Impact of Thermal Storage on Pellet Boiler Performance

T. Butcher, R. Trojanowski, A. Bennett, G. Wei, Y. Celebi

November 30, 2016

Note! Comments from the authors have been added in many of the slides to help understand the work presented. These appear with the next "click" after the slide when running in a slide show mode.

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery
U.S. DEPARTMENT OF ENERGY | Office of Science

Objectives of this work

- Detailed studies of the performance of a pellet-fired residential boiler:
  - with and without thermal storage
  - under standard test and emulated field load conditions.
- Support for effort to develop a test method for automatic feed boilers with thermal storage.

Outline

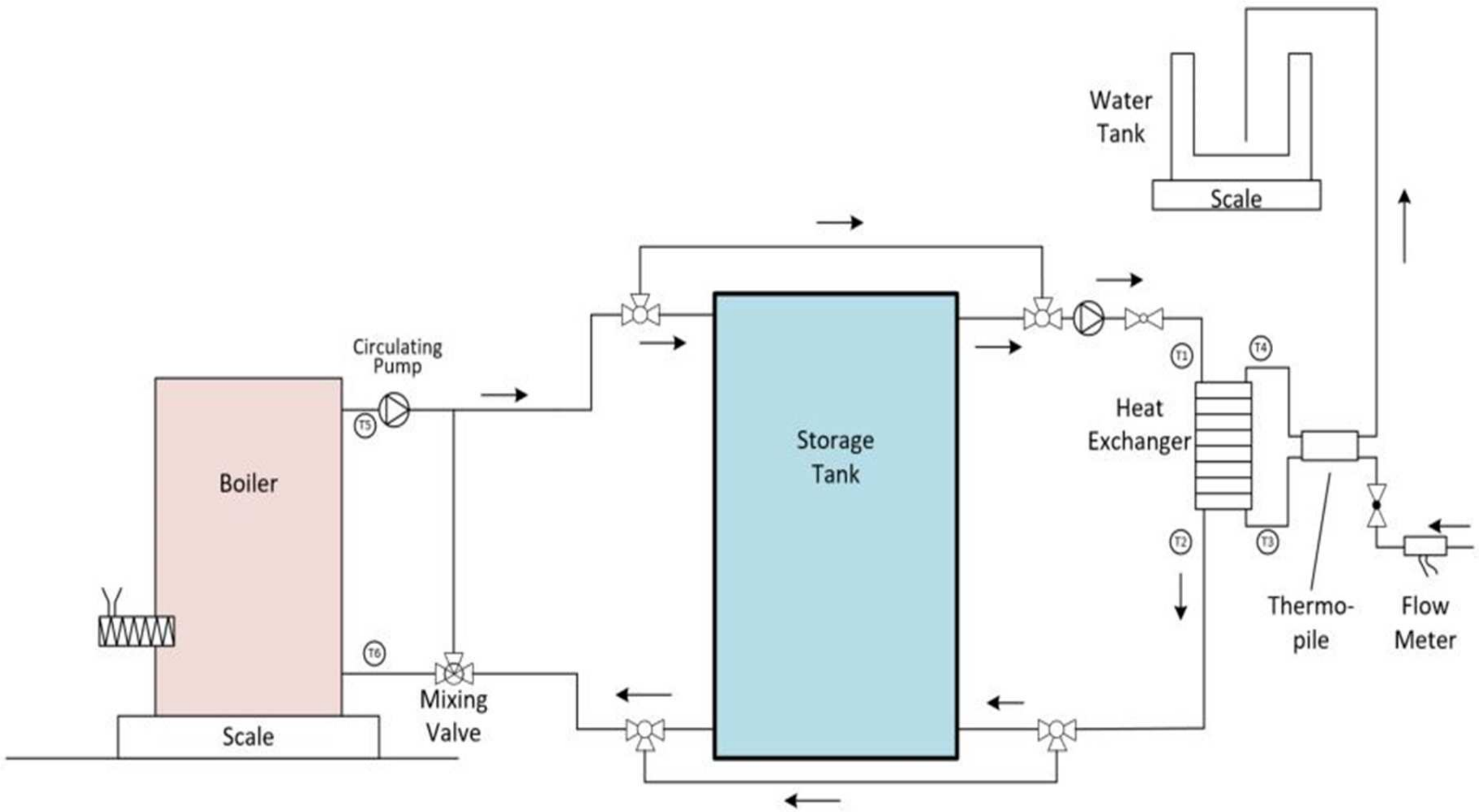
1. Laboratory setup and pellet boiler tested
2. Test plan
3. Operating characteristics of tested boiler
4. Impact of storage on Cat IV and Cat I test results
5. Emulated field load conditions
6. Comparison of test results under emulated field and standard fixed load conditions

Pellet boiler specifications

Pellet Boiler Specifications	
Rated output	85,000 Btu/hr (25 kW)
Water capacity	10 Gal. (38 liters)
Minimum external storage	119 Gal. (450 liters)
Lambda sensor (O_2)	
Secondary fan	
Exhaust fan	
Automatic ignition	
Boiler circulation pump & mixing motor to protect boiler from thermal shock	

Boiler can modulate to 30% of nominal load

Pellet boiler system set-up



Cooling water flow (load) is controlled by lab computer – either fixed load or programmed load profile. Cooling water flow measured with ultrasonic flow meter and direct scale mass.

Emission sampling at BNL

- PM in dilution tunnel
- Dual train – Teflon coated glass fiber filters
- Flue gas analysis with FTIR and paramagnetic O_2
- Real time dilution tunnel PM via TEOM

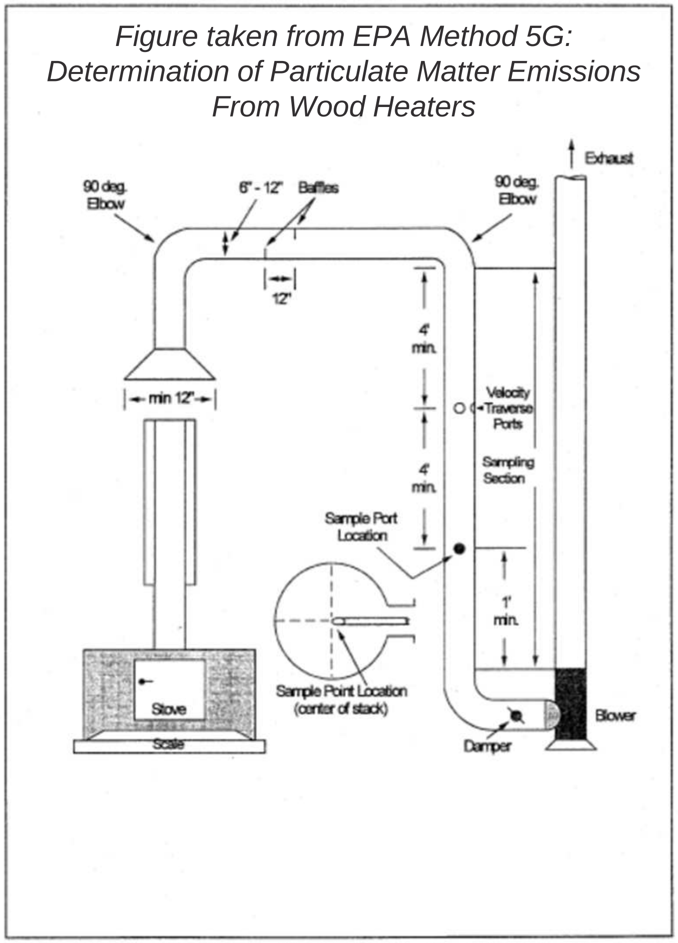
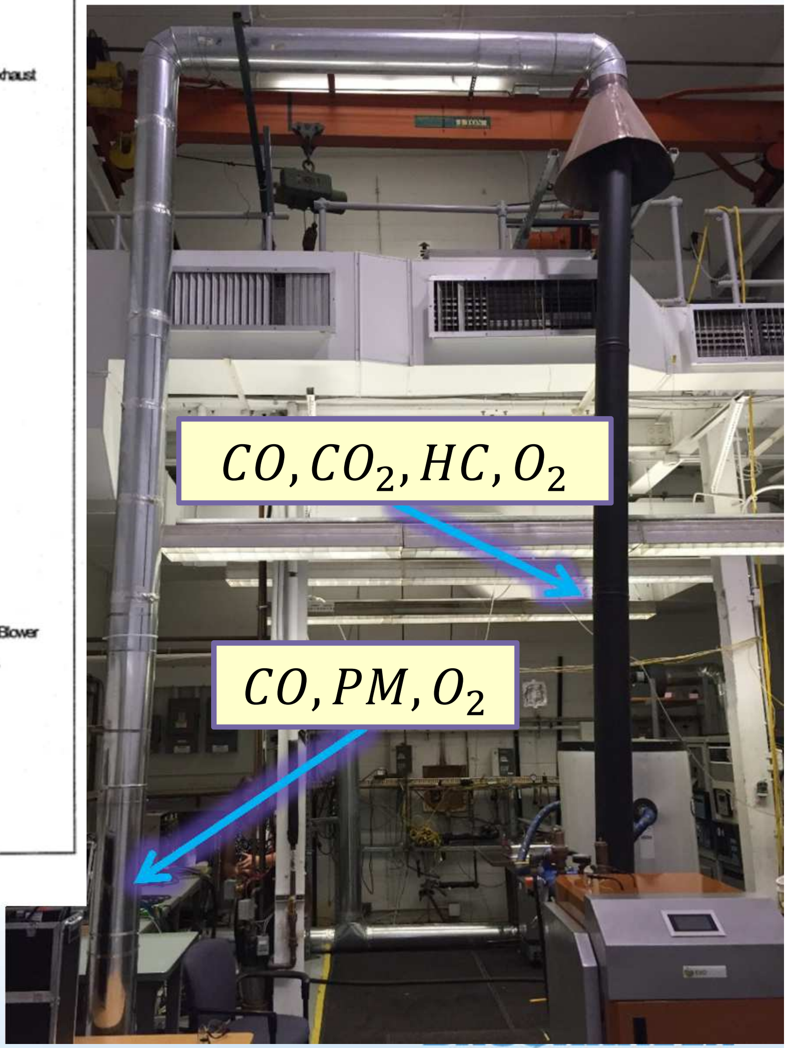


Figure 5G-2. Suggested Construction Details of the Dilution Tunnel.

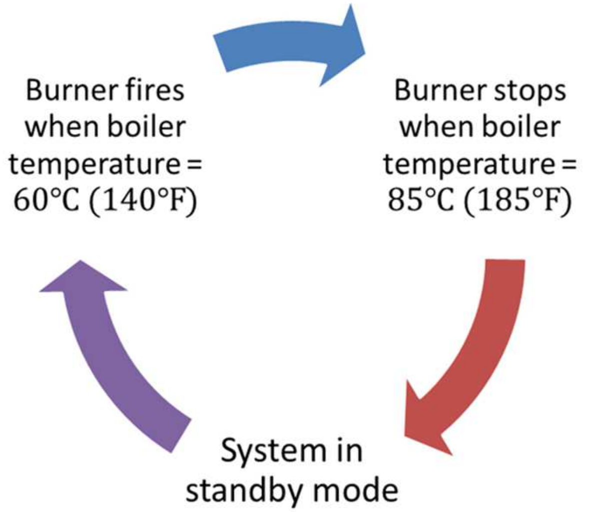


Test Overview

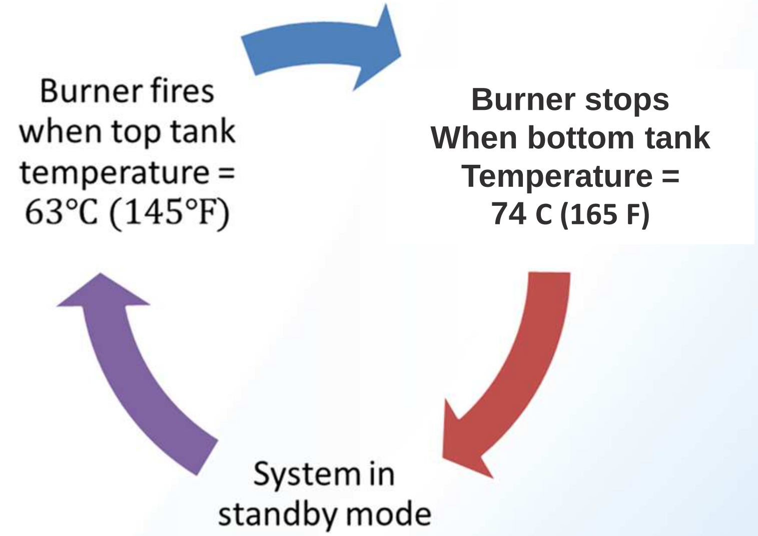
- Cat, IV, full load, steady state
- Cat I (<15% load) without storage, with 119 gal and 210 gallons of storage;
- Steady state – 30% load (non-cycling)
- Emulated load profiles – 24 hours, variable load

Boiler control strategy with or without storage

Without storage



With storage



This slide illustrates one setting condition. During the project the impact of changes to these control settings were explored. Most significant is the range over which the storage tank temperature changes during a typical cycle. A wider range provides more storage capacity.

Boiler control strategy

With Storage I

- Burner fires when top tank temp reaches 68 °C (154 °F)
- Burner stops when tank gets to 72 °C (161.6 °F)

ΔT= 4 °C (7 °F)

With Storage II

- Burner fires when top tank temp reaches 63 °C (145.4 °F)
- Burner stops when tank gets to 74 °C (165.2 °F)

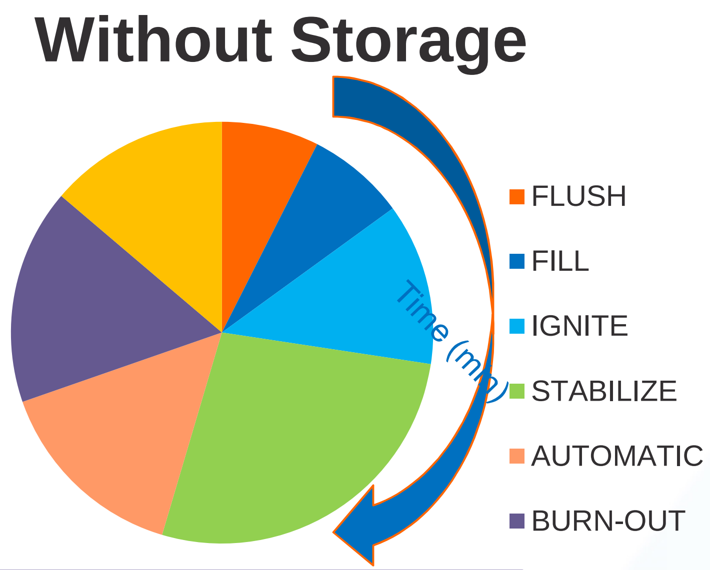
ΔT= 11 °C (20 °F)

Without Storage

- Burner fires until boiler temp reaches 85 °C (185 °F)
- Burner starts again when boiler gets to 60 °C (140 °F)

With storage, most of the testing was done with two different conditions. The first, Storage I, refers to the as-received case. Storage II represents a wider range in the storage tank temperature and these settings were selected as more typical of field installations, based on discussions with the manufacturer.

Boiler cycle: Category I



Time in standby: ~ 20 mins

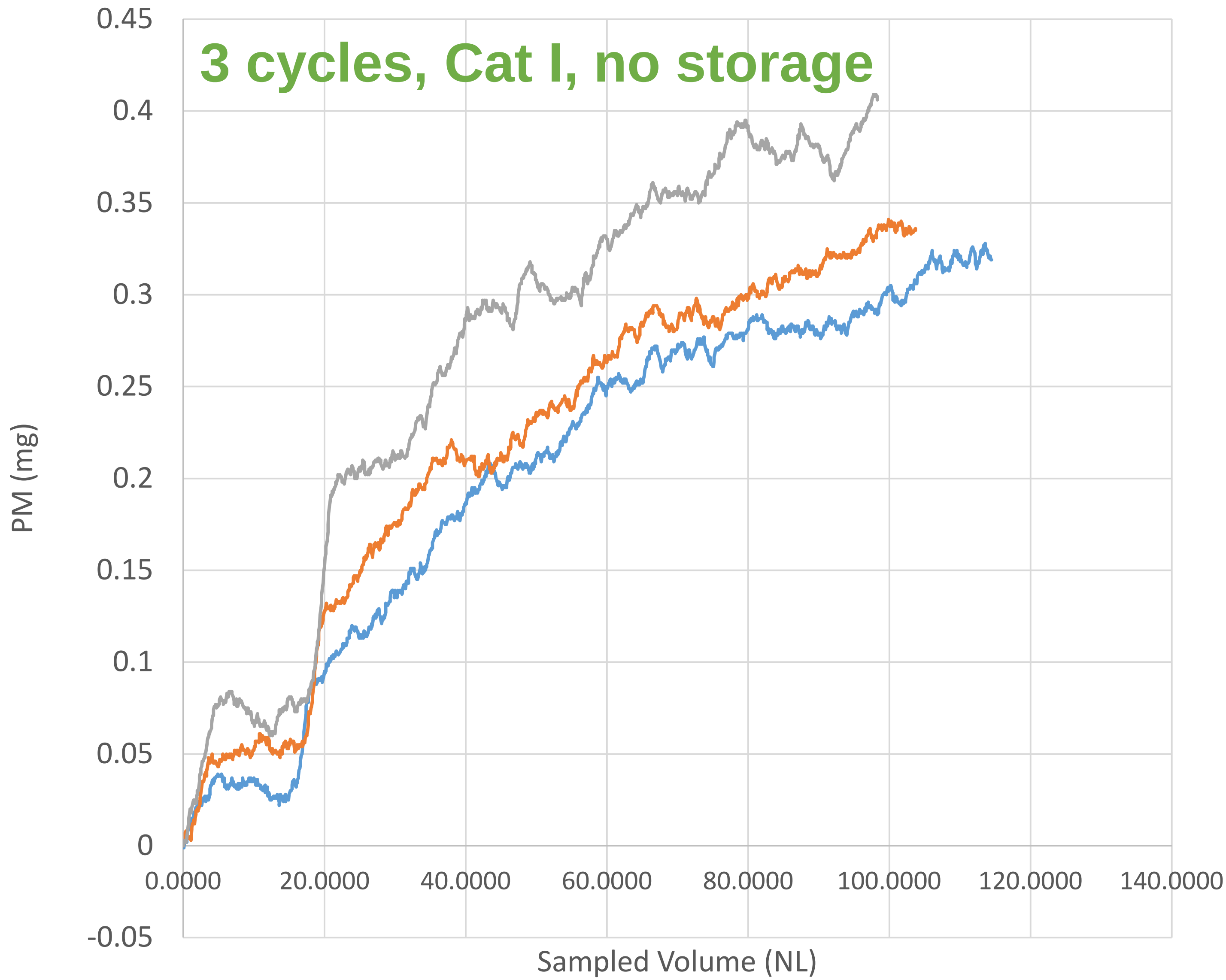
Every time a pellet boiler cycles it goes through a set of different stages. Some of these stages, for example flush, can reduce efficiency. Others can have high short term emissions, for example ignition and burn-out. Increasing the cycling rate, then, would negatively impact performance.

Real time PM analysis

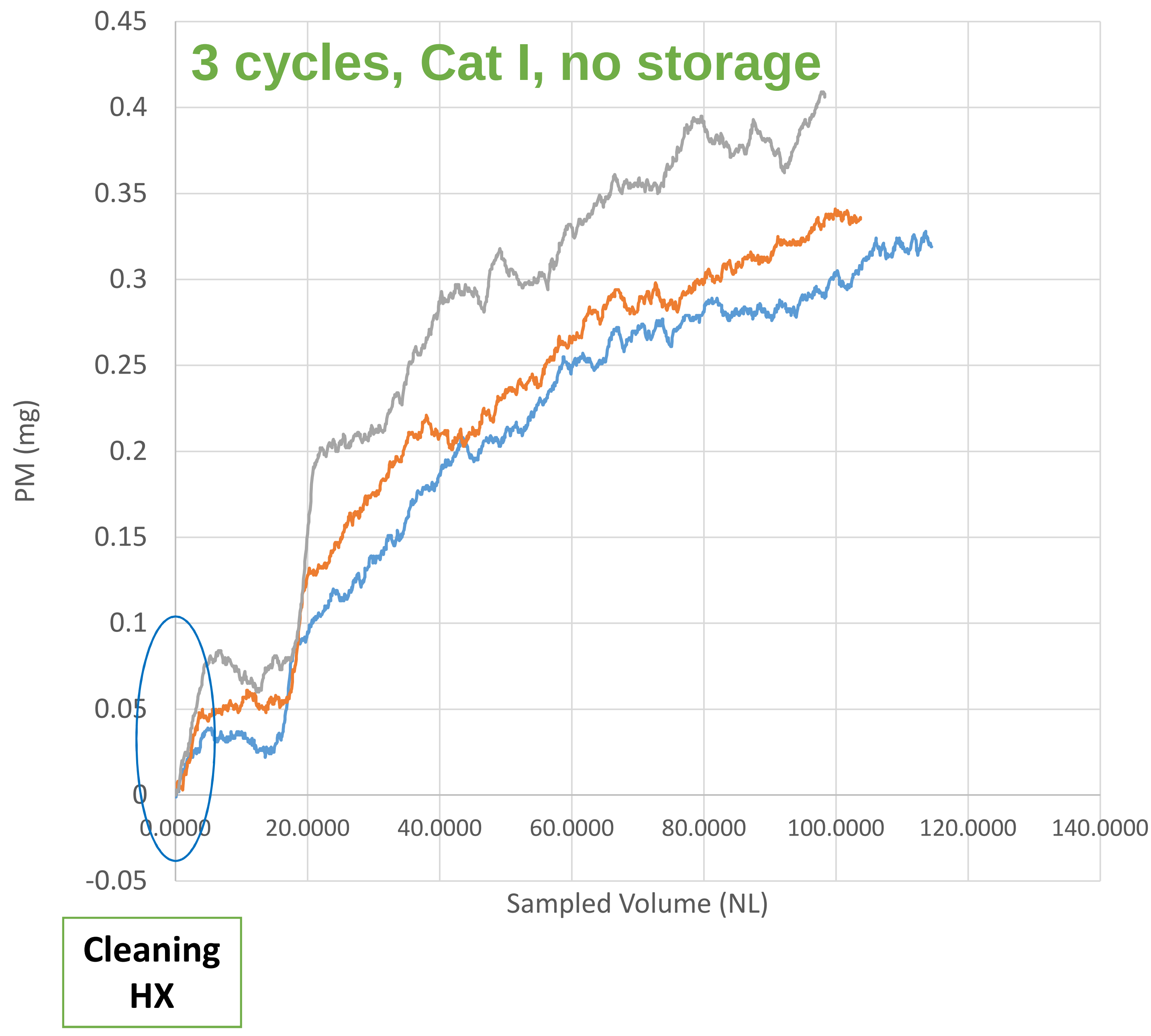
To help understand the impact of cycling on particulate emissions, studies of real-time PM emissions were done using a Wohler SM500 analyzer. The following slides present results for three consecutive startup cycles. Similar trends are shown in all three cases. The plots show total particulate captured vs sampled volume. In any time segment, a steeper slope corresponds to a higher particulate emission rate.

The flush, or cleaning phase where a high air flow blows particles out of the boiler and the ignition phase both have particularly high short term emissions.

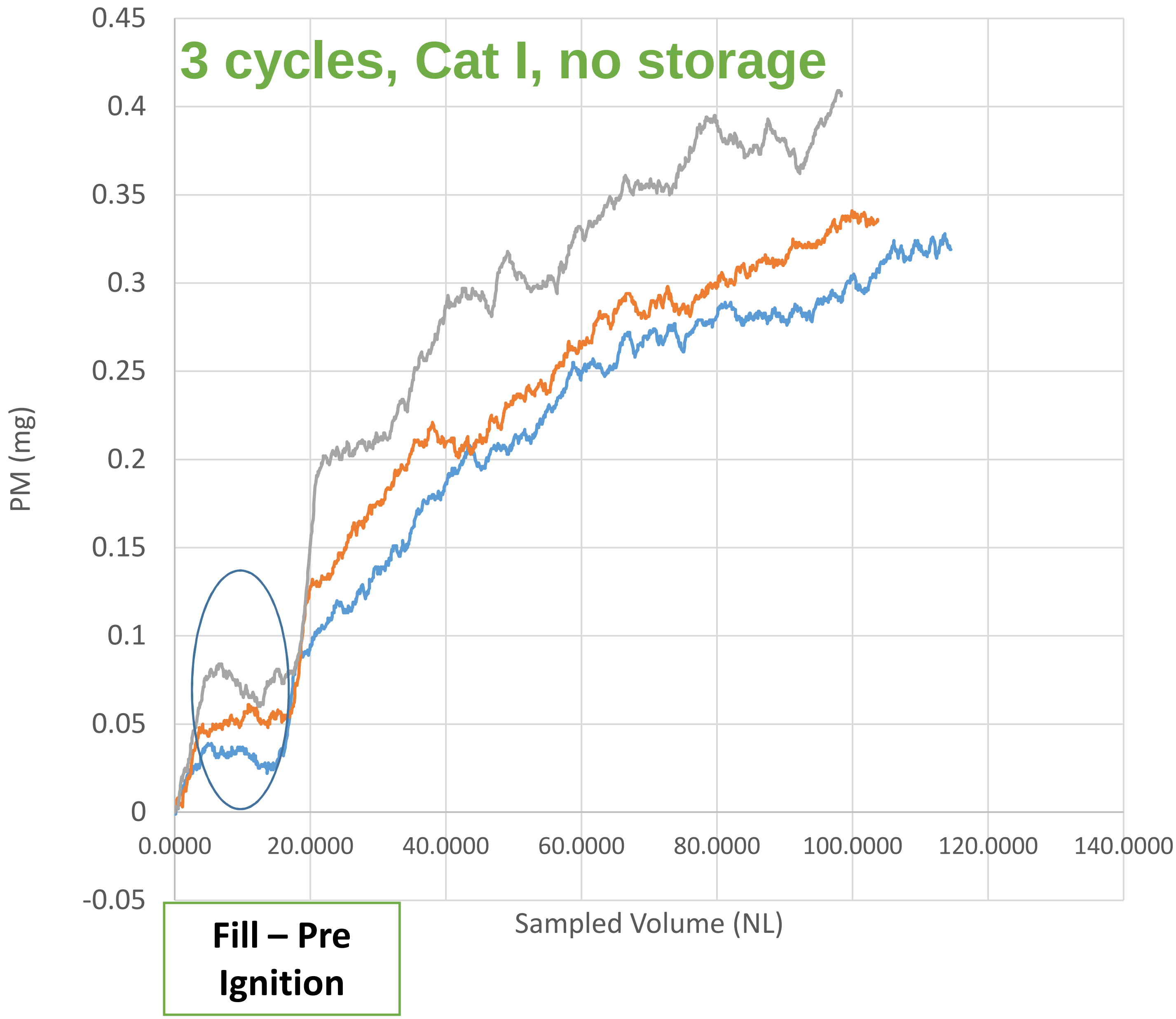
Wohler data- real time PM analysis



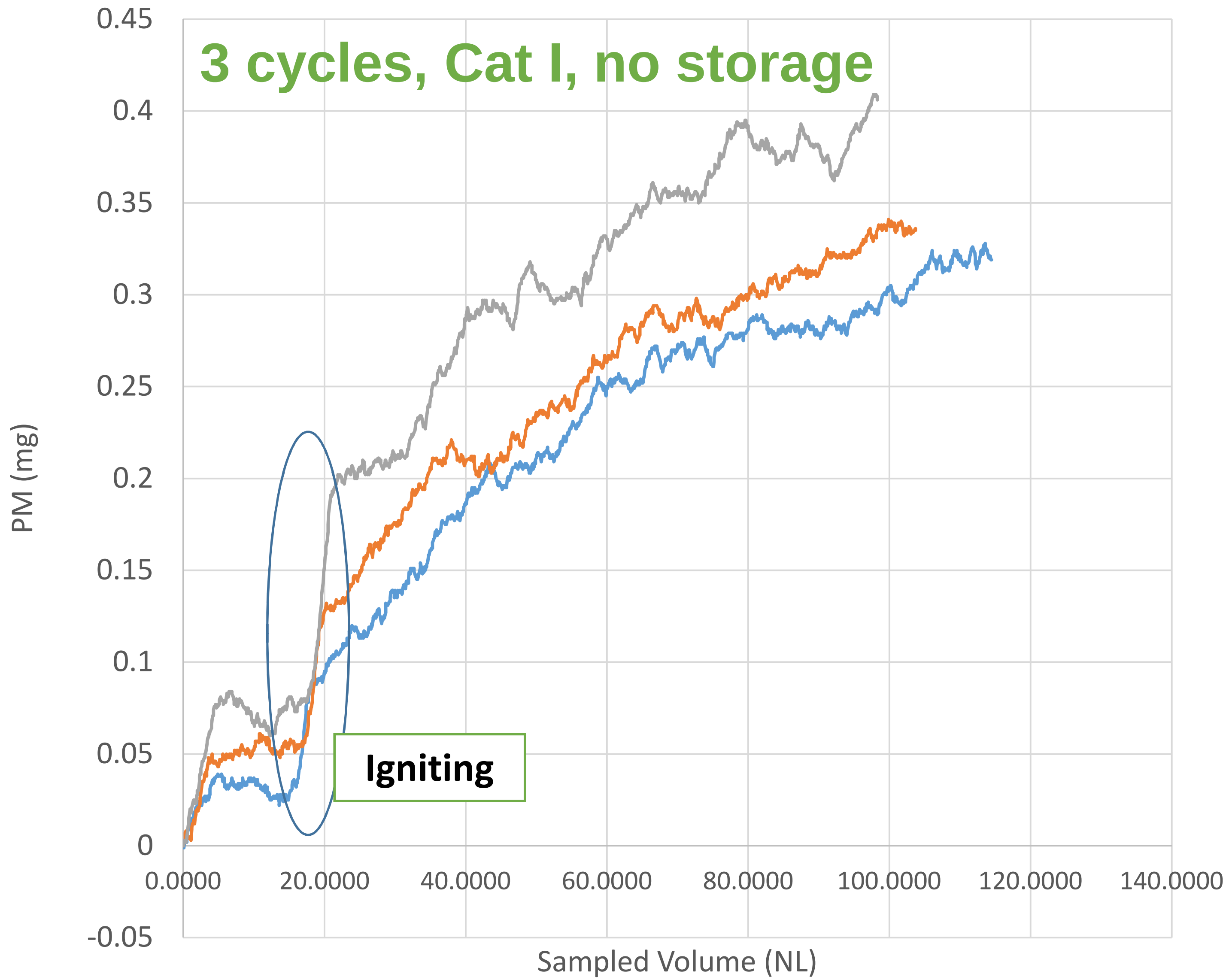
Wohler data- real time PM analysis



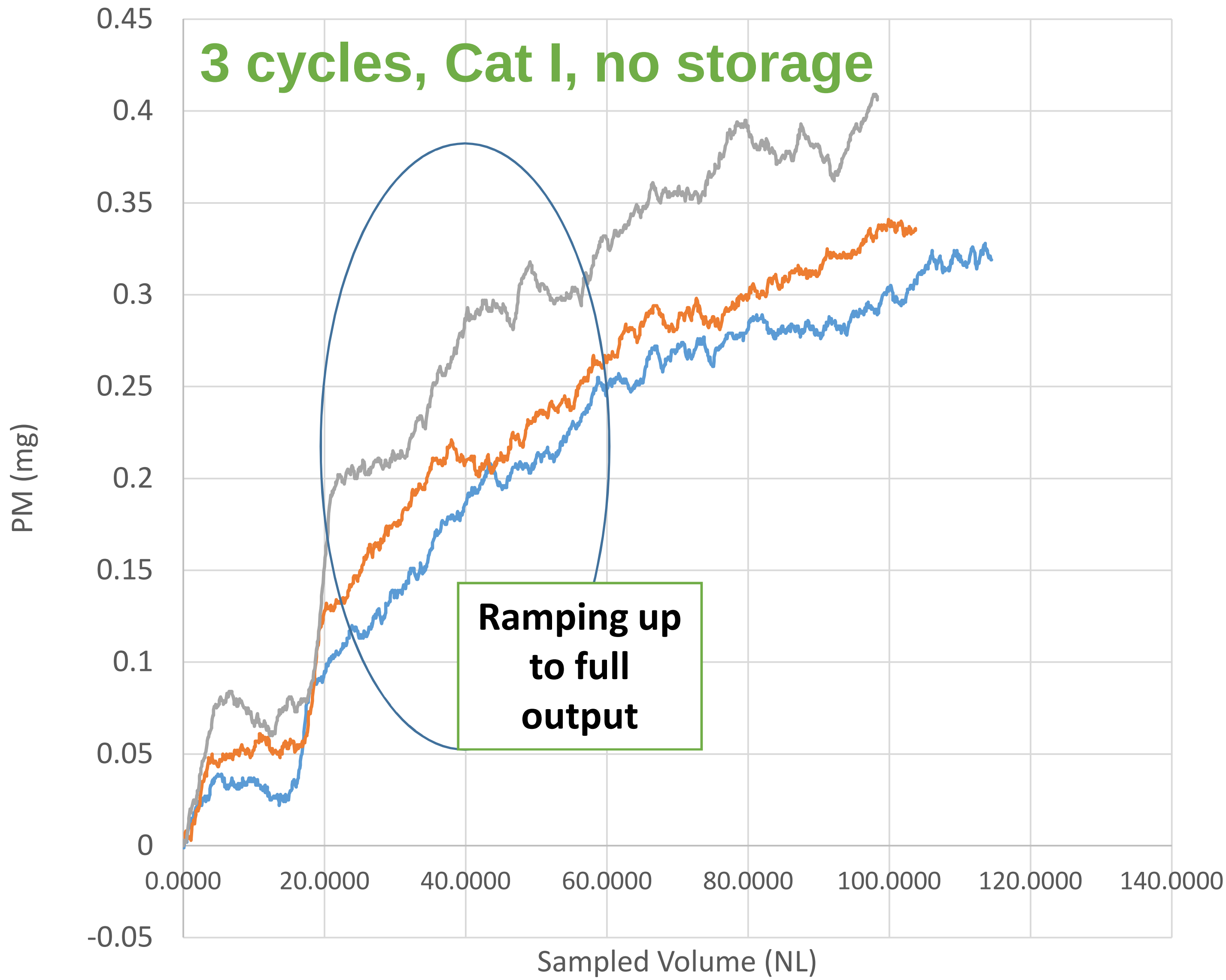
Wohler data- real time PM analysis



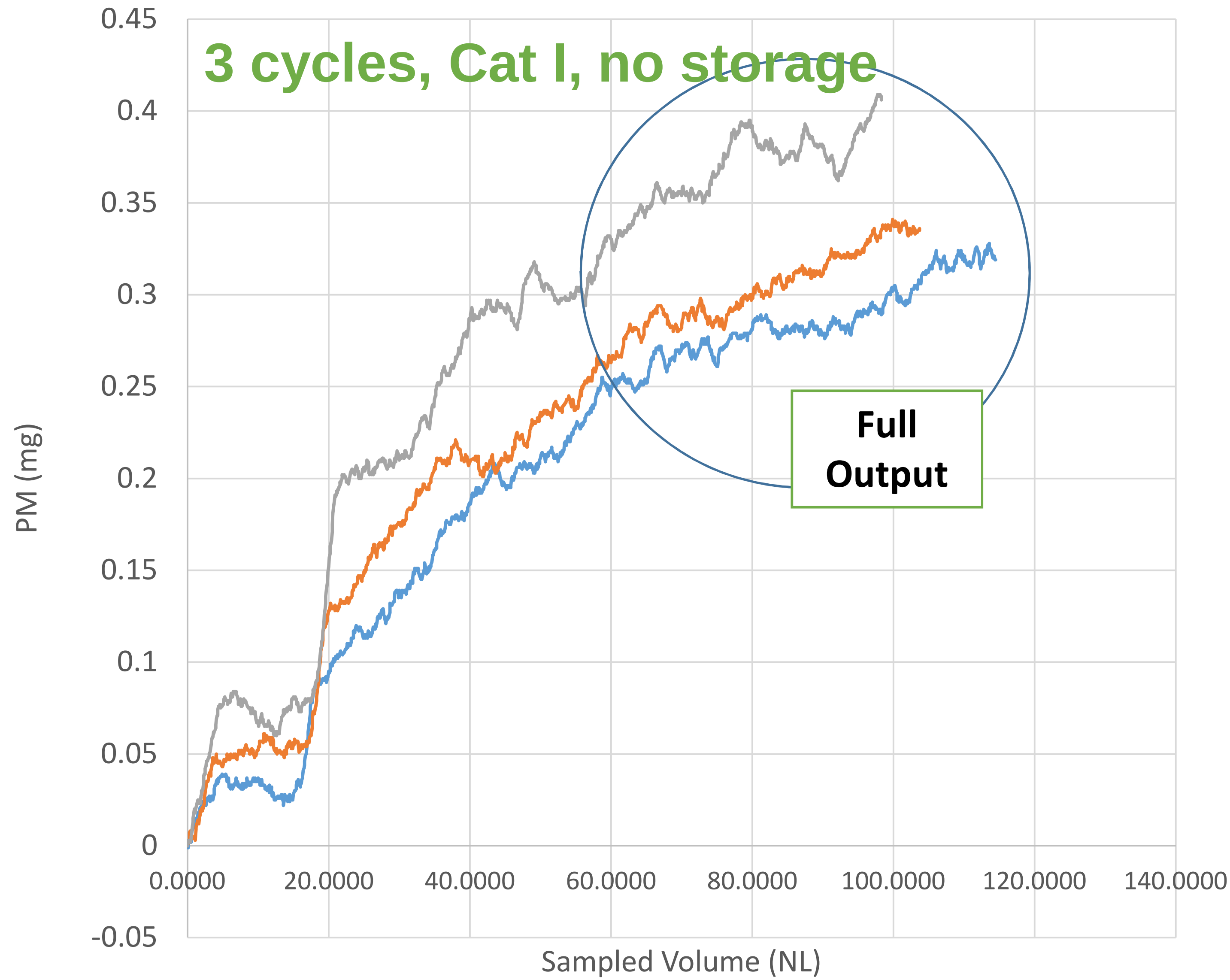
Wohler data- real time PM analysis



Wohler data- real time PM analysis



Wohler data- real time PM analysis



PM: 30% vs 100% boiler output steady state

30%

100%

Comparison of photos of PM measurement filters with steady state operation at 30% of full load and 100% of full load. At low load, the filters are markedly darker and filter plugging rates were much higher, indicating poor combustion quality and high unburned carbon emissions. This is likely due to poor mixing of the volatilized pellet fuel and air under low air velocity and low air turbulence conditions.

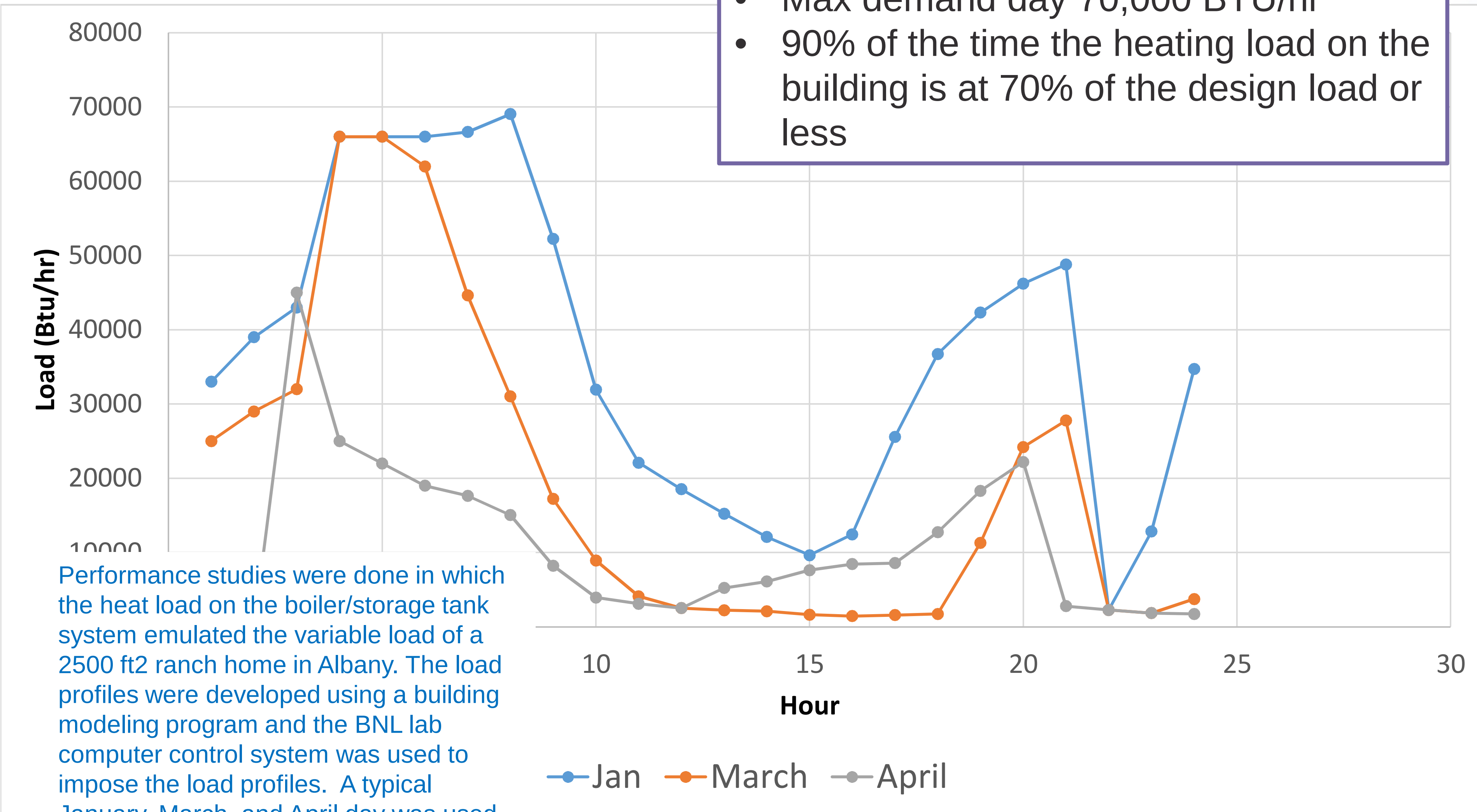
Particulate matter emission overview

Category	Storage	Emissions
		Output
		lb/MMBtu
IV	N/A	0.13
I _control settings 1	No	0.41
	Yes	0.20
I_control settings 2	Yes	0.13

This slide shows the impact of 119 gallons of storage on emissions under low load, Category I, conditions. In Category I, without storage, the PM emission factor is much higher than in steady state, full load combustion (0.41 vs 0.13). With 119 gallons and a narrow control range (I_control settings 1) emissions are lowered to 0.20. With the wider control setting range (I_control settings 2) the PM emission was measured at the same as in steady state full load.

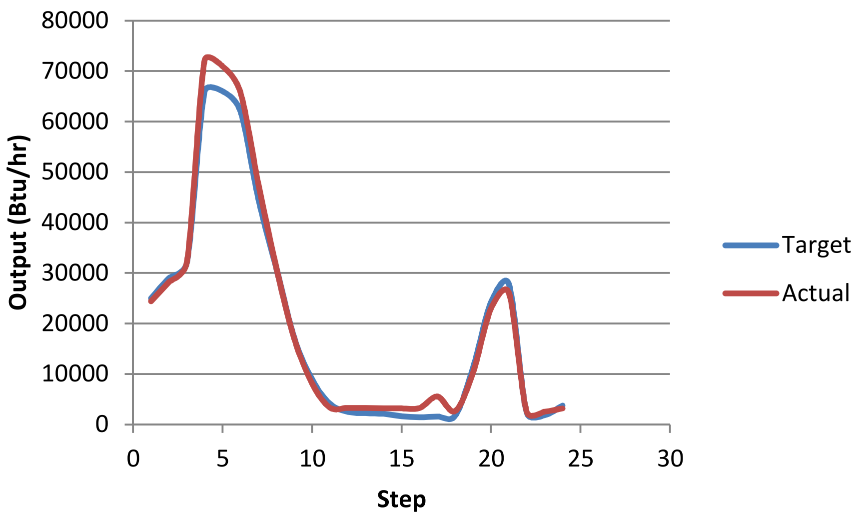
Load profiles run to date with & without storage

- Max demand day 70,000 BTU/hr
- 90% of the time the heating load on the building is at 70% of the design load or less

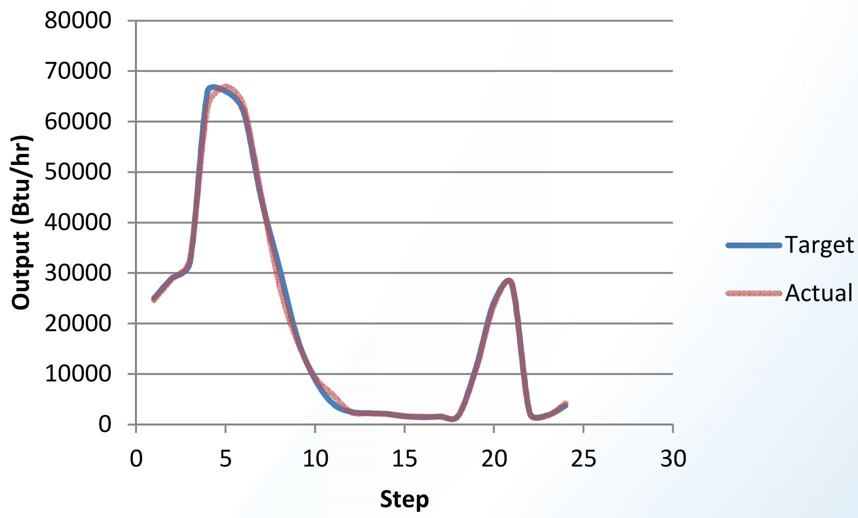


Performance studies were done in which the heat load on the boiler/storage tank system emulated the variable load of a 2500 ft2 ranch home in Albany. The load profiles were developed using a building modeling program and the BNL lab computer control system was used to impose the load profiles. A typical January, March, and April day was used for this.

March actual vs target load



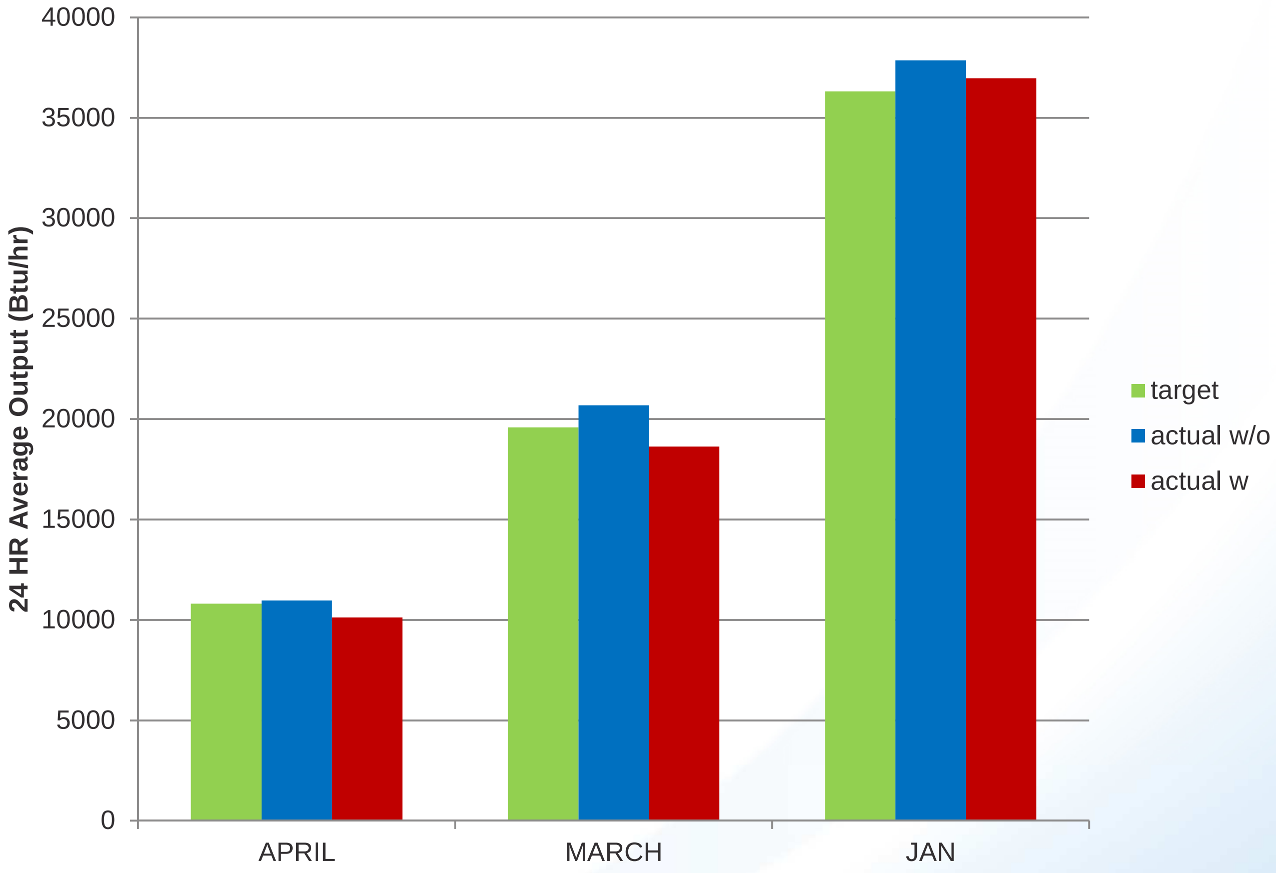
March Day – No storage



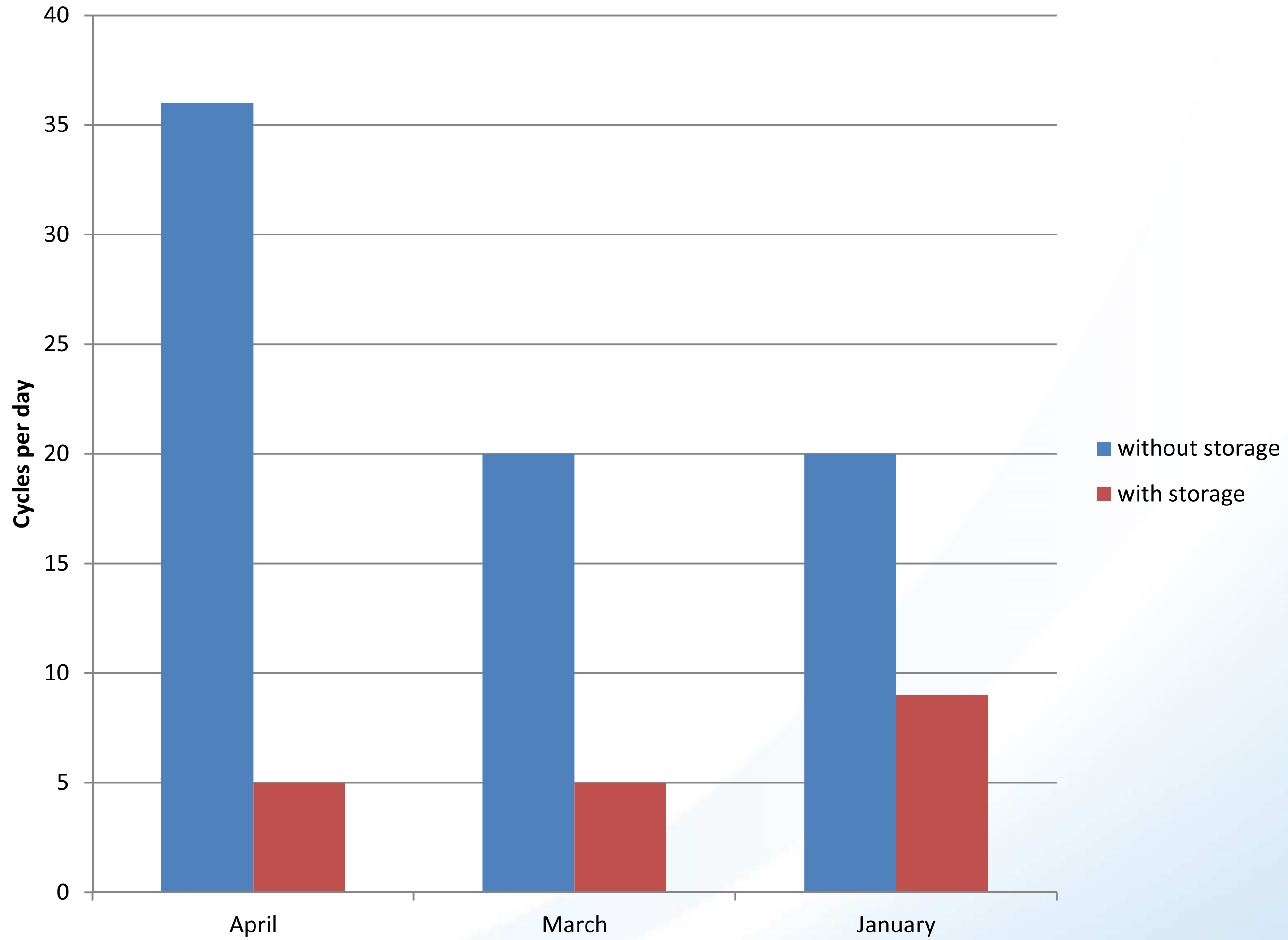
March Day – With storage

This slide simply shows that the lab control system was able to closely reproduce the target modeled load profiles. The match was better with storage simply because the temperature was steadier.

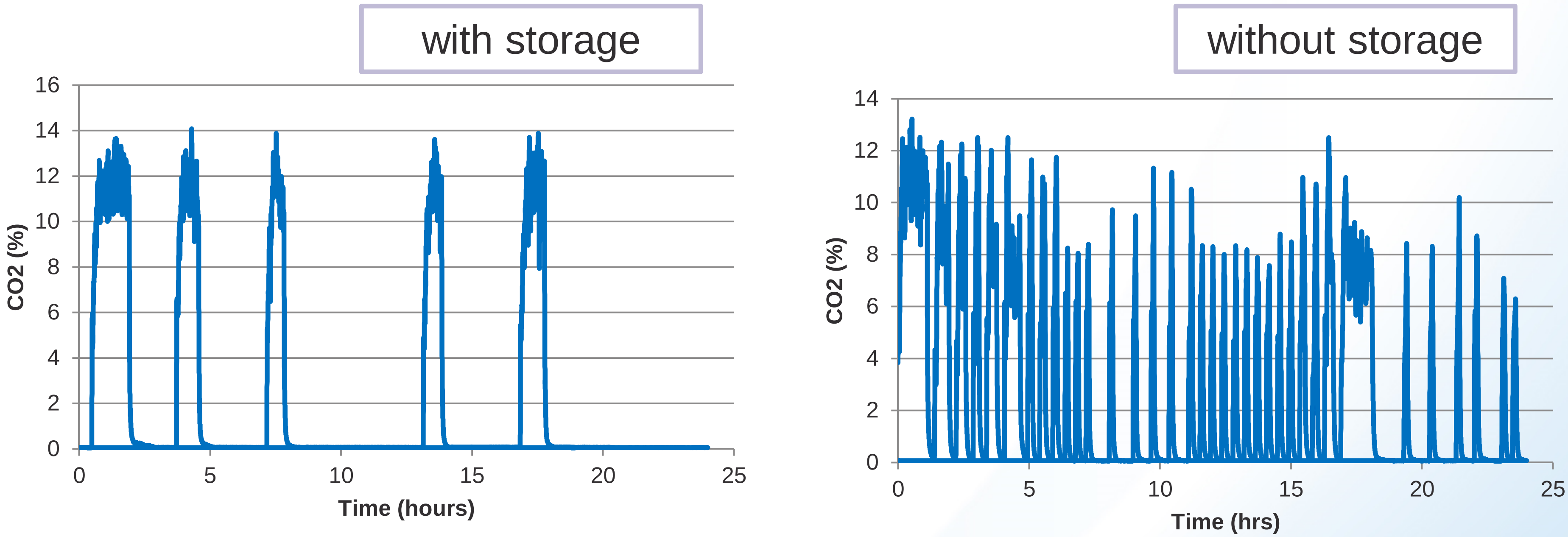
Average load vs target



Cycling frequency

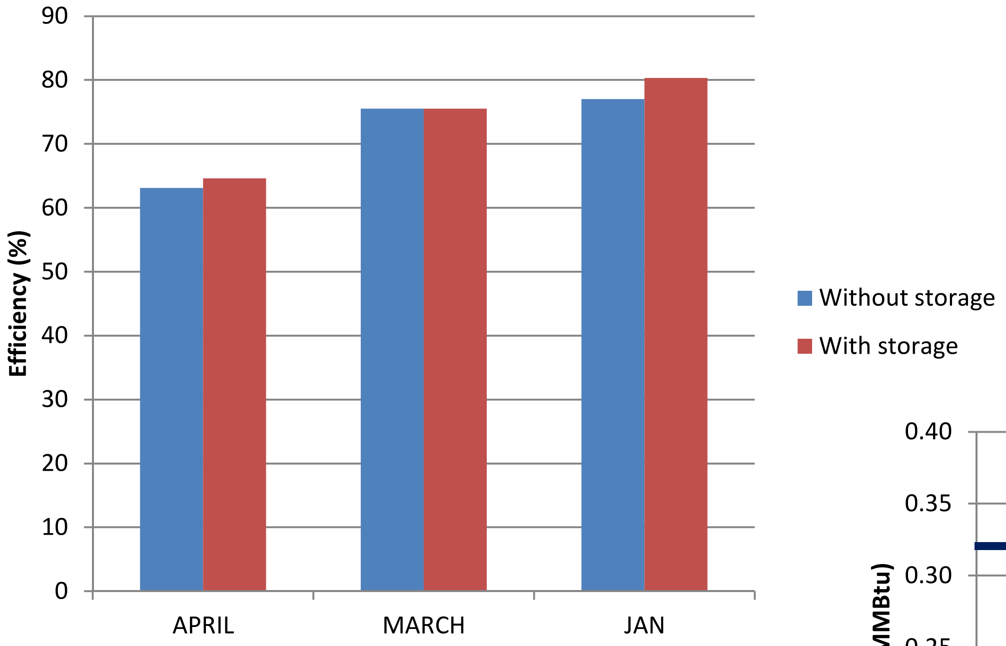


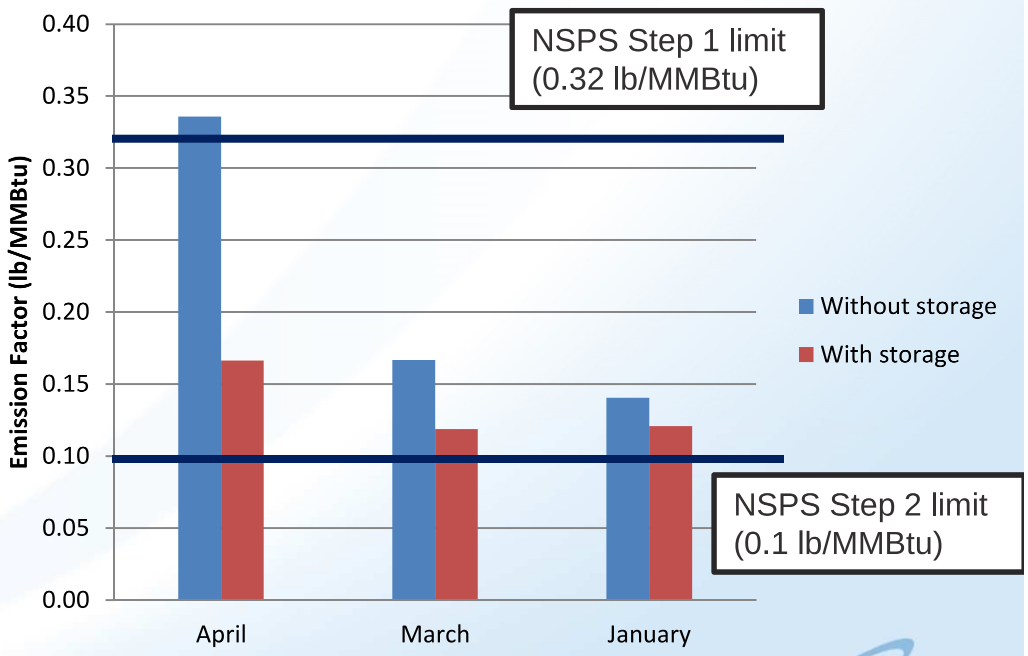
April day cycling



Graphic illustration of the impact of storage (119 gal) on cycling during the typical April day for the Albany home.

Delivered Efficiency and PM



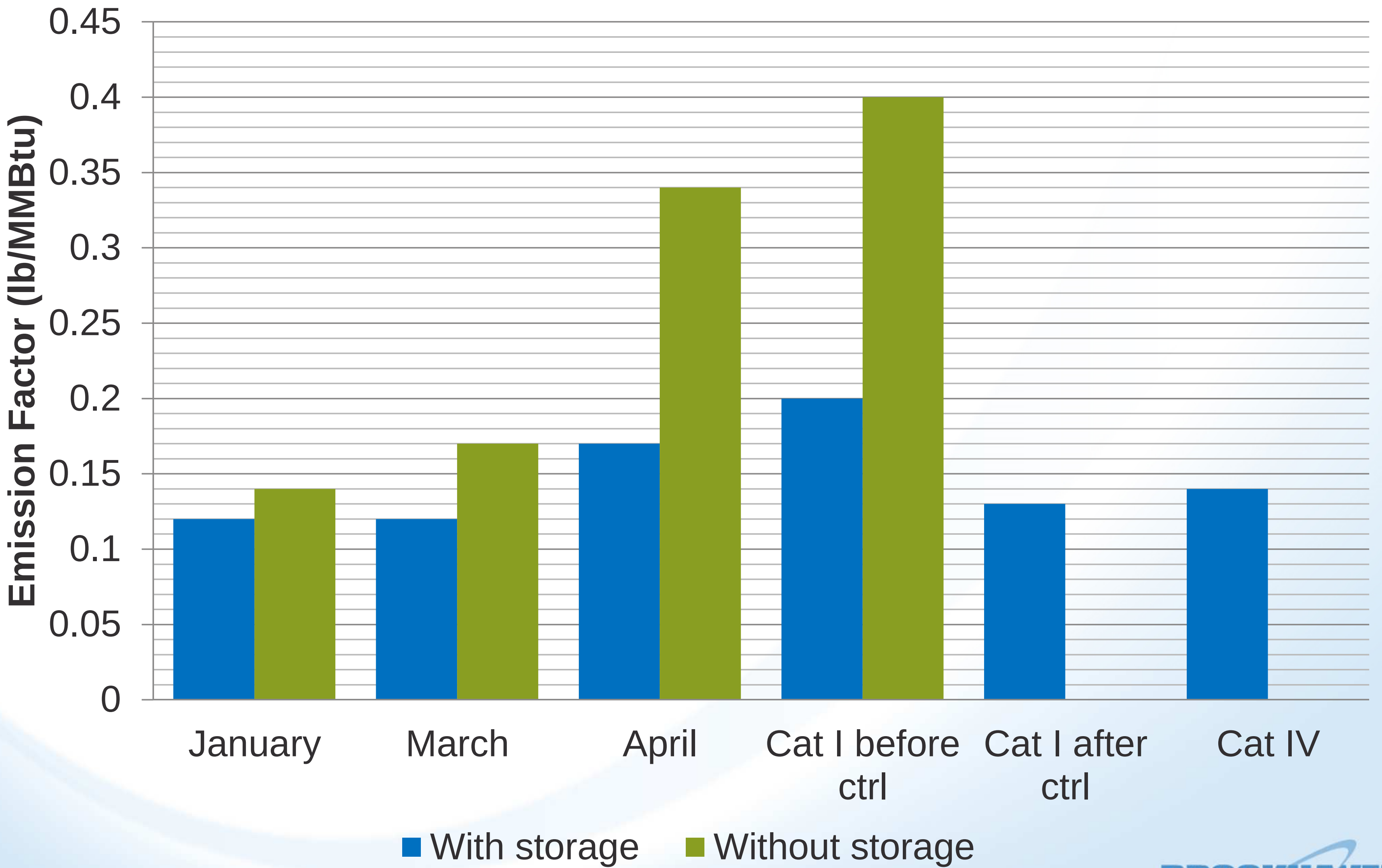


Average load comparison

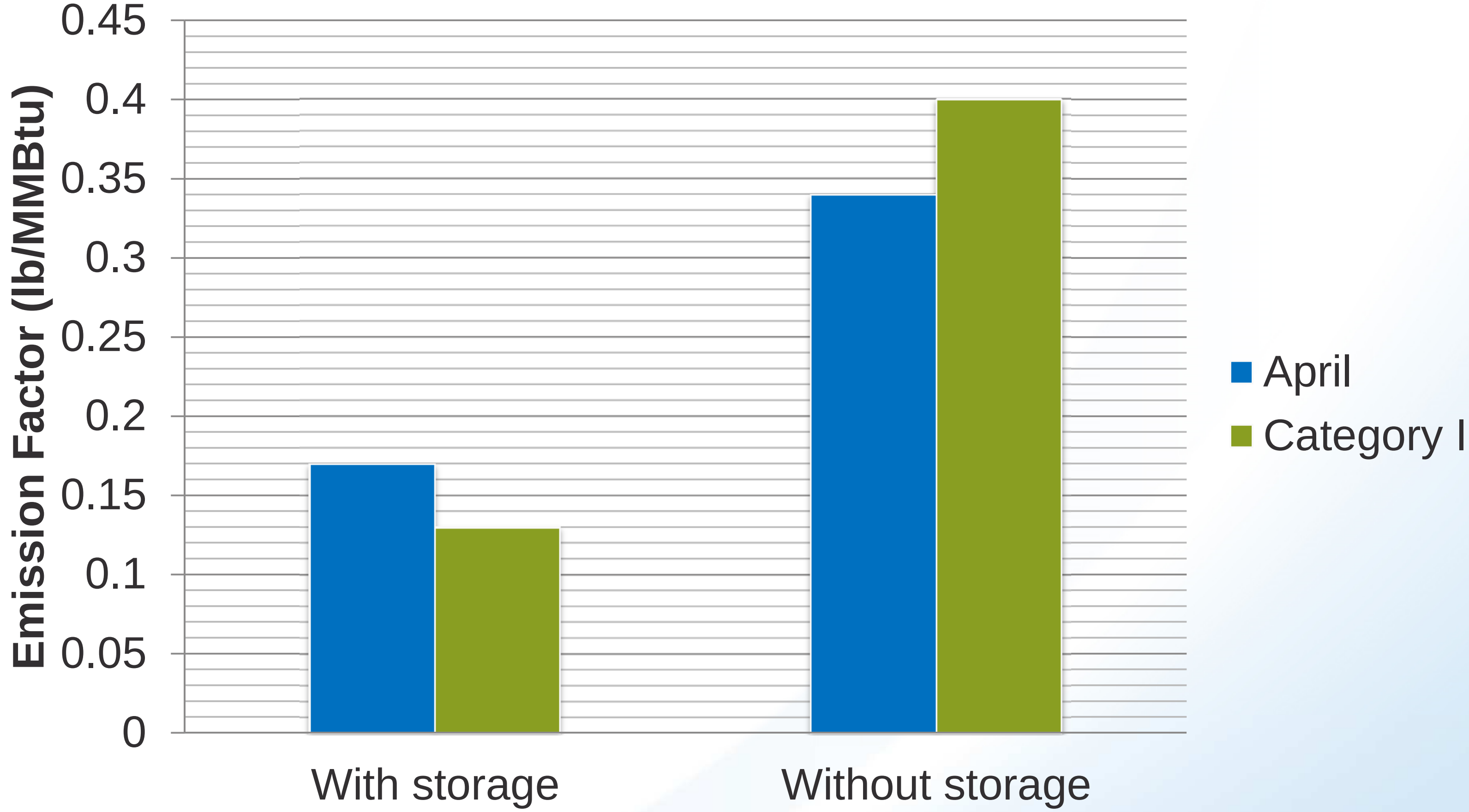
Load Profile	Storage*	Emission Factor *lb/MMBtu*
January	Yes	0.12
	No	0.14
March	Yes	0.12
	No	0.17
April	Yes	0.17
	No	0.34

*119 gallon storage tank

Emissions factor comparisons



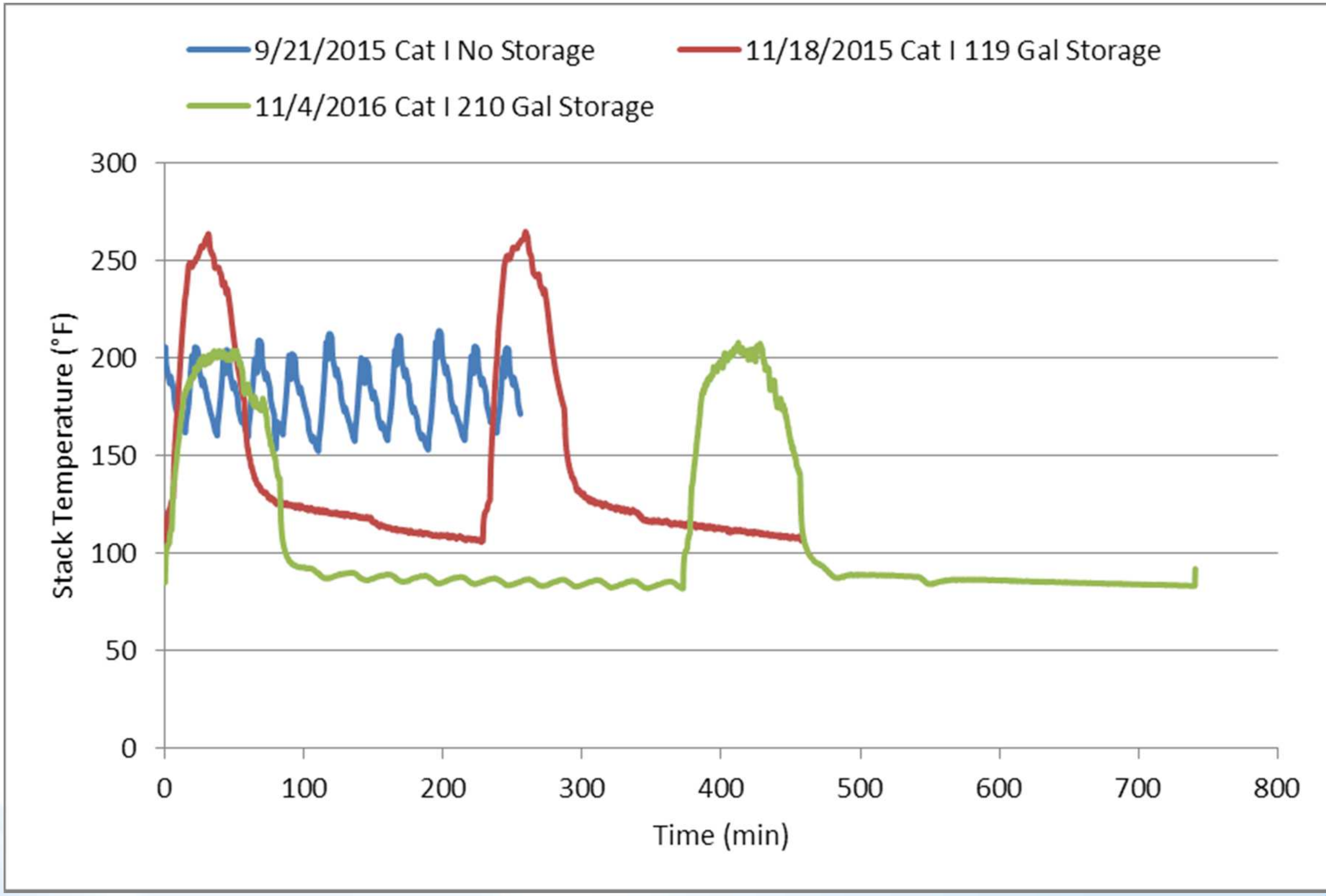
Comparing category I to April load profile



Results for Category I tests; single test days

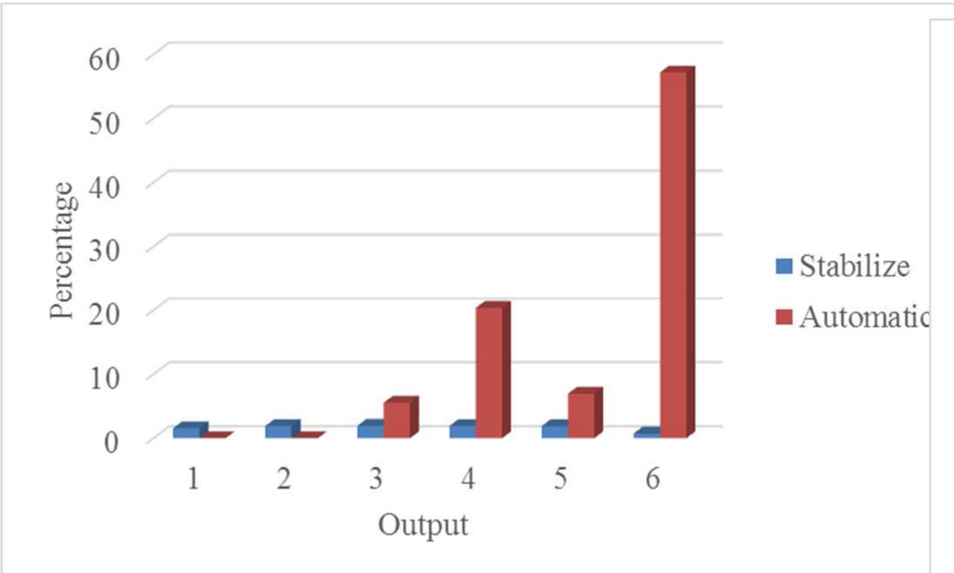
Storage			N	Y (119 gal)	Y (210 gal)
Output		*BTU/hr*	10,168	12,113	11,370
Emissions	**Rate**	*g/h*	1.97	0.97	1.21
	Index	*g/kg*	1.89	0.74	0.83
	Output	*lb/MMBtu*	0.41	0.13	0.15
Average burner run time		*min*	5.5	45.0	83.0
Average fuel consumed per cycle		*lbs*	1.32	7.61	12.3

Trends for Category I tests

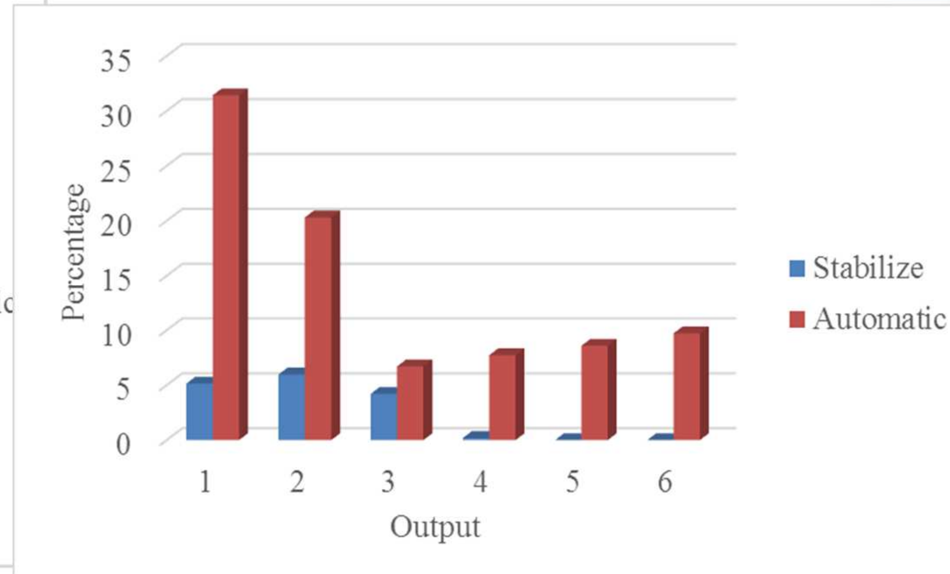


Burn rate distribution

With storage (119 gal)



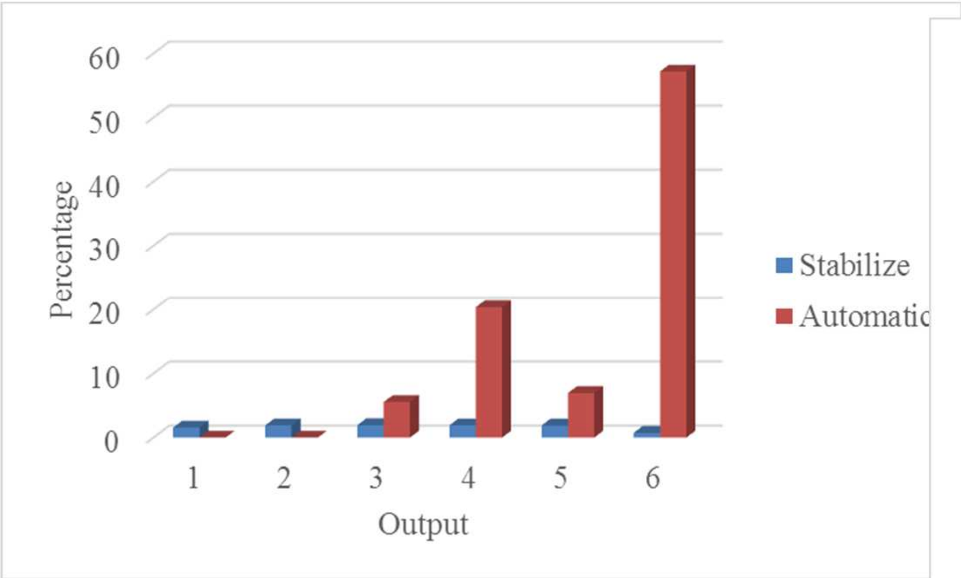
Without storage



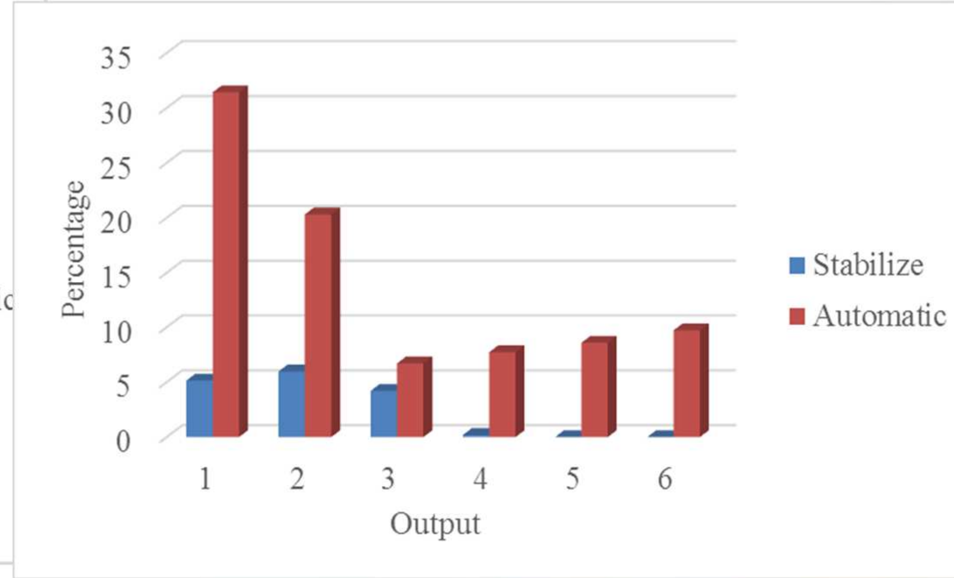
Slide shows burn rate distribution with and without storage. Output 6 is the highest firing rate and Output 1 is the lowest, nominally 30% of full load. This test is an April day (low load). With storage, the boiler spends a lot more time at high firing rate, which is the cleanest condition. Without storage, where it is cycling a great deal, the boiler spends more time at low load during warm up periods.

Burn rate distribution

With storage (119 gal)



Without storage



= operating in a ramp-up mode to full fire following startup

= after stabilize or ramp-up mode operating in full automatic mode

Conclusions

Adding thermal storage with an automatic feed boiler dramatically reduces cycling rate and particulate emissions;
The most significant impact of thermal storage is under low and moderate load conditions.

Thank you!