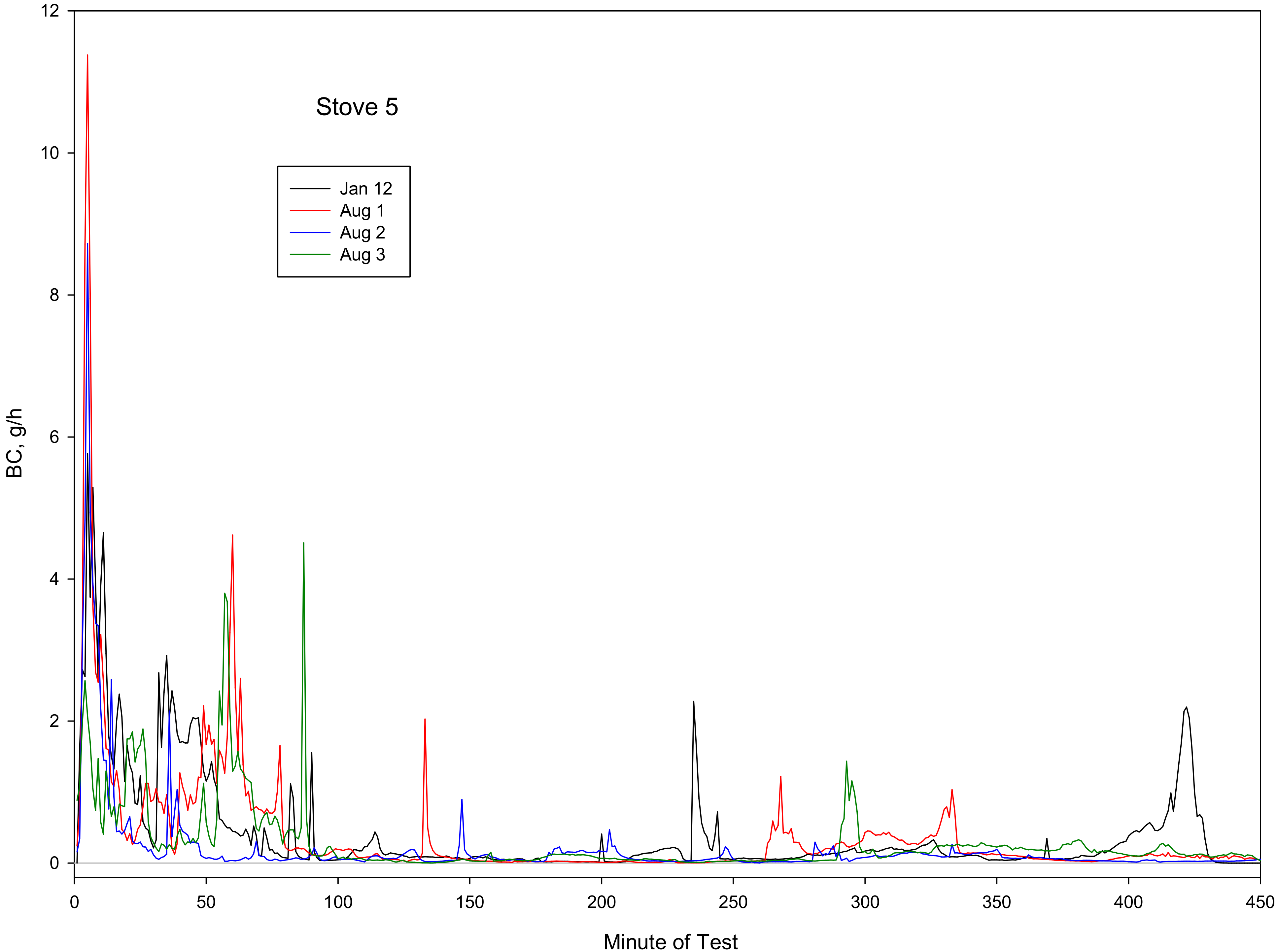


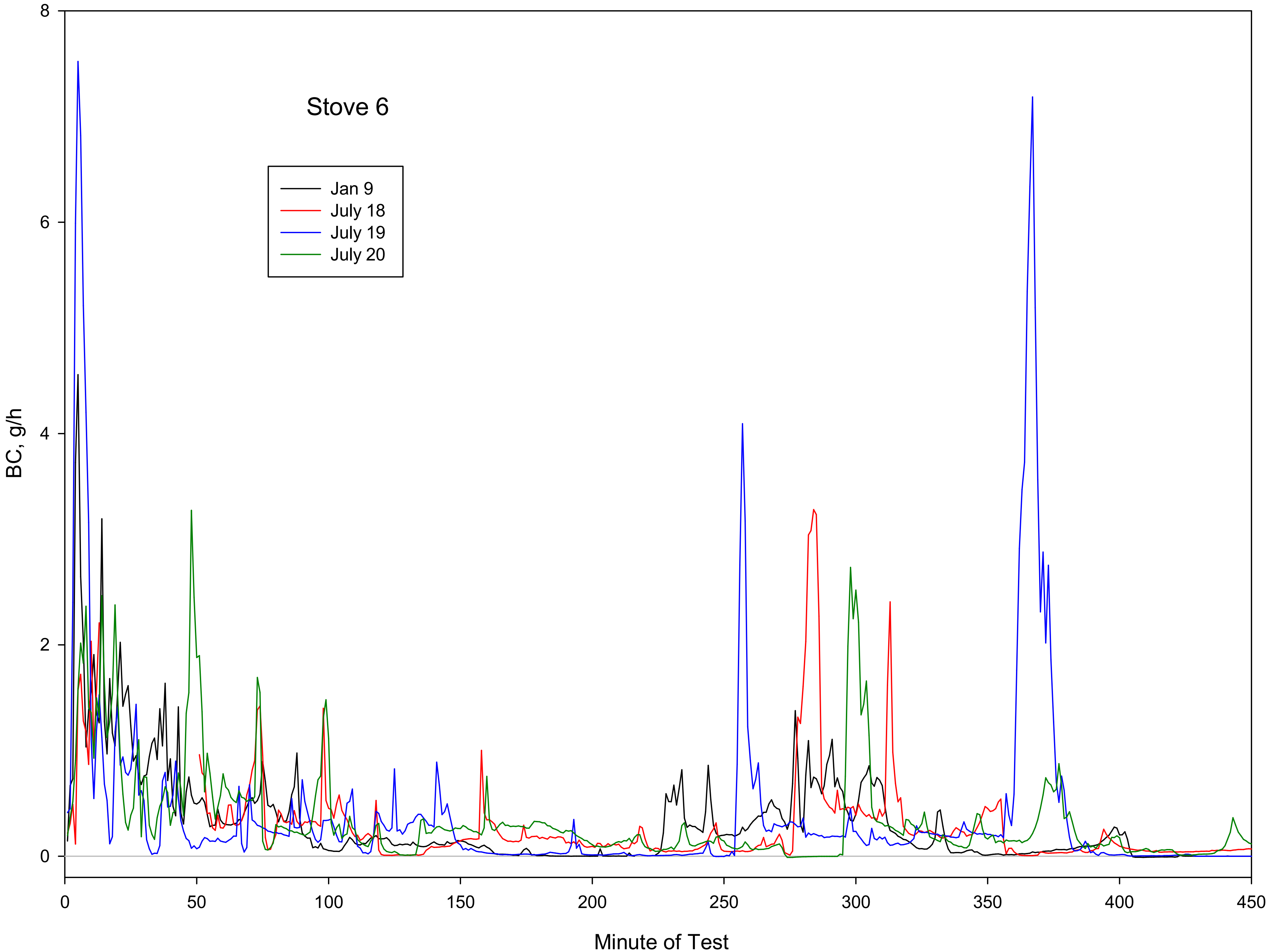
S7 7/26/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:24	Startup	2.7	45	0.86	0.64
45	10:09	L 1	1.9	141	0.20	0.46
186	12:30	L 2	1.1	178	0.07	0.22
364	15:28	L3	1.4	283	0.24	1.11
647	20:11	Full Run	1.5	647	0.23	2.43
	Full Run wood load, wet #:			49.8	grams bc/#:	0.049

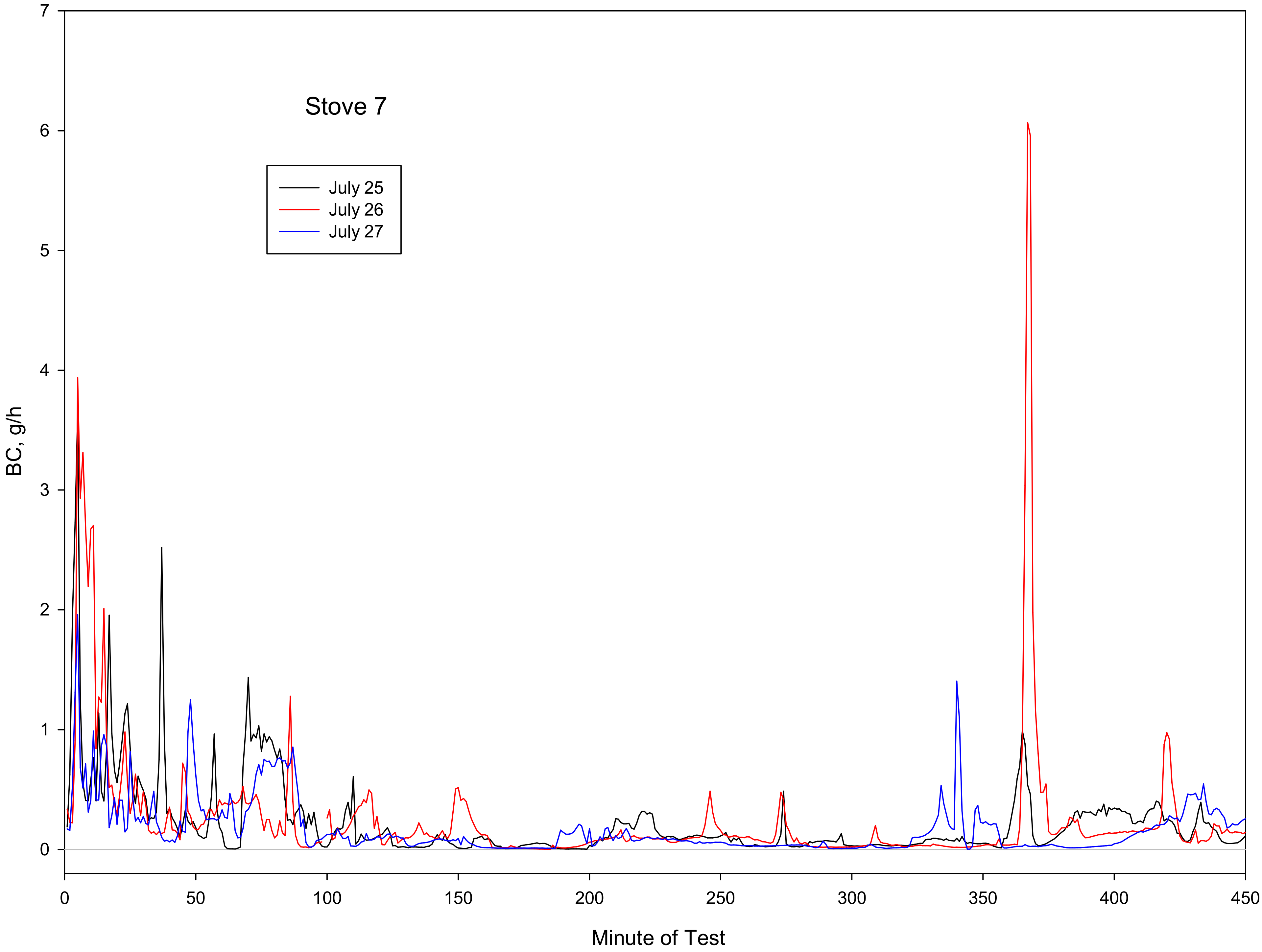


S7 7/27/18		Fuel	DBR			
ET	Time	Load	kg/h	Duration	avg BC, g/h	BC, grams
0	9:10	Startup	2.6	47	0.41	0.33
47	9:57	L 1	1.8	153	0.19	0.48
200	12:30	L 2	1.4	139	0.08	0.20
339	14:56	L3	1.2	315	0.14	0.72
654	20:11	Full Run	1.5	654	0.16	1.72
	Full Run wood load, wet #:			49.9	grams bc/#:	0.034

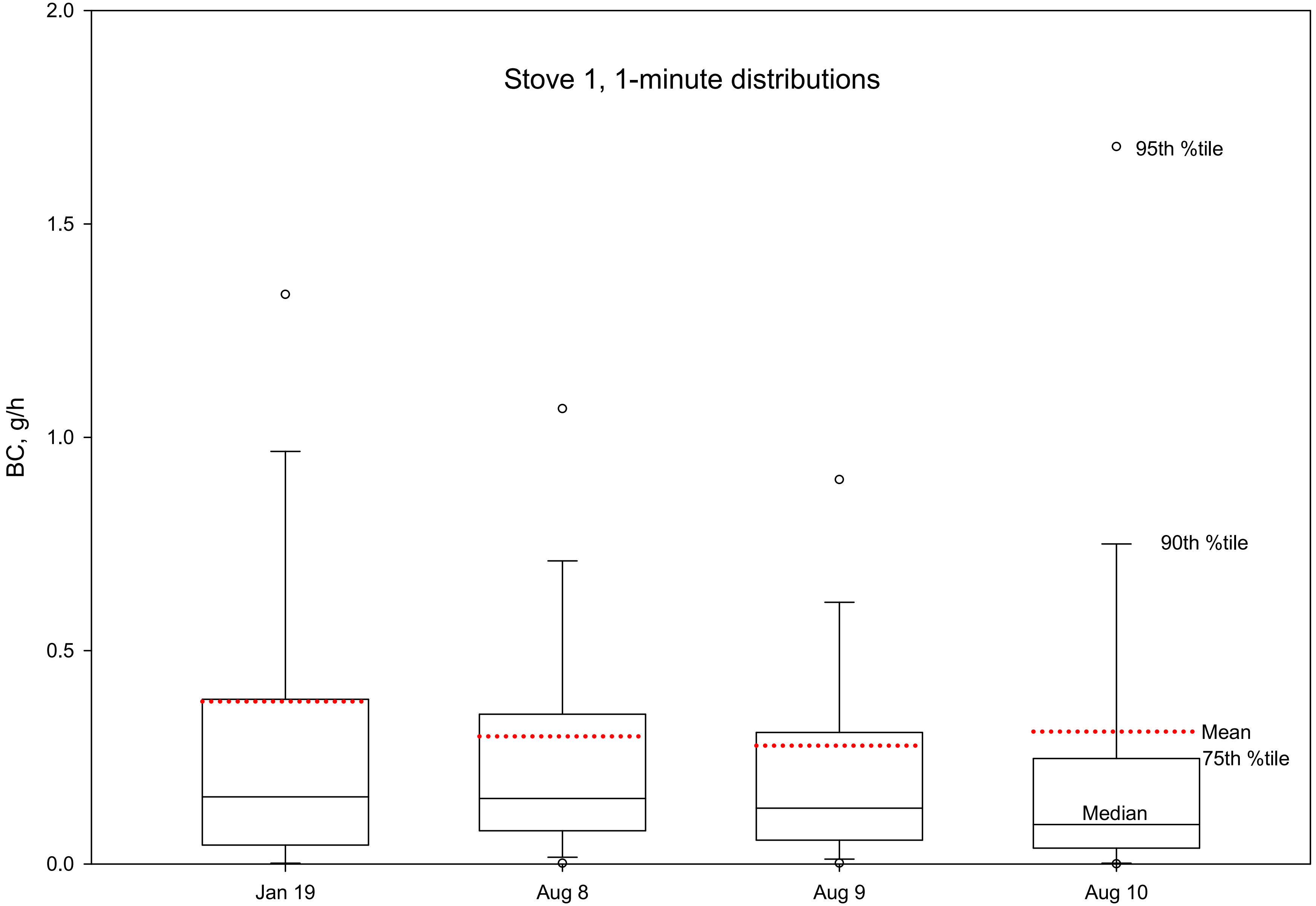

Stove 1
Jan 19
Aug 8
Aug 9
Aug 10
BC, g/h
Minute of Test
0
2
4
6
8
10
0
50
100
150
200
250
300
350
400
450


Stove 5
Jan 12
Aug 1
Aug 2
Aug 3
BC, g/h
Minute of Test
0
2
4
6
8
10
12
0
50
100
150
200
250
300
350
400
450

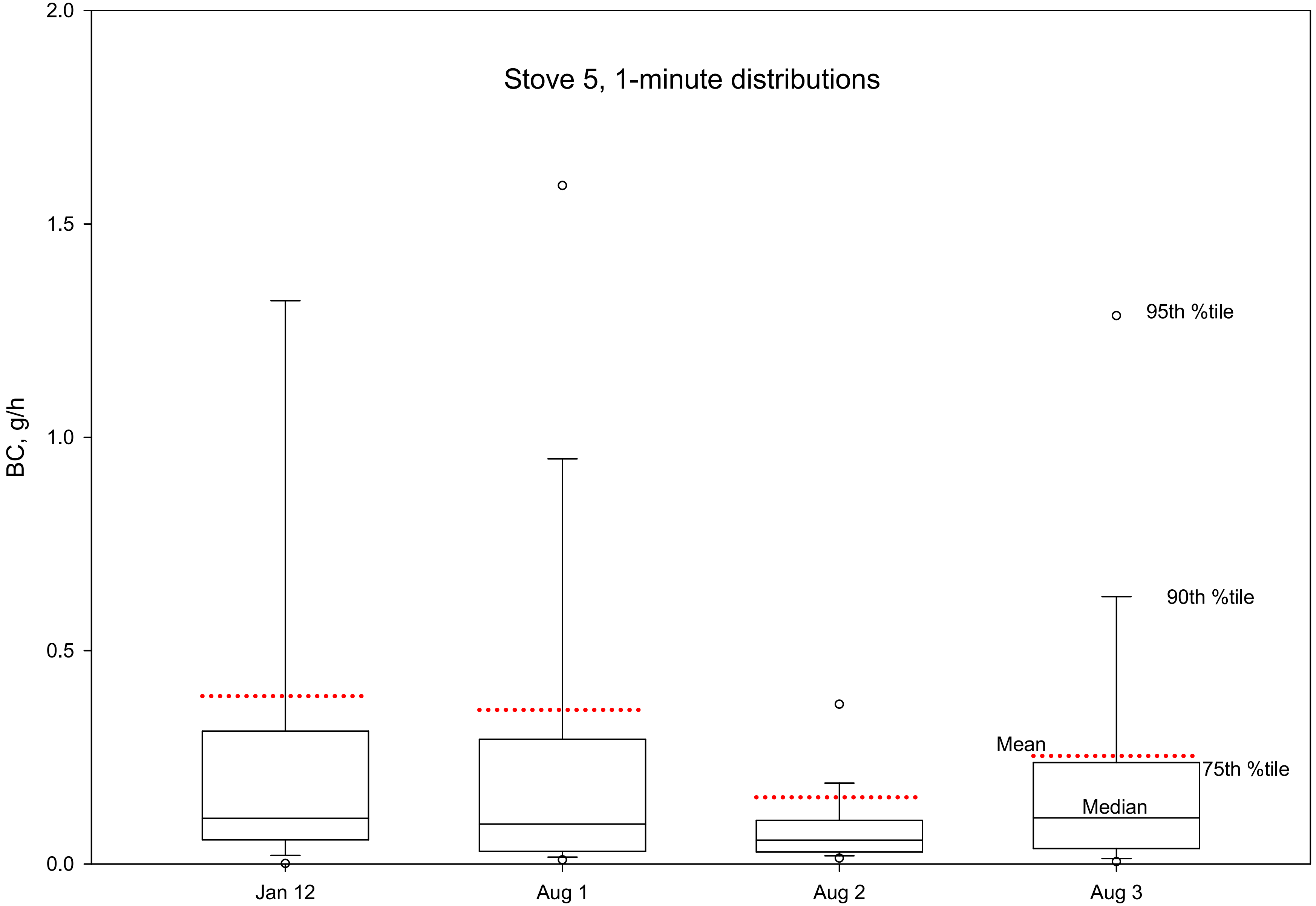

Stove 6
Jan 9
July 18
July 19
July 20
BC, g/h
Minute of Test
0
2
4
6
8
0
50
100
150
200
250
300
350
400
450



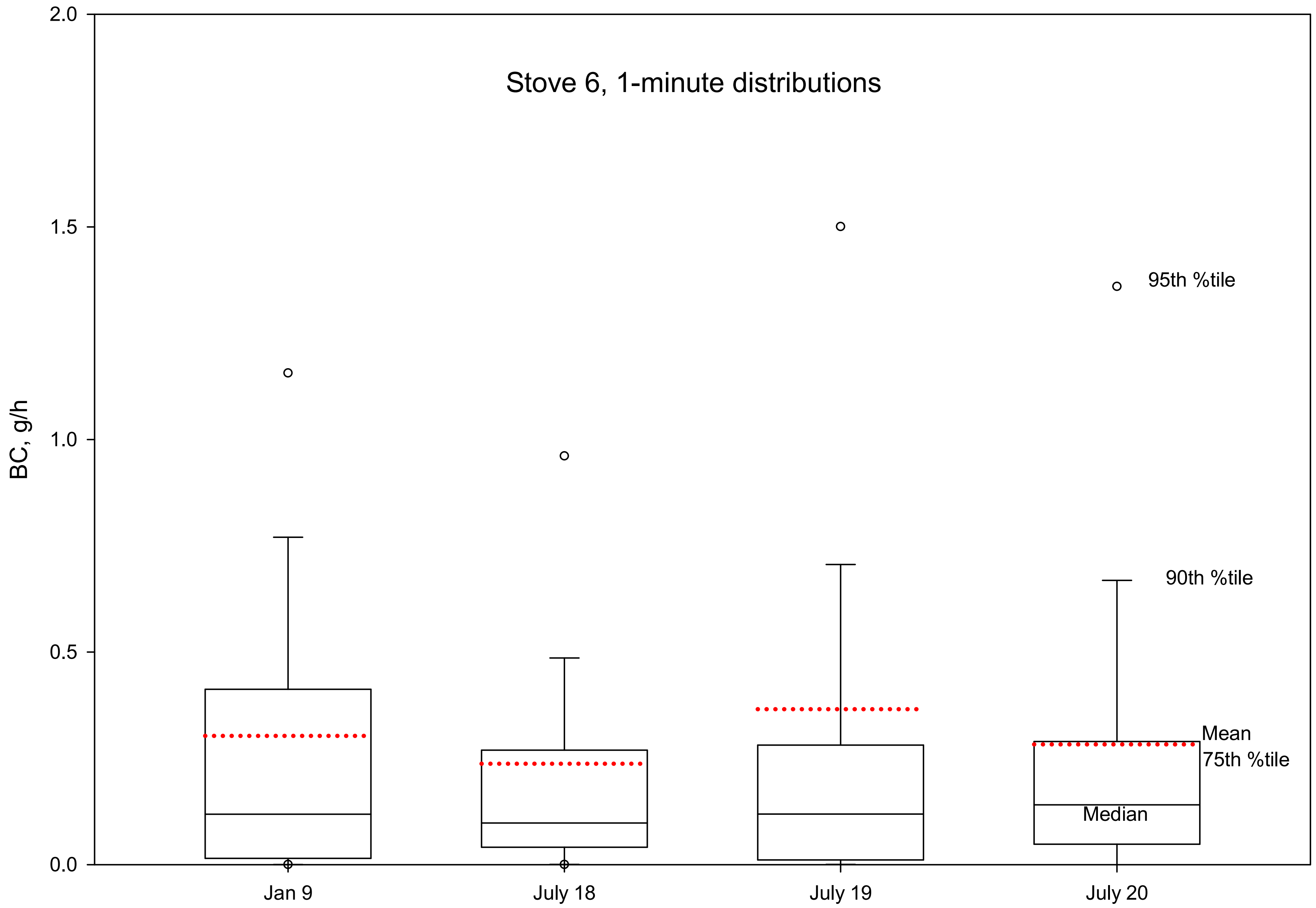
Stove 7
July 25
July 26
July 27
BC, g/h
Minute of Test
0
1
2
3
4
5
6
7
0
50
100
150
200
250
300
350
400
450



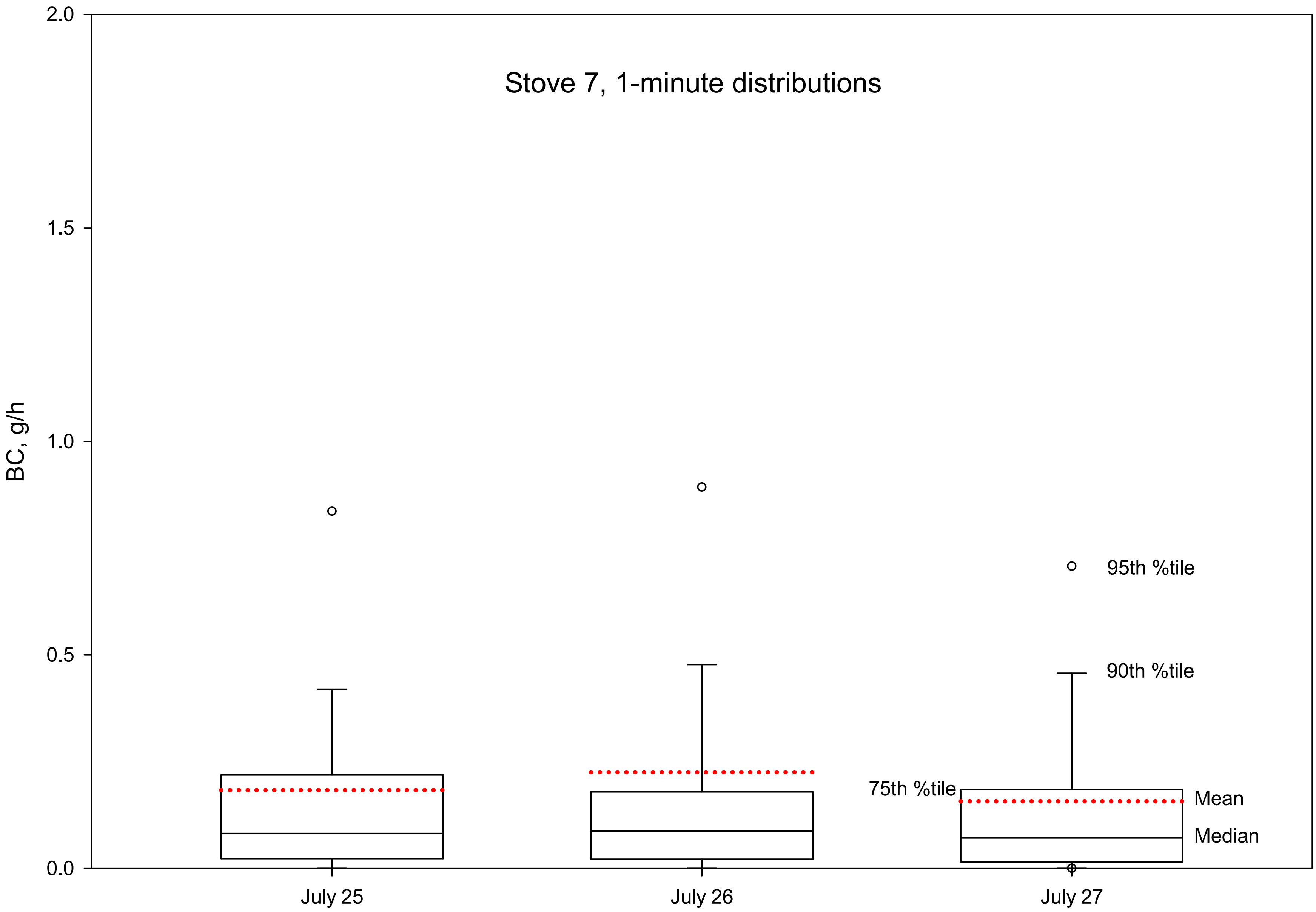
Stove 1, 1-minute distributions
BC, g/h
2.0
1.5
1.0
0.5
0.0
95th %tile
90th %tile
Mean
75th %tile
Median
Jan 19
Aug 8
Aug 9
Aug 10

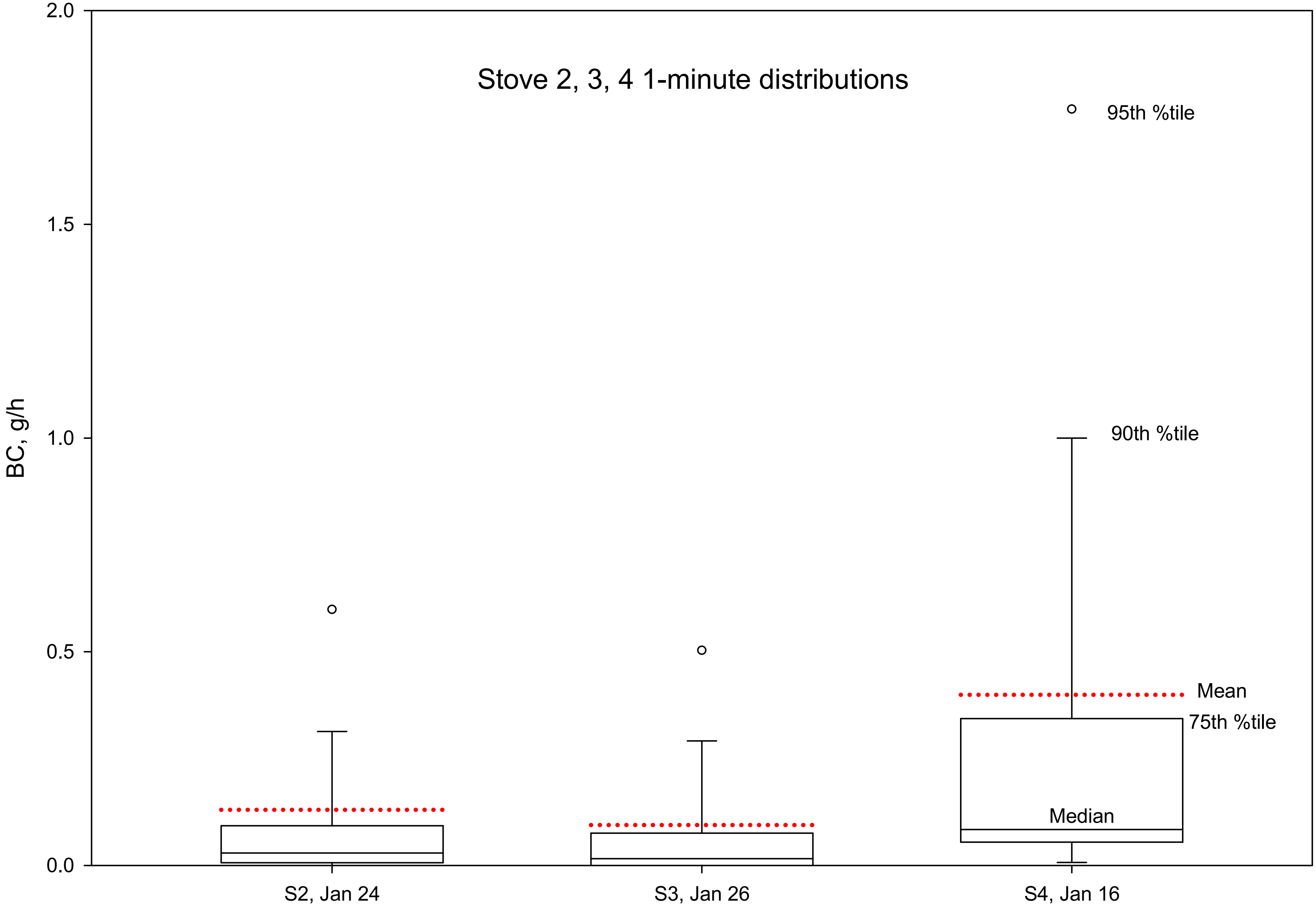


Stove 5, 1-minute distributions
BC, g/h
2.0
1.5
1.0
0.5
0.0
95th %tile
90th %tile
Mean
75th %tile
Median
Jan 12
Aug 1
Aug 2
Aug 3



Stove 6, 1-minute distributions
BC, g/h
2.0
1.5
1.0
0.5
0.0
95th %tile
90th %tile
Mean
75th %tile
Median
Jan 9
July 18
July 19
July 20


Stove 7, 1-minute distributions
BC, g/h
2.0
1.5
1.0
0.5
0.0
95th %tile
90th %tile
75th %tile
Mean
Median
July 25
July 26
July 27



Stove 2, 3, 4 1-minute distributions
BC, g/h
2.0
1.5
1.0
0.5
0.0
95th %tile
90th %tile
Mean
75th %tile
Median
S2, Jan 24
S3, Jan 26
S4, Jan 16