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Field Test of Boiler Primary Loop Temperature Controller

P. Glanville, P. Rowley, D. Schroeder, and L. Brand
Partnership for Advanced Residential Retrofit

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

AFUE	Annual Fuel Utilization Efficiency
ALM	Advanced Load Monitoring
BMS	Building Management System
Btu	British Thermal Unit
CNT	Center for Neighborhood Technology
CDD	Cooling Degree Day
DOE	U.S. Department of Energy
GTI	Gas Technology Institute
HDD	Heating Degree Day
MBH	Thousand Btu per hou
NYSERDA	The New York State Energy Research and Development Authority
OTR	Outdoor Temperature Reset

Executive Summary

Chicago's older multifamily housing stock is predominantly heated by centrally metered steam or hydronic systems, and the cost of heat for tenants is typically absorbed into the owner's operating cost and then passed to tenants via monthly housing charges. Thus any reduction in site heating costs, driven actively through efficiency measures or passively through reducing fuel costs, can result in lower tenant rents and more affordable housing.

As boilers typically have long service lifetimes, the incentive for retrofit system efficiency upgrades is greater than equipment replacement for the efficiency-minded owner. System improvements representing the "low-hanging fruit" are familiar, as simple as improved pipe insulation to aftermarket controls such as outdoor temperature reset (OTR) or lead/lag controllers for sites with multiple boilers (see Figure 1).

Figure 1. *M2G*-equipped boilers at test site

Beyond these initial system efficiency upgrades are an emerging class of advanced aftermarket controllers that dynamically respond to the boiler load, with claims of 10%–30% of fuel savings over a heating season. Limited to hydronic boilers specifically, these devices perform load monitoring, with continuous measurement of return—and in some cases supply—water temperatures. An onboard microprocessor with memory of past boiler cycling adjusts normal cycling by preventing the boiler from firing for a period of time, to prevent unnecessary and inefficient operation during perceived low load conditions. If these savings are realized, these advanced controllers offer an attractive alternative to an equipment upgrade (e.g., non-condensing to condensing boiler) with a similar magnitude of energy savings. In addition, it is claimed that savings can also be achieved post-equipment upgrade, for high-efficiency boilers as well, since the controllers reduce boiler cycling and minimally impact steady state boiler thermal efficiency. Quantifying the savings of one of these advanced controllers, the Greffen Systems *M2G*, is the primary goal of this field test subtask.

This field task is building on recent research performed on the *M2G* and similar competing advanced controllers, including an ongoing controlled laboratory assessment at the Gas Technology Institute (GTI). This task proposes to build on this research while focusing the field component on a unique application, low-rise multifamily housing, as prior field research focused on large commercial buildings (office space, hotels, and university dormitories). In addition to measuring realized savings over a heating season, the data collection offers a greater insight into the conditions under which the controllers "decide" to hold the boiler and how, if at all, adverse effects are created by dropping the low temperature limit (e.g., loss of thermal comfort).

Using two multifamily buildings within the Chicagoland area as sites to evaluate the *M2G*, which to date has been primarily applied in large commercial and industrial applications, the preliminary results are as follows:

- At a Chicago, Illinois, site, two boiler rooms serve separate heating loops within the same multifamily building. Each boiler room, A and B, is served by two hot water boilers. Boilers in room A were equipped with an advanced load monitoring (ALM) controller, the *M2G*, and those within room B were not, the latter serving as the control system. Comparing 2012–2013 to 2013–2014 cycling behavior, the control system saw little variation year-over-year when examining boiler differential, behavior of the existing OTR controllers, and the cycling statistics. The ALM-controlled boilers did see significant variation over the shoulder season monitoring period. Variable cycling rates were observed during ALM-controlled periods directly and indirectly, with year-over-year weather-adjusted reductions in boiler cycling of 32% and an estimated therm savings of 14% recorded, on par with prior studies. Unlike prior studies, these reductions in boiler cycling rates were observed while operating in parallel with an existing OTR system. The savings analysis distinguishes ALM controller savings from OTR savings, with ALM savings for this site of almost 0.4 therms/heating degree day, yielding an estimated payback of less than 4 years at local natural gas prices.
- At a Cary, Illinois, site, where ALM controllers were implemented on an alternating week-on/week-off schedule, the impact of the ALM controllers was demonstrably more muted for several reasons. The observed weather-adjusted therm savings of 3% on average, with 7% over the shoulder season, reflects how the Cary site boilers are less oversized than those at the Chicago site. With fewer cycles per day, in some cases with boilers operating continuously for several hours, the ALM controllers had fewer opportunities to reduce dry-cycling losses. Data and analysis from the site prove useful in identifying characteristics of sites ill-suited for cost-effective applications of ALM controllers: those with moderate to high utilization factors, fewer than 50 cycles/day on average, and with large operating differentials.

1 Introduction

For space heating applications, hot water boilers are generally oversized by a factor of 50%–100% under average conditions and 15%–30% under winter design conditions, causing the boilers to cycle hundreds of times per day (Wu et al. 2007). With this high cycling rate there are several factors that can affect system efficiency and boiler performance, including:

- **Thermal inertia of boiler:** As any heated metallic surface, the boiler heat exchanger requires time to get up to a steady-state temperature, limiting the boiler's thermal efficiency for an initial period each cycle. As the boiler cycles for short periods, the duration of firing at steady state efficiency (i.e., rated efficiency) is reduced. Fewer cycles for a given load mean longer cycles, whereby the boiler operates for longer durations at the rated efficiency.
- **More pre- and post-purge cycles:** Induced and forced draft hot water boilers (as opposed to natural draft) employ pre-purge and post-purge cycling of the combustion air in the blower and flue gas inducer to ensure proper ignition before and evacuation of combustion products from the venting after each firing cycle. This acts to cool off the mass of the heat exchanger and water contained, thus further extending the time required to reach steady-state thermal efficiency for each cycle. Fewer cycles reduce the number of pre- and post-purge cycles, thus reducing this enhanced cycling heat loss.
- **Thermal expansion:** Failures of hot water boiler heat exchangers occur primarily due to three factors: (1) corrosion, driven internally by cycling water impurities (including air) and externally by unintentional production of combustion condensate; (2) pressurization anomalies on the water side, caused by unwanted cavitation and/or steam production; and (3) thermal expansion and contraction of the heat exchanger. The third factor, thermal expansion and contraction, is accelerated with more frequent boiler cycling, thus fewer cycles reduce this impact on long term reliability.

In addition to well-established practices, such as improved pipe insulation, the building owner now has several retrofit options to address the delivered efficiency of their hot water boiler. Note that "delivered efficiency" differs from thermal efficiency, in that the former is a transient efficiency of the heating system including cycling losses and the latter is the steady state efficiency of the boiler alone. Many retrofit options for improved efficiency are well known, such as outdoor temperature reset (OTR), whereby an aftermarket controller adjusts the boiler aquastat set point in proportion to the outdoor temperature, adapting the boiler operation over seasonal and diurnal ambient temperature variations. As OTR controllers are widely used, some further details concerning their operation is provided to be used as a contrast to advanced load monitoring (ALM) controllers, such as the subject of this field test task.

Put briefly, the OTR controller attempts to match the heat input from the boiler to the heat output (or loss) from the building to the ambient environment. Concerning thermal comfort, the OTR controller reduces hot water temperatures proportional to outdoor temperatures, increasing thermal comfort by delivering more even heating over a range of outdoor temperatures. To determine this proportional relationship, an analysis of the building heat loss must be made prior to installing an OTR controller, as outdoor temperature is an insufficient indicator to inform aquastat adjustments from one building to another. To achieve this improvement in comfort the OTR controller adjusts the aquastat setting while maintaining a fixed differential,[1] or deadband.

While beneficial to occupant comfort, the primary benefit of an OTR controller is the efficiency gain. Beginning from aquastat settings appropriate for peak heating demand, the OTR reduces the aquastat setting during the warmer shoulder seasons, where without an OTR the higher aquastat settings would result in an increased heat loss of the building, with a higher indoor/outdoor temperature difference. Additionally with peak heating aquastat settings during the shoulder seasons, boiler firing cycles would be shorter in duration, as higher water temperatures lead to higher heat transfer rates to the conditioned space. Note that these may not be additive benefits depending on the heat loss response of the building, as an OTR controlled boiler may see similar cycling during shoulder seasons as a boiler without OTR control, due to the effective reduction in the heating load with OTR control.

While providing energy savings by effectively reducing the heating losses during the shoulder seasons, the OTR controller may exacerbate issues previously described from boiler oversizing by maintaining a constant differential while reducing the aquastat setting. For example, if an OTR controller equipped boiler has a 200°F aquastat set point with a 10°F differential during peak conditions and reduces the aquastat setting to 180°F, the boiler will be cycling more frequently and with shorter durations as (1) the lower return and supply water temperatures will improve the thermal efficiency of the boiler thus shortening the firing time; and (2) as the lower heating temperatures delivered to the space reduce the heat loss of the building, thus the load, the boiler is more oversized. In this example, it may seem odd to highlight two positive aspects of OTR performance, higher thermal efficiency during firing and a reduction of the building heat load during shoulder seasons, as detrimental to the delivered efficiency of the heating system. However, for the reasons outlined they may also contribute to increased cycling losses.

In contrast to OTR controllers that respond to an indirect indicator of the changing heating load, ALM controllers monitor the heating load directly through measurement of the return water, and often the supply water as well. Rather than improve delivered efficiency through the reduction of building heat loss during non-peak heating conditions, the goal of ALM controllers is to reduce cycling losses of oversized boilers by increasing the duration of cycles and reducing the number of cycles through dynamic management of the boiler differential. ALM controllers do not adjust the aquastat setting like OTR controllers, thus they are better suited for: (1) installations that have domestic hot water production; (2) installations equipped with building management systems (BMS),[2] which may include scheduling and sequencing of boilers; and (3) managing the potential for heat exchanger reliability issues with thermal expansion or flue gas condensate due to colder return water temperatures.

1.1 Background

As ALM controllers are load dependent in their performance, energy savings may vary significantly from site to site for a given climate, presenting a unique challenge in their evaluation for the research community. The proportional response of OTR-controlled boilers to

[1] Differential, also referred to as the deadband or variance, is the temperature difference between the aquastat set point and the low temperature limit. For example, with a differential of 10°F and an aquastat set point temperature of 180°F, the boiler will begin firing when the return water temperature drops below 170°F.

[2] In fact, some ALM controllers are compatible with OTR-controlled boilers, such as the *M2G*.

changes in outdoor temperature is static, whereas ALM-controlled boilers are dynamic in their response to changes in load patterns not linked to outdoor temperature, such as occupancy, solar loading (external and internal), wind impacts, and other efficiency improvements over time. As the outdoor temperature is readily measurable and the proportional response of the OTR-equipped boiler is well defined, OTR control methods were readily incorporated into building energy simulation software (Ellis et al. 2008). On the other hand, this challenge still remains for ALM controllers, due to a lack of available datasets and their level of complexity.

Commercialized ALM controllers, manufactured by Greffen Systems, Intellidyne, Sandler Energy Systems, and others, are unique in their approach but can all be described as *ALM controllers using return and possibly supply water temperatures to inform dynamic management of a boiler temperature differential*. Each controller uses real-time temperature measurements and prior on-cycle/off-cycle data to inform its decisions. In general, the ALM controllers do not require calibration or boiler adjustment, because they are "learning" controllers. As their controlling algorithms are a proprietary feature of their technology, developing a better understanding of their methods is important for predicting future savings.

1.1.1 Prior Testing of Advanced Load Monitoring Controllers

As ALM controllers are a relatively new class of retrofit efficiency solutions, prior published research is limited. An important study was performed for the New York State Energy Research and Development Authority (NYSERDA) by Intellidyne and Brookhaven National Laboratory (Hammer et al. 2007). In this evaluation, Intellidyne's ALM controllers were evaluated at several field industrial and commercial sites, covering a range of Intellidyne's controller products including those for hydronic heating, steam heating, air conditioning, and refrigeration. Of the hydronic ALM controllers evaluated, savings of 12%–13% were recorded, adjusted for heating degree day. In addition to the field evaluation, Brookhaven National Laboratory performed laboratory evaluations of ALM controller-equipped boilers to quantify pollutant emission rates per cycle with and without control. This study is important to the planning of the proposed task, as it was thorough in validation of energy and emission savings for a range of applications. To date, no other evaluation of the Intellidyne product has been published beyond brief case studies issued by the manufacturer.

Similarly spare in available published research, the more recently introduced Greffen Systems *M2G* has been evaluated only in field applications. Greffen Systems has issued a series of brief case study reports through its website, indicating 10%–30% energy savings. Subject sites are primarily commercial and industrial, with the only residential applications published concerning high-rise condominiums and university dormitories. Thus, the only published research on the performance of the *M2G* at this time is from Greffen Systems. In addition to energy analysis reports, published by Greffen Systems from extended monitoring of customer installations including schools, large office buildings, universities, manufacturing facilities, and high-rise condominiums,[3] the University of Texas A&M Energy Systems Laboratory collaborated with Greffen to validate performance claims for a Houston area school district, confirming 21% fuel savings over a 30-day monitoring period.

[3] See References section for complete list

1.2 Gas Technology Institute Testing of Advanced Load Monitoring Controllers

This field work focusing on the *M2G* is complementary to a recently completed natural gas utility-supported laboratory evaluations of ALM controllers by Gas Technology Institute (GTI). Both ALM controllers evaluated in the laboratory successfully reduced boiler cycling and decreased energy use. However, for this field study, the *M2G* was selected due to the lack of third-party field data on this specific ALM controller and its compatibility with the low-rise multifamily buildings identified as a potential new application of ALM controllers in general (Figure 2). The laboratory evaluation of ALM controllers evaluated the comparative response of ALM controllers to a series of dynamically controlled heating loads, simulating several building types with Chicago climate data. As quantifying thermal comfort and representing the two-way response of a heating load to an ALM controller are both very difficult with controlled laboratory experiments, this field task is necessary for a complete assessment of its performance.

Figure 2. Greffen *M2G* ALM controller

In a recently completed laboratory study comparing ALM products, an automated test stand was developed to evaluate their potential for energy savings with hot water boilers. The laboratory test stand was used for steady-- state testing and to simulate the heating demand from a typical building. The test stand subject, shown in Figure 3, was a residential boiler installed in a primary/secondary configuration. While the single-stage residential sized hot water boiler is a fraction of the size of typical boilers ALM controllers are installed on, the test stand was operated in a manner representative of typical installations, in agreement with the controls manufacturer. The boiler circulator pump and the secondary loop pump operate continuously throughout the tests at approximately equal flow rates, equivalent to a hydronic system simple circuit configuration with a system volume scaled appropriately to the boiler output.

Figure 3. GTI laboratory test stand

Heating profiles for 24-h tests were determined using EnergyPlus models based on two U.S. Department of Energy (DOE) reference buildings: a post-1980 Chicago secondary school and a post-1980 Chicago large hotel. These models were run with Typical Meteorological Year 3 climate data for Chicago, the modeled boiler capacity was based on a scale factor of 1.2 peak load, piping losses were simulated, and a primary/secondary hot water loop piping configuration was employed. Resulting heating loads were scaled for the test setup using the ratio of the reference building boiler capacity to the capacity of the test boiler.[4] Heating loads representative of an average winter and shoulder season day, with 31 and 11 heating degree days (HDDs), respectively (65°F baseline).

Comparing the *M2G* to baseline performance for single-day savings, results overall were in agreement with the 10%–30% savings quoted by manufacturer-sponsored studies. A summary of these results is shown in Table 1, highlighting the reduction in cycles and therm savings for the simulated daily test, the annualized therm savings over a heating season,[5] and average reduction in the secondary loop temperature. It is important to note that this comparison to baseline is assuming a fixed 5°F differential that may be uncommon in small- to medium-sized multifamily housing.

Table 1. Summary of Results From GTI Laboratory Testing of *M2G*

Building Simulated	Heating Profile	Percent Reduction in Cycles	Therm Savings (Actual)	Therm Savings (Annualized)	Average Reduction in Secondary Loop Temperature (°F)
Chicago-Area Secondary School	Winter	58.0%	7.9%	10.0%	9
	Shoulder Season	44.6%	15.5%		11
Chicago-Area Hotel	Winter	67.1%	16.3%	16.6%	11
	Shoulder Season	68.4%	17.4%		11

1.3 Relevance to Building America's Goals

Overall, the goal of the DOE Building America program is to "reduce home energy use by 30%-50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." To this end, we conduct research to "develop market-ready energy solutions that improve efficiency of new and existing homes in each U.S. climate zone, while increasing comfort, safety, and durability."[6]

ALM controllers as a retrofit performance optimization measure for multifamily hydronic heating is promising, with 10%–30% savings claimed by manufacturers. However, uncertainty remains in (1) where the actual savings will lie within or outside of that range; and (2) how these controllers will perform in low-rise multifamily applications. If fuel savings are realized at 15%, these ALM controllers will be demonstrated as a viable and commercially available retrofit efficiency measure. As the Chicagoland area is a heating-dominant climate zone with an average

[4] For the methodology and preliminary full datasets, consult the recent ASHRAE publication (Rowley et al. 2012)
[5] Heating season assumed as all days with HDD > 5°F day
[6] http://www1.eere.energy.gov/buildings/building_america/program_goals.html

of roughly 6,500 HDDs and 800 cooling degree days (CDDs) and with 470,000 multifamily units, it is an appropriate location for this field evaluation.

1.4 Cost Effectiveness

The combined installation and equipment cost of the *M2G* is $7,700. If 15% savings are realized for a multifamily building owner with an annual heating cost of $25,000, the ALM controller will pay for itself in a little over 2 years.[7] The *M2G* is a "one-size-fits-all" ALM controller, operating as designed typically on 700 MBH and 15.0 MMBH hydronic boilers alike, thus, the higher the heating cost the greater opportunity for savings and the shorter the payback period.

As described in the background section, ALM controllers derive savings through the reduction of boiler cycling losses and are dynamically responsive to changes in load patterns. It is important in this and future field evaluations to consider the combined impact of other heating retrofit energy efficiency measures on ALM controller performance. For example, on the one hand, envelope improvements act to further oversize a hot water boiler, thus yielding improved savings from ALM controllers. On the other hand interactions with OTR controllers or sequencing controls act to improve cycling behavior to "right-size" the boiler(s), thus reducing the benefit of ALM controllers.

1.5 Tradeoffs and Other Benefits

The primary benefit of ALM controllers is the reduction in boiler cycling losses, thus increasing performance. However, through dynamic management of the aquastat differential there are additional non-efficiency benefits:

- Reduced thermal cycling of the heat exchanger results in longer life of boiler
- Fewer cycles of longer duration increase the steady state efficiency of the boiler in addition to reducing its cycling losses. With more operating time at design conditions, fewer pollutants (e.g. carbon monoxide and nitrogen oxide) associated with startup and shutdown are emitted.
- Ease of installation; for example, the *M2G* does not require cutting into water or gas pipes since the temperature sensors are surface mounted. Install times average 90 minutes per boiler.
- Adaptive control without calibration. ALM controllers do not generally require initial calibration or adjustment over their period of use.
- While both OTR and ALM controllers reduce the low limit water temperature, the ALM adjusts it dynamically and can better manage issues brought on by cold return water temperatures (thermal stresses, unwanted flue gas condensation). OTR controllers decrease the aquastat setting and maintain a given differential, therefore do not independently measure or control the return water temperature.

As mentioned concerning the NYSERDA evaluation of Intellidyne's ALM product line, hot water boilers are one of many targets of ALM controllers. This field evaluation may inform field evaluations of air conditioning, refrigeration, and other non-boiler ALM controller studies.

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[7] Note that one *M2G* is required per boiler, thus sites with backup boilers will have reduced payback times.

2 Research Methods

2.1 Research Questions

- What energy savings are realized over a heating season by an *M2G* equipped hot water boiler in a low-rise multifamily building?
- Do the savings differ from those observed for commercial and industrial field evaluations? If so, what is unique about the low-rise multifamily sites to cause this?
- Under what conditions does this ALM controller “decide” to hold the boiler from firing and when does it allow the boiler to fire?
- What is the minimum temperature to which this ALM controller allows the return water to drop?
- Is there a perceived change in thermal comfort from heating with and without an ALM controller?

2.2 Site Selection

Partnership for Advanced Residential Retrofit team member Center for Neighborhood Technology (CNT) assisted GTI in recruiting hydronically heated low-rise multifamily buildings as potential test subjects for this ALM controller field test. Working in cooperation with the *M2G* manufacturer, Greffen Systems, a list of site requirements and ideal site qualities was developed:

- The site must have central heat from a hot water boiler.
- OTR, BMS, or other additional controls are OK.
- Target annual heating costs are $25,000 or more.

Ideal site qualities were:

- Boiler aquastat differentials must be less than 15°F.
- Site is served by a single hot water boiler, individually metered.
- Pipe layout is in primary/secondary loop architecture.
- Thermostat is controlled centrally or tenants agree to not change thermostats or modify building heating load.

Prior to installation and initial recruitment of test subjects, GTI and a representative from Greffen Systems visited each site and made installation recommendations. Between in-kind support from Greffen Systems and cost-sharing from GTI, the project team agreed to provide installation of *M2Gs* at no cost to the test subjects. Greffen has offered that if the site owners are pleased with the performance, they can keep the *M2G* controller.

2.2.1 Site Selection Challenges

Surprisingly few properties within the CNT database initially met the requirements of this field test program, at 6% of hydronically heated buildings. With properties predominantly within the City of Chicago, the primary issue is the specification of low-rise multifamily housing. For a building to be sufficiently large so as to have annual heating costs in excess of $25,000, they often are four stories or taller. Due to the older age of the Chicago-region housing stock, large low-rise multifamily housing (30 or more units) are more sometimes served by central steam boilers, both one and two-pipe systems. During initial site visits, one initially qualifying site was found to have a central steam boiler despite confirmation with the site to the contrary. Additional leads were ultimately found to be incompatible or not interested in participating with the field testing. As commercial central heating has historically shifted from steam to hot water, multifamily buildings have experienced this trend as well (Zuluaga et al. 2012).

Eventually, success was found working with a Chicago-based property management company with a focus on affordable housing (specifically "Section 8" housing), offering several potential properties that met the requirements of the field testing. Following initial screening site visits, two were identified as candidates and the *M2G* installation was scheduled. The installation at the first site in Chicago, Illinois, was successful. At the second site in Cicero, Illinois, unfortunately access could not be gained to the necessary aquastat leads during the installation of an *M2G* controller. The *M2G* interacts with the boiler through splicing into these wires, which were for the Laars model boilers (Figure 4) were part of an integrated circuit board, preventing the *M2G* installation at this site. This lack of access for the *M2G* installation is a concern for the vendor, who has plans to address this with future product offerings.

Figure 4. Incompatible boilers at Cicero site

Seeking a second host site, GTI leveraged its relationship with Nicor Gas, screening multifamily customers throughout the Chicago suburbs with survey data on multifamily central heating systems. Candidates were identified, screened through interviews and in some cases initial site visits. Following the identification of an acceptable test site in Cary, the site contact expressed interest and presented the details of the test program to their board of directors at their subsequent board meeting. Ultimately accepting, the *M2G* and data collection equipment were installed promptly thereafter.

2.2.2 Field Test Site Characteristics

2.2.3 Site #1: Chicago Site

This three-story "S"-shaped affordable housing apartment building, shown in Figure 5, has two separate boiler rooms serving a total of 51 units that do not have individual control over unit heat. Its most recent year-over-year natural gas consumption was 46,770 therms (2011–2012).

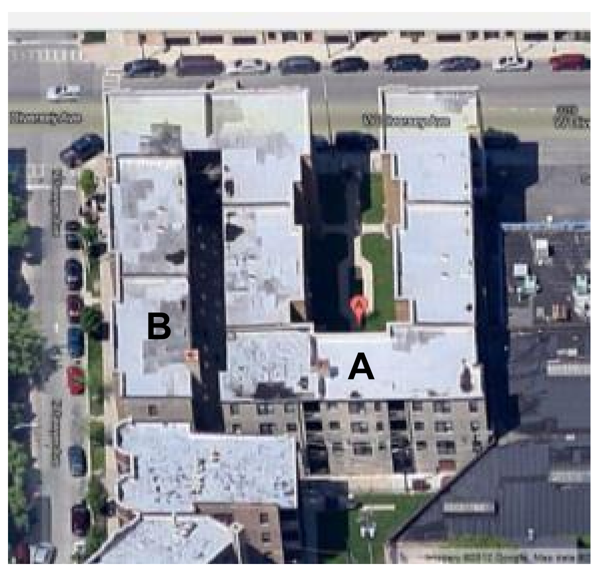

Figure 5. Aerial view of Chicago site

The two boiler rooms located as shown (A and B), each with two hot water boilers for space heat, serve separate heating loops within the building. *M2G* controllers were installed in one of the two boiler rooms (A), with the other serving as a control group, with non-*M2G* boilers monitored as well. Each heating loop operates with constant speed circulators and boilers operate with fixed temperature differentials. Additionally, each boiler room has its own common meter, which in the case of boiler room A includes two storage water heaters serving the entire buildings domestic hot water needs.

2.2.4 Site #2: Cary Site

The two story, two building apartment complex in Cary, IL, approximately 45 miles northwest of downtown Chicago, served as the second test site. M2G controllers were installed on each of the two hot water boilers serving the first of two buildings, on the left-hand side of the aerial photo in Figure 6. This building has 26 apartments, which like the first field site do not have tenant control of heat. The building is served by a single gas meter, including gas-fired cooking appliances and central domestic hot water production with space heating. Over 2011, the building consumed 13,090 therms.

Figure 6. Aerial view and photograph of Cary site

In both cases of monitoring *M2G*-equipped boilers, within boiler room A at the Chicago site and the Cary site, two water heaters are tied into the same gas meter as the two boilers are, necessitating monitoring of water heater cycling in addition to boiler cycling. The characteristics of the hot water boilers and water heaters at each site are summarized in Table 2.

Table 2: Boilers and Water Heaters at Two Field Sites

Site		Gas Boilers	Gas Water Heaters
Chicago	A	Two boilers in parallel Make: Teledyne Laars Model: "Mighty Therm" Two-stage firing: 1.2 MMBtu/h/0.3 MMBtu/h Controller: Tekmar 264 (sequencing and OTR)	Two Heaters in Parallel **WH1 -** Make: American Std. Model: D100 199AS Input: 199,000 Btu/h Volume: 100 gallons **WH2 -** Make: Ruud Model: G100-200 Input: 199,900 Btu/h Volume: 100 gallons
	B	Two boilers in parallel Make: Teledyne Laars Model: "Mighty Therm" Two-stage firing: 850,000 Btu/h/212,500Btu/h Controller: Tekmar 264 (sequencing and OTR)	N/A
Cary		Two boilers in parallel Make: Weil-McLain Model: LGB-4 Single-Stage Firing: 400,000 Btu/h Controller: Tekmar 252 (sequencing and OTR)	Two heaters in parallel **WH1 -** Make: A.O. Smith Model: BT-100-300 Input: 75,100 Btu/h Volume: 98 gallons **WH2 -** Make: Bock Model: 80G-1995SD Input: 199,900 Btu/h Volume: 80 gallons

2.3 Setup and Installation

To answer the questions outlined in Section 2.1, the field test sites must measure the inputs recorded by the *M2G*; the supply and return water temperatures via surface thermocouples on the water pipe exterior; and quantify the fuel consumption of the boiler, directly via dedicated metering or indirectly via state logging of the gas valve activation using rated firing rates. In addition, the ambient temperature within the boiler rooms and several mixed primary loop water temperatures downstream of junctions using surface thermocouples are measured. Mounted exterior to the return and supply piping, thermocouples are insulated when the balance of piping is. Piping at the Cary site was not insulated and the Chicago site was, as shown in Figure 7. State loggers that individually track gas valve openings are mounted on the respective boiler and water heater. Note in the case of the Chicago site two-stage boilers, the high and low firing stages both have a state logger. A summary of data collection equipment is shown below in Table 3.

Figure 7. *M2G*-equipped boilers at Cary (left) and Chicago (right) sites

Table 3. Data Collection Summary

Data Collected	Method of Measurement	Method of Data Logging	Data Sampling Interval
Indoor Air Temperature	3M ambient temperature logger		15 minutes
Return/Supply Water Temperatures	K-Type surface thermocouple	Extech 3-channel TC logger	5 seconds
Primary Loop Mixing Temperatures	K-Type surface thermocouple	Extech 3-channel TC logger	5 seconds
Boiler/Water Heater Cycling and Fuel Consumption	Dent SmartLogger CT time of use logger		N/A, records all events to nearest second

Water temperatures are the only feedback ALM controllers use to actively control boiler differentials, reducing cycling losses. Since the ALM controllers are dynamic and the M2G samples every 10 seconds, the level of accuracy and time resolution for temperature measurements is critical. As the *M2G* only inhibits the boiler from firing following a call for heat (it cannot stop a firing boiler, nor can it activate an idle boiler), the following scenarios will prompt the *M2G* to release the boiler to begin firing from a detected call for heat from the aquastat (Escatel 2012):

- Supply temperatures have dropped more than 14°F.
- Return temperatures have dropped more than 5°F.
- The *M2G* has held the boiler from firing for 15 minutes or more.
- The proprietary algorithm onboard determines it is a true call to heat, as opposed to standby firing due to losses (“dry cycling”), consulting onboard memory of prior cycles.

With water temperatures monitored at the supply and return of each boiler and mixed return and supply temperatures, the first three scenarios can be readily detected. In the same manner as the *M2G* controller, which does not require any calibration to boiler system settings but rather infers what the aquastat set points and differentials are (allowing for compatibility with OTR or other temperature-based controllers), a suppressed call for heat can be detected through data analysis based upon a boiler's supply temperature at the end of a previous cycle. These temperatures are measured with K-type surface thermocouples and logged every 5 seconds using the three-channel TC logger manufactured by Extech with expanded onboard memory. For each boiler room, temperature loggers were setup within a custom case and ambient temperature loggers were mounted close by, as shown in Figure 8.

Figure 8. Chicago site—TC logger in room A (right) and monitored boilers in room B (left)

In order to provide a comparison to baseline performance at the Chicago site, the cycling activity of the *M2G*-equipped boilers in room A is compared to the boilers without *M2G*s in room B, with similar occupancy schedules and building-ambient environment interaction. At the Cary site, the *M2G*s are activated by a weekly timer for week on/week off operation. In other words the *M2G* controls the boiler operation one week, starting on Tuesdays at midnight, and will not interfere with boiler operation the following week. As such, a period of baseline data collection is not necessary. With the week on/week off sequencing of the *M2G* during periods of stable weather and with the permission of the site owner, the project team interviewed maintenance staff concerning tenant complaints and service calls, to see if there was a noticeable change in comfort from the use of the *M2G*.

3 Results and Discussion

3.1 Site-Specific Discussion

As is common with small sample size field evaluations, the resulting data can be highly biased by the conditions of the field site. Over the sample periods noted previously, the initial datasets from the Chicago and Cary sites are no different in this regard. The following sections describe field conditions that may add bias to the resulting datasets.

3.1.1 Chicago Site

In total between boiler rooms A and B at the Chicago site, *M2G*-equipped and baseline respectively, there are two water heaters and four boilers monitored serving two separate primary and secondary hot water heating loops. All four boilers at the Chicago site are controlled by the Tekmar 264 controller, for sequencing and outdoor temperature reset control, where settings may be modified by the end user. As opposed to operating the *M2G* boilers as week on/week off, comparisons can be made between the *M2G*-controlled boilers in boiler room A during portions of the 2013–2014 monitored heating season with the previous 2012–2013 heating season, during which the *M2G*s were disabled (for reasons discussed in subsequent paragraphs) and also with the baseline boilers in boiler room B, monitored over both heating seasons.

Useful data from the *M2G*-equipped boilers in boiler room A during the 2013–2014 heating season were unfortunately limited to a month-long period due to two difficulties experienced with the host site, a catastrophic failure of an *M2G*-equipped boiler during the 2012–2013 heating season (not related to the *M2G* controller), and an interruption in testing during the 2013–2014 heating season requested by the host site due to:

- **Failure of boiler #1 within boiler room A during 2012–2013 heating season:** Following installation of the *M2G*s and data collection hardware, monitoring began in November, 2012. During the installation, boiler #1 within boiler room A (equipped with an *M2G*) was operational, as Greffen requires that boilers be functional and eventually tested during an *M2G* installation. This boiler was operable, but observed to be periodically tripping a fault. Maintenance staff noted that the boiler was scheduled to be serviced shortly and would be operating in early December nearing the peak heating months.

The boiler was found to be catastrophically damaged and taken out of service for the balance of the heating season. According to site maintenance staff, following servicing and operation of the boiler, insulating firebrick began crumbling and falling to the burners and below, and subsequently the boiler was taken out of service. As shown in Figure 9, the boiler and the removed burner assembly show signs of heat damage, appearing as discoloration of the boiler exterior (in comparison to boilers in room B, Figure 8) and burner surfaces. The state loggers on the high and low stage of boiler #1 indicate the unit was fired for 8 days in late December with consistent and frequent short cycling, later found to be due to an undiagnosed faulty ignition system which led to large, irregular loop temperature swings damaging the firebrick. Confirmed by the extent of the damage, maintenance staff attribute this failure to the age of the boiler and in no way connect the boiler's failure to the *M2G*.

Figure 9. Damaged boiler #1 at Chicago site A with removed burner assembly (right)

The boiler was not replaced until September 2013, and assuming the two pairs of boilers in rooms A and B were specified with the same oversize factor,[8] this places an undesirable bias on assessing the impact of *M2G*-equipped boilers. With one boiler serving the A heating loop (the other was disabled) and two boilers serving the B heating loop over the 2012–2013 season, the former closer to right-sized on average and potentially undersized during peak winter conditions. As the *M2G* achieves energy savings proportional to the degree to which a boiler is oversized, by limiting idling losses (so-called "dry cycling"), the impact of the *M2G* on boiler #2 in room A was expected to be muted outside of the shoulder season during the 2012–2013 heating season, when boiler #1 was disabled.

Cycling behavior and loop temperatures were monitored for both boiler rooms A and B over the 2012–2013 heating season despite the removal of the boiler in Figure 9 from service. Through sequencing control of the Tekmar controllers, as observed over both 2012–2013 and 2013–2014 heating seasons, the boilers within each pair (A and B) were observed to only operate individually, switching daily from one boiler to the other in the early morning, thus data collected from boiler #2 in room A was usable as a baseline.

- **Interruption in *M2G* functionality during 2013–2014 heating season:** Following the replacement of boiler #1 in boiler room A and the subsequent installation of an *M2G* onto this boiler in October, 2013, a cold snap in late November followed by a series of tenant heating complaints led the site property management firm to request that the *M2Gs* be taken out of service believing they were the cause of the unacceptably low loop

Figure 10. Replacement boiler #1

[8] To the knowledge of the property management company, this is the case.

temperatures. Investigating this issue, GTI found that these low loop temperatures were experienced prior to installation of the *M2Gs* and were in fact due to poor calibration of the existing OTR/sequencing controls to the new boiler. In regaining permission to continue testing following this investigation, further delayed by periodic Section 8 inspections during the peak winter months, the site did not permit reactivation of *M2Gs* until late February. Data collection was continuous over both heating seasons; however, data useful for analysis are described in the results section, specifically in Table 14.

3.1.2 Cary Site

The *M2G*s at the Cary site were programmed to operate week on/week off on the pair of boilers providing hot water for space heat. The weekly timer switch activates the *M2G* controllers each Tuesday at midnight, intended to minimize the impact of variable occupancy over weekends and holidays. The two boilers at the Cary site are controlled by the Tekmar 252 controller, for sequencing and outdoor temperature reset control, where settings may be modified by the end user.

During the installation of the *M2G* controllers and data acquisition hardware, it was found that the first of two water heaters ("WH1" per Table 2) was not compatible with the state loggers to monitor runtime, due to design of its gas valve. To infer runtime, a temperature measurement of the flue gas was used as a proxy of runtime. In post-processing shown with the example in Figure 11, actual firing cycles are differentiated from ambient heat pickup from boiler runtime that can be observed as the oscillation at flue gas temperature peaks and valleys (such as water temperature measurements, this flue gas temperature measurement is made with an external surface thermocouple.

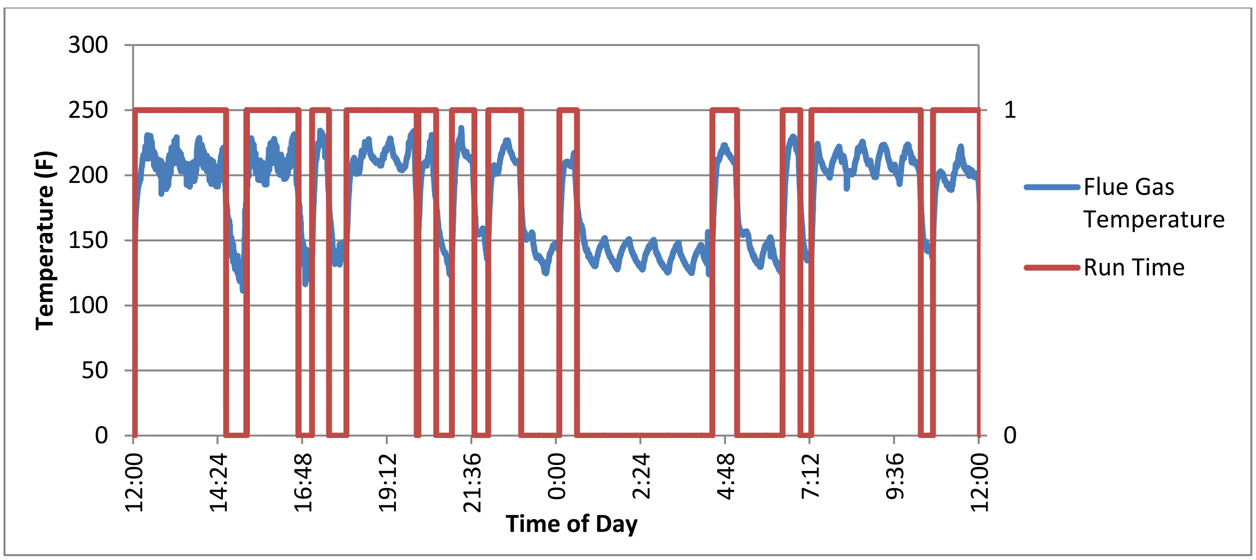

Figure 11. Using WH1 flue gas temperature to infer cycling—Cary site (1/18/13 to 1/19/13)

During the first site visit and data collection, it was found that the first of two boilers was disabled. The data logger indicated that the boiler last fired shortly after the installation of the *M2G*. On-site maintenance staff did not recall why the unit was disabled, as maintenance is not typically scheduled during the middle of the heating season, and the unit was promptly powered on. Luckily, tenants did not notice any loss in comfort over this period of more than 5 weeks, which included several days with daily highs below freezing temperatures. The maintenance staff noted the opposite: that several tenants commented on improved heating over previous heating seasons.

While the data acquisition hardware was not compromised as a result of this oversight, with one boiler firing the heating system was far from oversized, thus the results are biased. This limits the functionality of the *M2G*, which primarily achieves energy savings from inhibiting boilers from cycling during idle periods. If both boilers were active, they would collectively be oversized to a given heating load by a factor of 2 from a single boiler. One cannot apply this factor to the potential savings offered by a dynamic ALM controller, like the *M2G*, as its behavior does not neatly scale with such an oversize factor for reasons discussed in Section 2.3. Thus, results are presented as measured and for the balance of the heating season, mid-February through mid-May (2013). Sampled data of use to this program were from January 8, 2013 to May 7, 2013 and October 29, 2013 to April 1, 2014.

3.1.3 Accommodating for Wider Differentials (Both Sites)

Targeted for larger hot water boilers serving steadier loads, the *M2G* is designed to operate with moderate to low differentials, 10°F or less. Where greater temperature variation can be tolerated within the primary heating loop, these tight differentials are not common in residential heating, which would lead to short-cycling and significant inefficiencies. During initial monitoring at both the Chicago and Cary sites in 2012–2013, the boilers were found to operate with differentials of 20°F or greater, not atypical for these applications. Following a review of the 2012–2013 results with Greffen Systems, they requested that the *M2Gs* have a chip replaced within the units which allows the controllers to function well with differentials wider than 15°F. These chips were replaced for all *M2Gs* prior to the 2013–2014 heating season. While Greffen does not ship the *M2G* standard with this chip, they do on occasion specify them for high differential applications at no change in cost to the consumer (note that *M2G* installations are largely by staff or preferred contractors, who would be able to discern the need for said chips).

Figure 12. M2G control board with replaced chip at Cary site (circled)

3.2 Results

3.2.1 Energy Savings

The installation and equipment cost of the *M2G* is $7,700 per boiler. With the natural gas savings, measured indirectly via state loggers, the cost effectiveness of this ALM controller for this application can be determined via comparison to baseline boiler cycling. Therm savings are adjusted for weather using standard HDD analysis methods and non-heating building gas consumption (e.g., water heating) is tracked and removed from total consumption using direct measurement or engineering judgment. Total cost effectiveness can be ascertained by calculating simple paybacks from yearly financial savings and measure costs.

3.2.2 Cary Site: 2012–2013 Heating Season With M2G as Shipped

Over the first year of data collection, *without the added control chip to permit operation with higher differentials*, the west building (Figure 6) was served temporarily by one *M2G*-equipped boiler for six weeks of week on/week off operation; subsequently, both boilers were operational for the balance of the heating season. With the second *M2G*-equipped boiler disabled over this period, the boiler was far less oversized for these peak winter heating loads, thus lower savings were anticipated. To illustrate this effect, the cycling of the boiler with and without the M2G active is shown in Figure 13 over two Tuesdays, a week apart. Cyclic behavior looks to be very similar and quantifying this difference in Table 4 confirms this. For each day, with similar HDDs,[9] number of cycles and average cycle duration are similar.

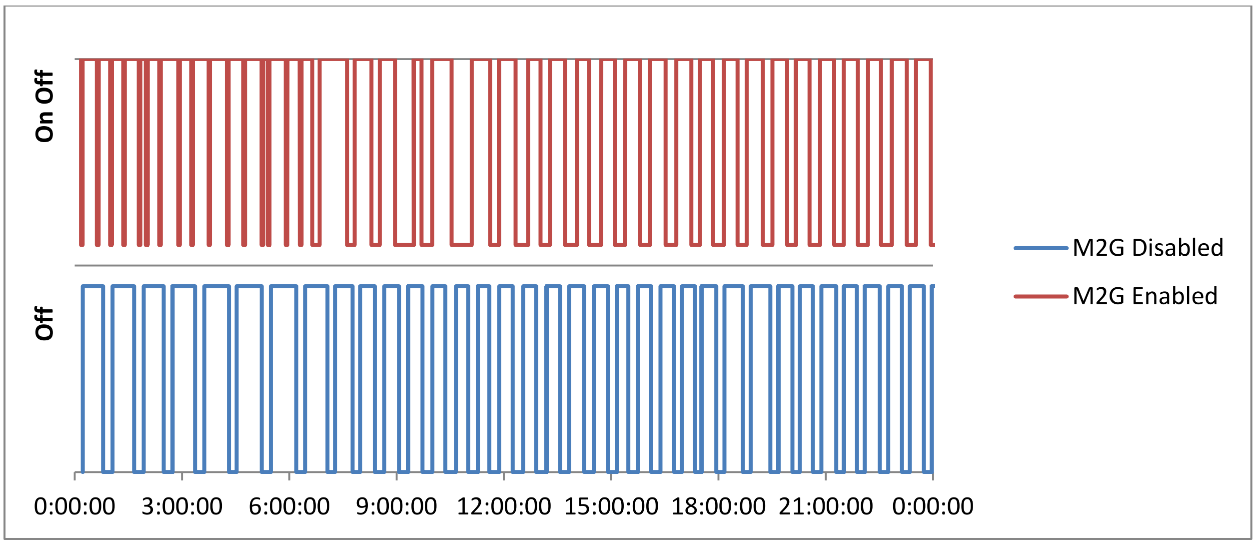

Figure 13. Comparing cycling of boiler at Cary site with/without *M2G* control (over 2/5/13 and 2/12/13 respectively)

Table 4, Daily Comparison of *M2G* Controlled/Not Controlled Boiler Operation Corresponding to Figure 13

Date	HDD	No. of Boiler Cycles	Average Cycle Duration (min)	Daily Therms/HDD
2/5/13 – *M2G* On	45.6	40	23.8	1.39
2/12/13 – *M2G* Off	41.9	35	26.6	1.48

Looking at cycling statistics, shown in Table 5, this trend in minor differences between *M2G*-controlled and baseline weeks is seen, in contrast to prior published studies and to recent testing under controlled laboratory conditions. While the average cycle durations appear normal (20–30 minutes), the maximum cycle durations between weeks 2 and 4 indicate that the single boiler is

[9] Weather data for HDD from weather station in McHenry, Illinois, 11 miles from the test site.

right-sized or undersized for these peak winter conditions, utilization factors over this period range from 0.47 to 0.72. With fewer idling cycles and a wider differential, marked by much shorter durations, this leads to very few opportunities for the *M2G* to hold the boiler from firing to limit losses and increase savings.

Table 5. Weekly Cycling Statistics at Cary Site Over Initial Sampling Period—Single Boiler Operation

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
***M2G* On/Off**	On	Off	On	Off	On	Off
Days of Data Collection	6.6	7.0	7.0	7.0	7.0	3.4
Total Cycles	238	227	189	221	235	120
Average Cycle/day	36.3	32.5	27.2	31.7	33.6	35.5
Average Cycle Duration (min)	18.7	29.5	38.3	31.4	22.2	20.5
Min Cycle Duration (min)	2.3	2.3	5.3	5.0	8.0	4.5
Max Cycle Duration (min)	64.9	277.0	578.2	508.6	60.3	47.9

Table 6 shows weekly estimates of savings, adjusting for weather variations. For the three on and three off weeks, the average energy savings are 3%, inconsistent with previous field and laboratory results. Without data from a shoulder season, where the ALM controllers are more effective, and acknowledging the circumstances of this dataset with only one of two boilers active, an extension to annual cost savings and payback analysis cannot be performed.

Table 6. Estimated Energy Savings at Cary Site Over Initial Sampling Period—Single Boiler Operation

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
***M2G* On/Off**	On	Off	On	Off	On	Off
Total Firing Time	74.2	111.8	120.8	115.6	86.9	41.0
Total Therms	296.9	447.2	483.1	462.4	347.6	164.1
HDD	208.1	297.4	320.6	309.8	269.0	122.1
Therms/HDD	1.43	1.50	1.51	1.49	1.29	1.34

Using utility bill data from prior years, these therms/HDD values are consistent with the two boilers operating in parallel, with average therms/HDD at 1.46 and 1.35 for February 2012 and 2011 respectively.

With two boilers in service for the balance of the 2012–2013 heating season, cycling behavior and estimated energy savings data are shown in Table 7 and Table 8. Similar to the previous sampling period, due to the boiler controls, boiler #1 meets the majority of the load, with much of the sampling period showing no cycling activity by boiler #2. However the Boiler #1 shows to be more oversized as the shoulder season begins. Shown graphically, taking into account the impact of weather fluctuations, Figure 14 shows the daily average gas consumption and cycling. The shoulder season sets in towards late March, where the weekly HDD decreases to 150 and below. Overall, during this period with two boilers operating in parallel, there is little noticeable change in gas consumption or cycling behavior when adjusting for weather fluctuations. Surprisingly, average therm savings are on a weather-adjusted basis are lower during the shoulder season, with two boilers operating in parallel than during the peak winter season with a single boiler operating.

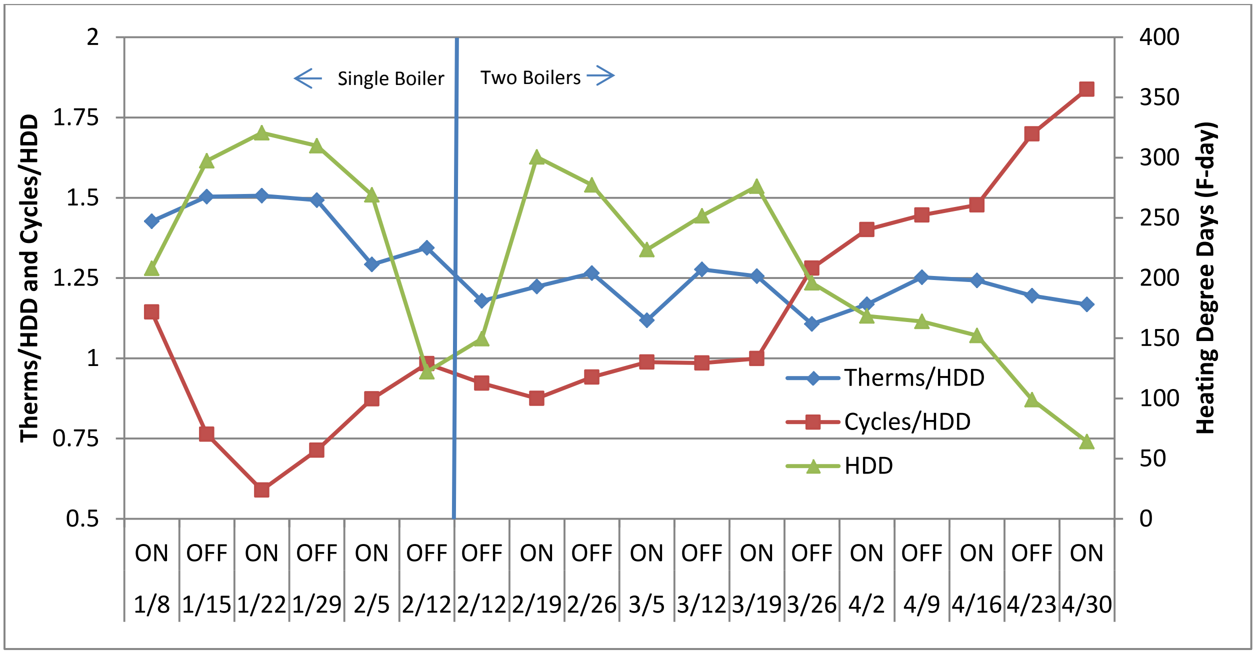

Figure 14. Cary site 2012–2013 cycling and gas consumption (therms) per HDD (°F·day)

Initial results for cycling and gas consumption are shown in Figure 14, in which the weekly gas consumption (therms) and cycles are shown adjusted for local HDDs (base 65°F). In general, the ALM controller offers a slight reduction in gas consumption through reduced boiler cycling when adjusted by HDD. For the single boiler and two boiler periods, as noted in Figure 14, the gas savings per HDD are 4.0% and 3.2%, respectively. Over the sampling period, residents did not notify the site owner of insufficient heating, nor did they notice changes week to week.

The impact of the *M2G* is muted, operating with a differential of 22°F on average for this first year of sampling, ranging from 25° to 35°F, energy savings noted above are of a magnitude such that they cannot be directly attributed to these ALM controllers. Beyond operating with a wider than designed differential, these realized savings are less than those observed in controlled laboratory testing for two primary reasons: the field site boilers are equipped with OTR controllers, which provide savings of their own and are expected to be at most additive with ALM controllers, and these boilers do not cycle frequently enough, yielding significant cycling losses, for the *M2G*'s algorithm to widen the differential and reduce cycling. Greffen reports appreciable energy savings (>10%) in case studies where baseline boiler cycling rates are 50/day and greater (up to 250/day), not 40/day and below in this case. As a result, cycling rates do not vary significantly from day to day with the *M2G* as shipped in this case.

Table 7. Weekly Cycling Statistics at Cary Site Over Initial Sampling Period—Dual Boiler Operation

	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18
M2G On/Off	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Days of Data Collection	3.6	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Boiler #1													
Total Cycles	121	229	241	220	248	250	249	236	237	225	168	118	44
Average Cycle/day	33.9	32.7	34.4	31.4	35.6	35.7	35.6	33.8	34.0	32.2	24.0	16.9	6.3
Average Cycle Duration (min)	20.5	22.4	21.0	17.0	19.4	19.7	13.0	12.5	13.0	12.6	10.6	9.5	13.0
Min Cycle Duration (min)	12.6	9.6	9.2	9.0	10.0	7.9	4.3	0.9	5.8	1.6	2.4	6.4	10.0
Max Cycle Duration (min)	39.3	48.6	53.7	33.5	39.2	51.8	27.2	26.0	20.2	22.7	17.7	17.4	20.4
Boiler #2													
Total Cycles	17	34	20	1	0	26	2	0	0	0	0	0	0
Average Cycle/day	4.8	4.9	2.9	0.1	0.0	3.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Average Cycle Duration (min)	9.9	11.1	9.7	9.1	0.0	10.5	14.2	0.0	0.0	0.0	0.0	0.0	0.0
Min Cycle Duration (min)	7.8	7.7	7.1	9.1	0.0	7.4	13.9	0.0	0.0	0.0	0.0	0.0	0.0
Max Cycle Duration (min)	11.4	15.4	12.9	9.1	0.0	12.3	14.5	0.0	0.0	0.0	0.0	0.0	0.0

Table 8. Estimated Energy Savings at Cary Site over Initial Sampling Period—Dual Boiler Operation

	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18
***M2G* On/Off**	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Days of Data Collection	3.6	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Boiler #1													
Firing Time (h)	41.3	85.6	84.5	62.4	80.3	82.1	53.8	49.2	51.3	47.3	29.5	18.7	9.6
Total Therms	165.1	342.5	337.9	249.4	321.3	328.6	215.1	196.9	205.3	189.2	118.2	75.0	38.3
HDD	150.4	300.5	277.3	223.6	251.7	276.2	176.3	168.5	163.9	152.3	98.9	64.2	101.4
Therms/HDD	1.1	1.1	1.2	1.1	1.3	1.2	1.2	1.2	1.3	1.2	1.2	1.2	0.4
Boiler #2													
Firing Time (h)	2.8	6.3	3.2	0.2	0.0	4.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Total Therms	11.2	25.1	12.9	0.6	0.0	18.3	1.9	0.0	0.0	0.0	0.0	0.0	0.0
HDD	150.4	300.5	277.3	223.6	251.7	276.2	176.3	168.5	163.9	152.3	98.9	64.2	101.4
Therms/HDD	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

3.2.3 Cary Site: 2013–2014 Heating Season With Chip for Wider Differential Operation

Over the 2013–2014 heating season, 23 weeks beginning the final week in October, the control chips on the *M2Gs* were replaced to allow the ALM controllers to operate with wider differentials than 10°F. While this resulted in evidence of the *M2G* reducing cycling rates, yielding energy savings, this was only observed in the shoulder season. The 2013–2014 heating season was exceptional for the Midwest, with numerous records broken in the Chicago metropolitan area, including the most days at or below 0°F. As a result, boiler #1, which is the primary boiler, was at or above 50% utilization over the majority of the heating season, which was not the case during the 2012–2013 heating season as shown in Figure 15. These boilers are not significantly oversized with respect to their load, so cycling rates are low, as is the opportunity for energy savings from reducing cycling losses.

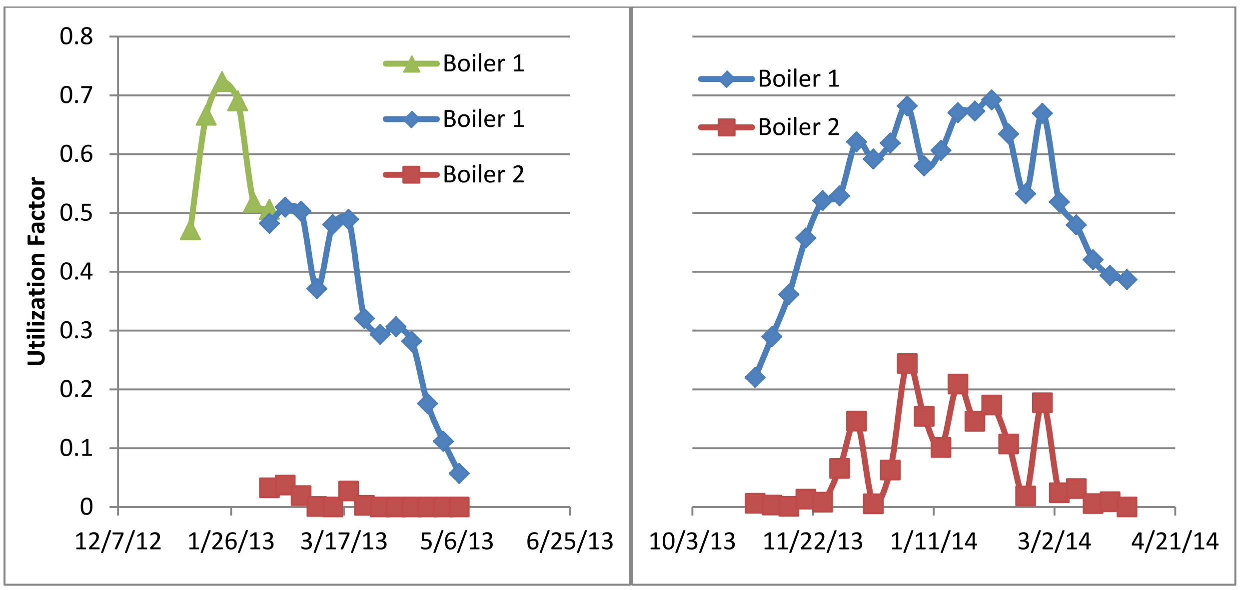

Figure 15. Comparing utilization factors over 2012–2013 versus 2013–2014 heating seasons[10]

Full datasets reported for the 2013–2014 heating season in Table 10 through Table 13 and graphically summarized in Figure 16. Seasonal cycling rate reduction and energy savings are summarized in Table 9.

Overall, cycling reduction and energy savings are similar to that of the previous year, that is low enough to indicate the *M2G* is not operating as intended, yielding less than 5% energy savings and with no reduction in cycling. However, when broken into "shoulder" and "winter peak" periods, the influence of the ALM controller can be seen, with a 16.5% reduction in cycles during the "shoulder" period yielding a therm savings of 7.1%. Coupling the Cary site characteristics, with few boiler cycles per day (< 50/day on average) and occasional long boiler runtimes (periodically running several hours at a time), and the unseasonably cold 2013–2014

[10] For the 2012–2013 heating season, note that due to low utilization of boiler #2, the impact of single versus dual boiler operation on boiler #1 utilization (green versus blue) is small.

winter, the opportunity for significant energy savings from the reduction of cycling losses was small, despite allowing the *M2G* to operate with a wider differential.

Table 9. Summary of Cary Site 2013–2014 Heating Season

Data	M2G Operation	Total	Shoulder[11]	Winter Peak[10]
HDD	With	3210.8	1140.3	2070.5
	Without	3230.9	1503.7	1727.2
Cycles/HDD	With	1.42	1.15	1.57
	Without	1.39	1.38	1.40
	% Reduction	–2.1%	16.5%	–12.0%
Therms/HDD	With	1.40	1.29	1.45
	Without	1.44	1.39	1.47
	% Reduction	2.8%	7.1%	1.4%

[11] "Winter peak" are the weeks from December 10 to February 25; "shoulder" are weeks before and after this period.

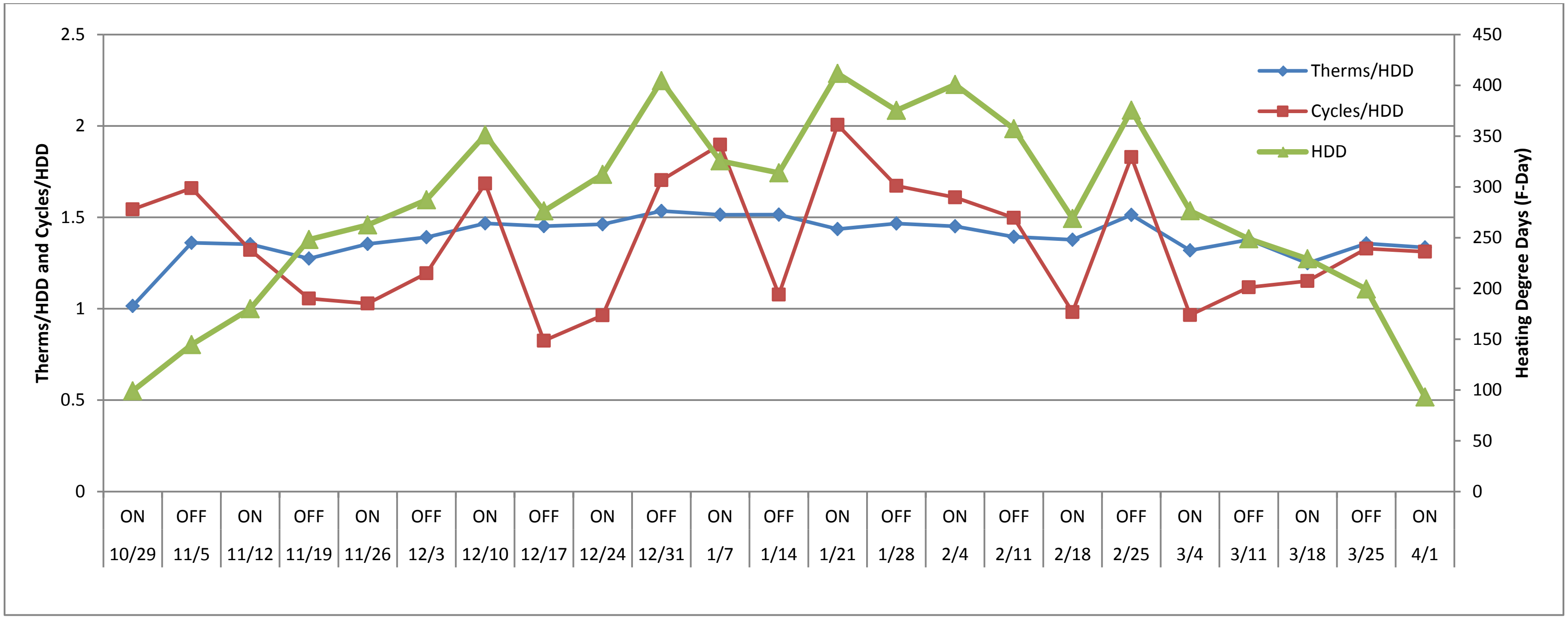

Figure 16. Cary site 2013–2014 cycling and gas consumption (therms) per HDD (°F·day)

Table 10. Estimated Energy Savings at Cary Site Over Second Sampling Period—Dual Boiler Operation

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
M2G On/Off	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Days of Data Collection	4.6	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Boiler #1												
Firing Time (h)	24.4	48.6	60.7	76.8	87.5	88.9	104.3	99.4	103.6	114.4	97.4	101.9
Total Therms	97.8	194.6	242.8	307.4	350.0	355.6	417.2	397.5	414.5	457.5	389.6	407.4
HDD	99.1	144.6	180.0	248.1	262.5	287.3	351.2	276.3	312.3	404.5	325.6	313.8
Therms/HDD	1.0	1.3	1.3	1.2	1.3	1.2	1.2	1.4	1.3	1.1	1.2	1.3
Boiler #2												
Firing Time (h)	0.7	0.5	0.2	2.2	1.4	11.0	24.5	0.9	10.5	40.9	25.9	17.0
Total Therms	2.8	2.2	0.8	8.9	5.6	44.1	98.1	3.6	42.1	163.6	103.6	68.0
HDD	184.3	144.6	180.0	248.1	262.5	287.3	351.2	276.3	312.3	404.5	325.6	313.8
Therms/HDD	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.1	0.4	0.3	0.2

Table 11. Estimated Energy Savings at Cary Site Over Second Sampling Period—Dual Boiler Operation

	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23
M2G On/Off	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON
Days of Data Collection	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	3.3
Boiler #1											
Firing Time (h)	113.1	116.3	106.5	89.5	112.3	87.1	80.4	70.6	66.1	31.0	113.1
Total Therms	452.4	465.2	425.9	357.9	449.3	348.5	321.8	282.5	264.6	124.2	452.4
HDD	375.4	400.8	357.2	268.9	375.5	276.5	248.8	229.2	199.4	93.0	375.4
Therms/HDD	1.2	1.2	1.2	1.3	1.2	1.3	1.3	1.2	1.3	1.3	1.2
Boiler #2											
Firing Time (h)	24.5	29.1	18.0	3.2	29.8	4.1	5.3	1.0	1.5	0.0	24.5
Total Therms	98.0	116.6	72.0	12.6	119.0	16.3	21.1	3.9	6.0	0.0	98.0
HDD	375.4	400.8	357.2	268.9	375.5	276.5	248.8	229.2	199.4	93.0	375.4
Therms/HDD	0.3	0.3	0.2	0.0	0.3	0.1	0.1	0.0	0.0	0.0	0.3

Table 12. Weekly Cycling Statistics at Cary Site Over Initial Sampling Period—Dual Boiler Operation

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
***M2G* On/Off**	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
Days of Data Collection	4.6	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Boiler #1												
Total Cycles	150	236	236	248	260	266	375	222	238	381	386	244
Average Cycle/day	32.4	33.7	33.7	35.4	37.1	38.0	53.6	31.7	34.1	54.5	55.1	34.9
Average Cycle Duration (min)	9.8	12.4	15.4	18.6	20.2	20.1	16.7	26.9	26.1	18.0	15.1	25.0
Min Cycle Duration (min)	6.8	0.3	6.2	6.1	0.1	3.4	3.2	5.6	3.1	1.1	1.8	1.6
Max Cycle Duration (min)	17.2	25.3	38.4	56.3	63.3	80.8	57.0	598.1	584.8	96.3	45.6	69.5
Boiler #2												
Total Cycles	3	4	2	14	10	77	217	6	63	308	232	94
Average Cycle/day	0.6	0.6	0.3	2.0	1.4	11.0	31.0	0.9	9.0	44.1	33.1	13.4
Average Cycle Duration (min)	13.9	8.2	6.3	9.6	0.0	8.6	6.8	0.0	0.0	0.0	0.0	1.0
Min Cycle Duration (min)	13.8	0.1	4.3	7.7	4.9	3.3	3.1	8.6	4.8	2.5	3.3	7.0
Max Cycle Duration (min)	14.0	14.1	8.4	10.9	11.0	14.4	13.6	9.6	16.7	24.9	19.6	14.1

Table 13. Weekly Cycling Statistics at Cary Site Over Initial Sampling Period—Dual Boiler Operation

	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23
M2G **On/Off**	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON
Days of Data Collection	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	3.3
Boiler #1											
Total Cycles	516	385	392	359	245	410	242	248	257	256	122
Average Cycle/day	73.7	55.0	56.0	51.3	35.0	58.6	34.6	35.5	36.7	36.6	36.5
Average Cycle Duration (min)	13.1	17.6	17.8	17.8	21.9	16.4	21.6	19.5	16.5	15.5	15.3
Min Cycle Duration (min)	2.3	2.2	3.4	0.4	10.5	2.1	11.3	11.9	8.5	7.6	3.6
Max Cycle Duration (min)	91.4	100.6	158.9	68.2	81.0	71.2	56.5	64.5	33.0	51.1	19.6
Boiler #2											
Total Cycles	310	243	253	176	19	277	25	30	7	9	0
Average Cycle/day	44.3	34.7	36.1	25.2	2.7	39.6	3.6	4.3	1.0	1.3	0.0
Average Cycle Duration (min)	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
Min Cycle Duration (min)	3.3	3.3	1.3	2.7	8.4	1.8	7.6	5.8	3.7	6.5	0.0
Max Cycle Duration (min)	19.6	17.5	20.1	18.4	12.4	15.0	14.8	13.0	10.6	12.1	0.0

3.2.4 Chicago

Operating continuously controlled, not week-on/week-off in the case of the Cary site, data from the *M2G*-equipped boilers operating in boiler room A were analyzed without and with the control chips allowing for operation with wider differentials, for the 2012–2013 and 2013–2014 heating seasons respectively, with the former serving as a baseline. Serving as a secondary baseline, the boiler room B boilers without *M2Gs* were monitored over the same period, which for reasons described in Section 3.1.1 focused on the months between late January and early April for each year.

As observed with the Cary site and previous laboratory testing, there are several methods to confirm that the *M2G* is operating and manipulating the boiler differentials dynamically, which in all cases this was confirmed during testing at the Chicago site:

- **Noticeable effect on cycling rates:** Only during the shoulder season at the Cary site was a noticeable reduction in boiler cycling observed, 16.5%, which was small for a baseline of ≤ 50 cycles/day, yielding proportionately small energy savings. In the case of the Chicago site, the four boilers operating in pairs serving loops A and B are demonstrably oversized with cycling rates of ≥ 100 cycles/day. Comparing boiler cycling rates year-over-year in Figure 17, in boiler room B without the *M2G* the average daily cycle duration is within a band of 4–8 minutes, without significant change from year to year. For colder days, with daily HDD > 40, cycle durations increase which is not surprising. In boiler room A, with the *M2G* enabled in the 2013–2014 heating season by virtue of the replacement chip, a significant change in cycle duration is observed, with proportionally longer cycles for warmer days (during which the *M2G* is more likely to delay boiler cycles thus, lengthening cycles). Average cycles per day for boiler room B reduce from 79 to 39 when the *M2G* is enabled over the respective sampling periods.

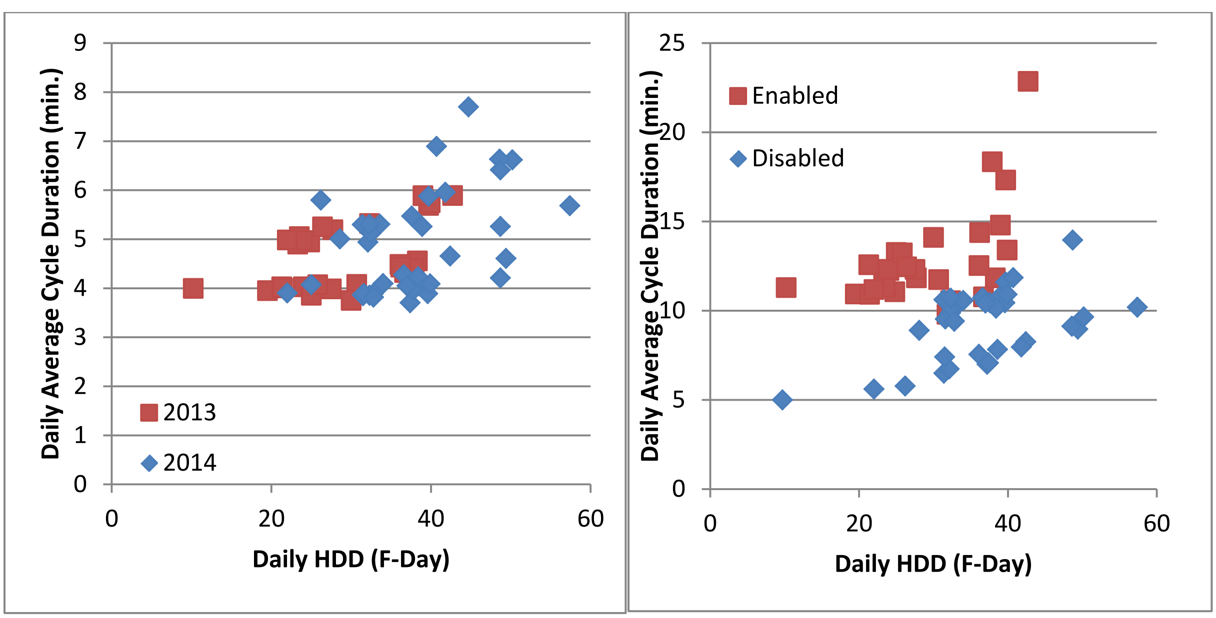

Figure 17. Daily average cycle duration for boiler room B (left) versus boiler room A (right)

Similarly, comparing boiler on-time with and without the *M2G* enabled in Boiler Room A, as shown in Figure 18, the band of percent on-time for a given daily HDD is much wider with the *M2G* operating, reflecting its dynamic nature. Without *M2G* operation, boiler on-time for a given cycle is more closely a function of daily HDD.

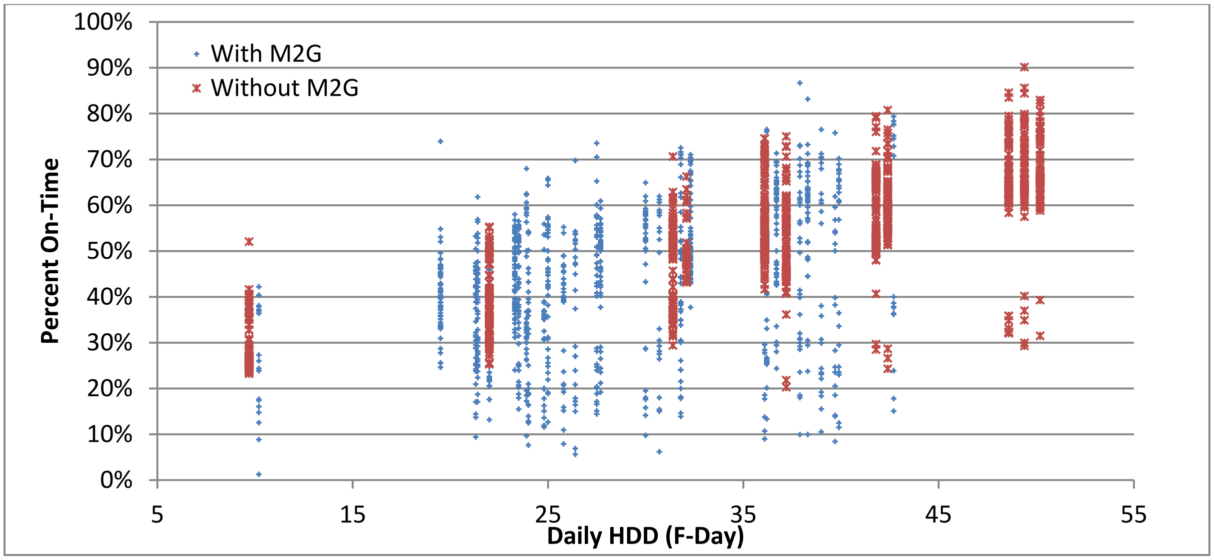

Figure 18. Percent boiler on-time in room a versus daily HDD

- **Dynamic widening of boiler differential:** Comparing the boiler differential is another means of observing *M2G* activity. With or without an OTR controller, the boiler differential should be fairly static as the OTR controller raises the "cut-in" and "cut-out" temperatures together. This can be seen in Figure 19 in the left-hand figure, which shows linear cut in/cut out temperatures for boiler room B as a function of daily HDD.

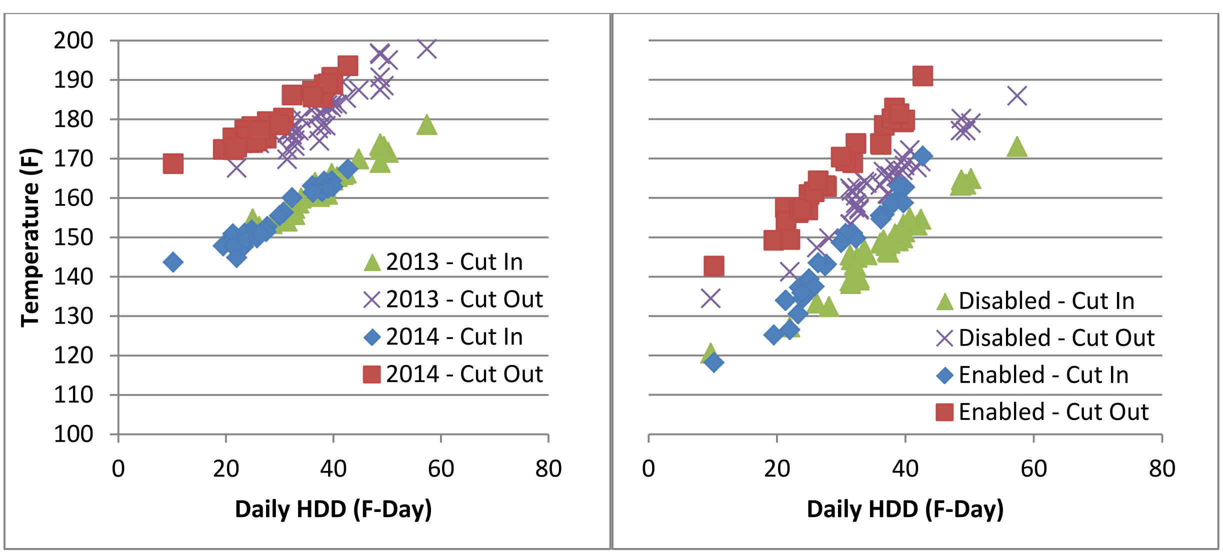

Figure 19: Boiler cut in and cut out temperatures versus HDD for boiler room B (left) and A (right)

Shown in Figure 20, an example of cut in/cut out temperatures for rooms A and B over the same time period, the former with the *M2G* actively managing the differential. As shown in Figure 19, the impact of OTR control dictates the simultaneous adjustment of the cut in/cut out temperatures to outdoor temperatures for both *m2g*-equipped boilers in boiler room A and those without in boiler room B alike. The *M2G* does influence the cut in temperature however, in managing the differential through delaying boiler firings (see Figure 21). With the *M2G* disabled, the differential for each cycle is within a narrow band for a given daily HDD. However when enabled, the differential is widened by 10°F or more, with a wider range of differentials observed for a given daily HDD.

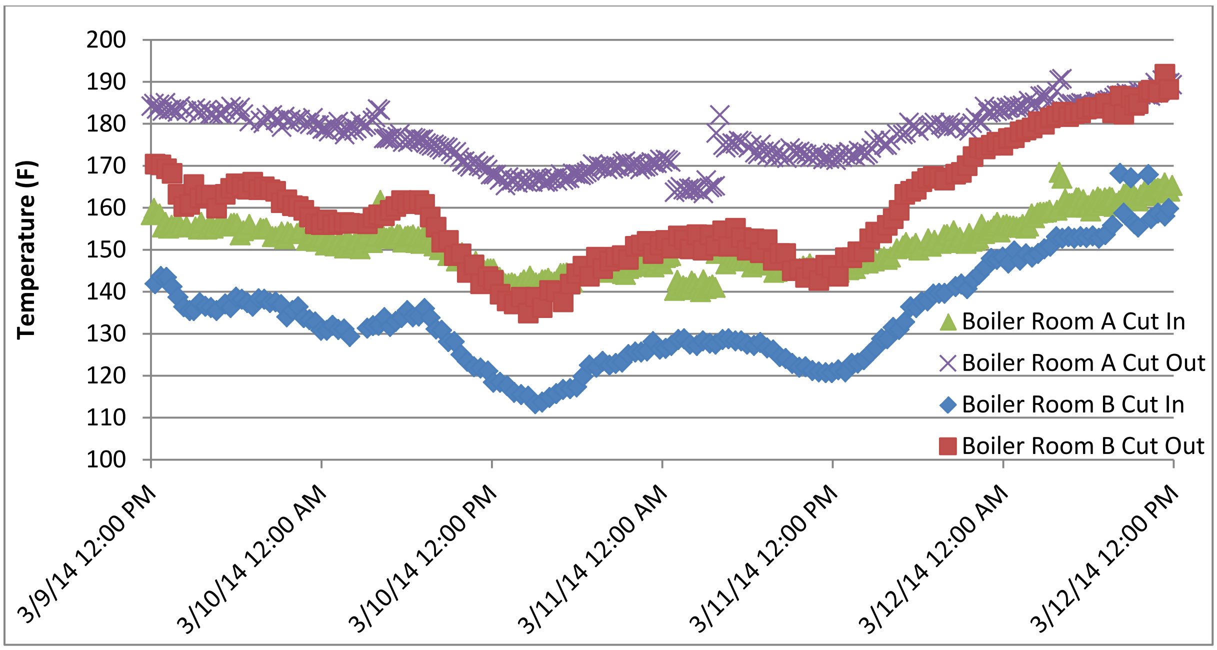

Figure 20. Boiler loop temperatures during cut in/cut out for rooms A and B

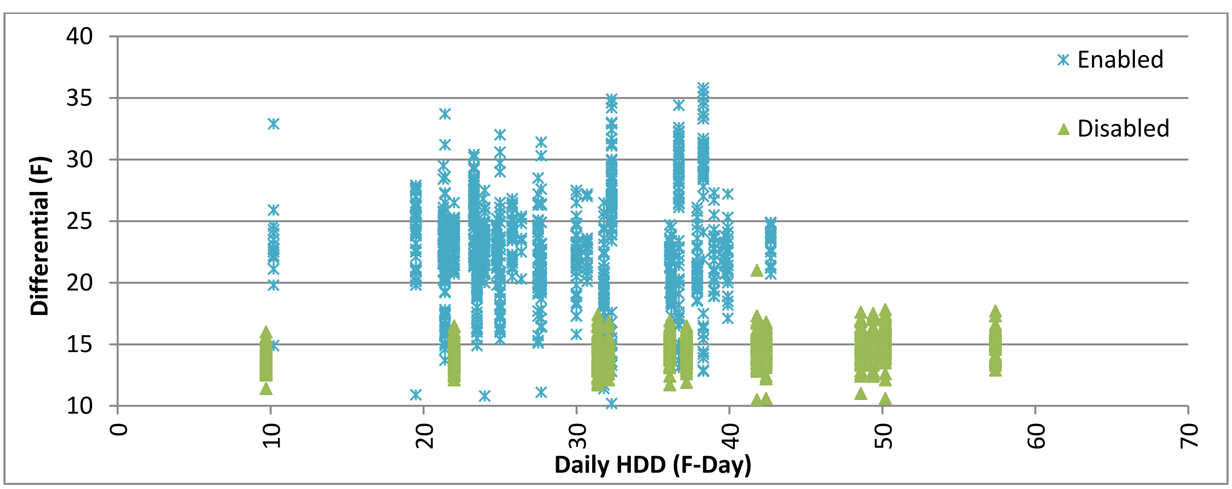

Figure 21. Differential of boilers in room A with *M2G* enabled/disabled

Conversely, in Figure 22, the relatively static differentials for the baseline boilers in boiler room B are shown. For each day, without respect to ambient conditions, the differentials are maintained within a tight band for the two years of observation. Note that the alternating bands between days are the cycling between boilers #1 and #2, which have different differential settings per the Tekmar OTR/sequencing controller. Also, these differential settings were changed by the site year-over-year as shown.

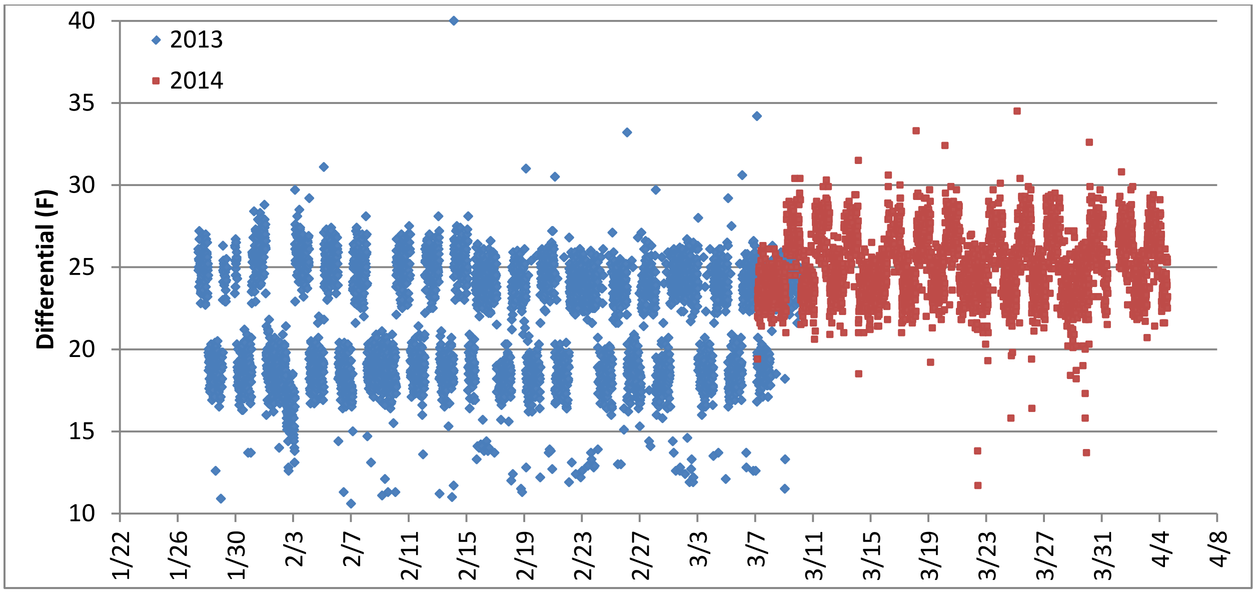

Figure 22. Differential of boilers in room B without *M2G*s

From the data reviewed showing both a distinct variation in cycling behavior and dynamic management of the boiler differential, the *M2G*-equipped boilers in boiler room A were confirmed to be operating as designed with the control chip retrofit in 2014. The results from these monitoring periods for boiler rooms A and B are shown in Table 14. Though the sampling periods are brief, for reasons described in Section 3.1.1, these reflect a diverse range of HDD as shown in previous data. Comparing year-over-year data in boiler room A, the impact of the *M2G* is apparent with a 32% reduction in cycles and a 14% reduction in natural gas consumed, in line with expectations. For the baseline boiler room B, a negligible change in cycling and energy consumption is observed for the same period.

Table 14. Summary of Chicago Site 2012–2013 and 2013–2014 Seasons

Data	Boiler Room A			Boiler Room B		
	2013 (*M2G* Disabled)	2014 (*M2G* Enabled)	Reduction	2013	2014	Reduction
Sampling Period	1/27–2/14; 2/19–3/10	3/6-4/4		1/26–3/10	3/7–4/4	
HDD	1310.5	817.6		1470.1	785.8	
Cycles/HDD	1.97	1.35	31.8%	3.86	3.92	–1.8%
Therms/HDD	0.96	0.83	14.4%	0.61	0.60	1.2%

Like the Cary site, however, during the colder winter peak months the energy savings from the *M2G* are expected to be muted. Viewing daily data for boiler rooms A and B over the sampling periods, shown in Figure 23 and Figure 24, the following can be concluded:

- Low-rise multifamily buildings will primarily be skin-loss dominant in their heat loss, therefore building space heating will be a strong function of outside temperature. For the boilers in Boiler Room B serving half of the Chicago building site, the space heating therms consumed per HDD are strong linear functions of HDD, with R^2 values for linear fits of 0.77 and 0.73 for 2013 and 2014, respectively. This is also the case for 2013 sampling from boiler room A, wherein the *M2G* was disabled, with an R^2 value of 0.74. This is seen clearly both in Figure 23 and Figure 24.

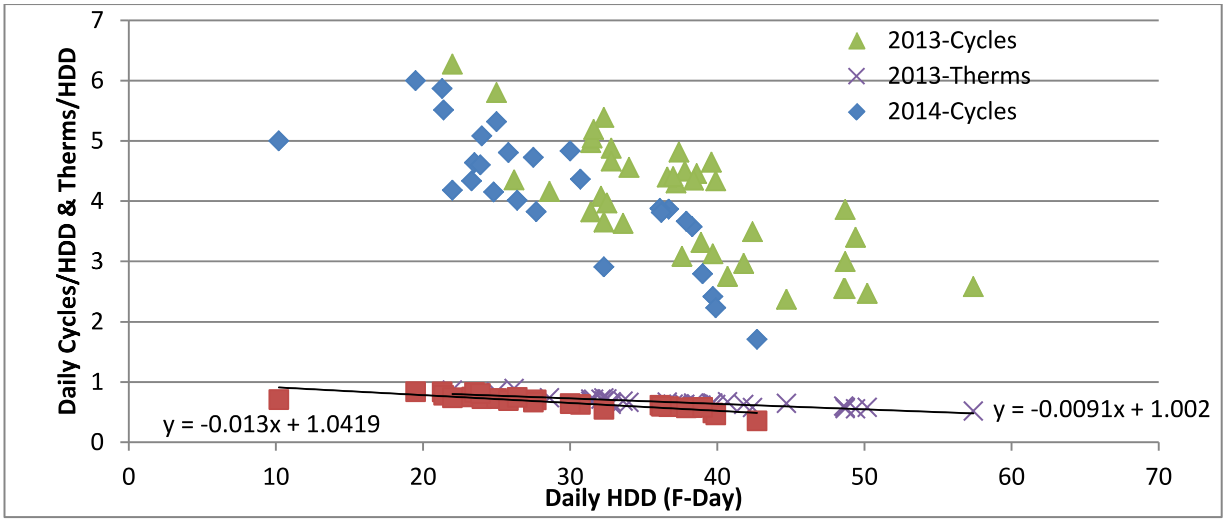

Figure 23. Data summary for boiler room B

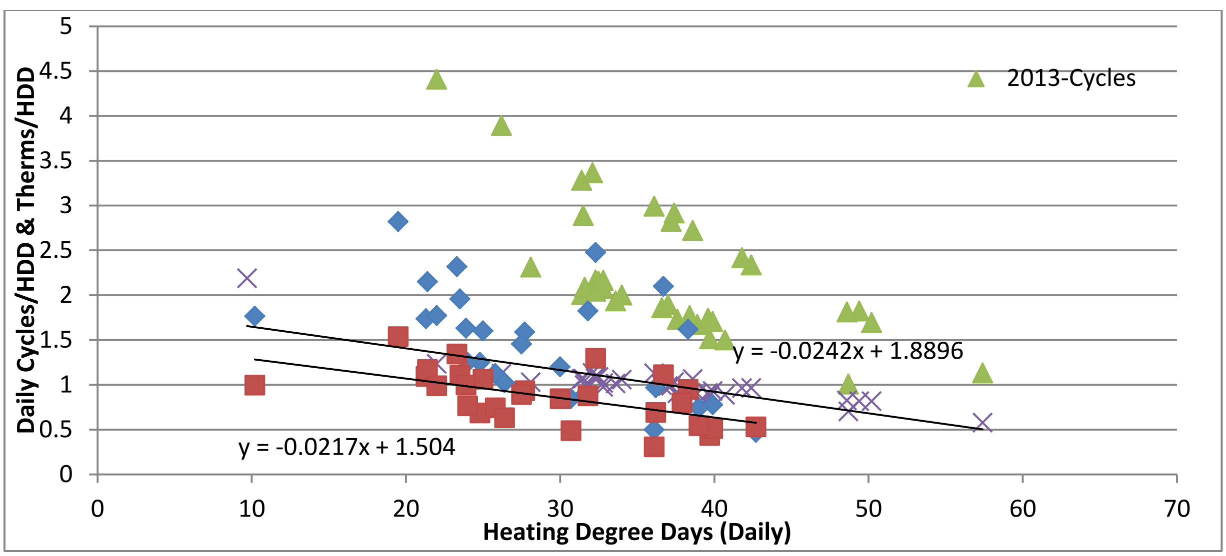

Figure 24. Data summary for boiler room A

- Daily cycles/HDD do not have the same linear fit to HDD as more variables influence the cycling rate beyond the outdoor temperature (e.g. sequencing controls). Despite this, for boilers in boiler room B, cycling behavior is strongly influenced by outdoor temperature and year-over-year the variation appears consistent. The *M2G*-equipped boilers in boiler room A show a marked influence on cycling, flattening the cycles/HDD versus daily HDD as shown in Figure 24 comparing 2013 (disabled) to 2014 (enabled) results. It is through this flattening towards the shoulder season (daily HDD < 30) that this ALM controller derives its energy savings.
- In Figure 24, the therms/HDD when the *M2G* is enabled show a larger spread, with an R^2 value of 0.33 for a linear fit, reflecting the variable differential. For periods when the building is heated with a lower temperature primary loop, with wider differentials, the data scatter more for a given daily HDD due to this secondary influence on the building heat demand. Note that the *M2G* does not appear to change the influence of outdoor temperature on building heat demand (i.e., the slope of the linear fits with and without the *M2G* are near equal), but rather it is this scatter in the data showing periods of time where the *M2G* is able to remove the "demand" of boiler dry-cycling by limiting these losses. Note that like the building space heat demand, this dry-cycling "demand" of the boiler is also a function of outdoor temperature as the OTR controller varies primary loop temperatures with daily HDD (see Figure 19). As the magnitude of the boiler dry-cycling losses is in part installation specific, the cycling losses are influenced by easily known parameters such as primary loop temperatures (either static or set by the OTR controllers as a function of outdoor temperature) and difficult to ascertain parameters such as boiler system utilization factors and sequencing controls, this secondary heat "demand" is difficult to quantify for the general case. Thus the elimination of this component from the therms/HDD versus HDD curve is challenging to know *a priori*, as the overall reduction in the "y-intercept" of the linear fit, which complicates predictability of ALM controller-provided energy savings as compared to OTR controllers yielding more predictable savings. As shown, this site could expect to save almost 0.4 therms/HDD for days with fewer than 45 HDD.

3.2.5 Advanced Load Monitoring Controller Behavior

By its nature, the ALM controller is a dynamic "black box," rendering predictions of energy savings difficult. For this reason most utilities that include ALM controllers, like the *M2G*, in their incentive programs use field-verified savings as the benchmark for their incentives. With this ALM controller behavior in a controlled experimental environment, summarized in Table 1, the monitoring results from a complete heating season will benefit through comparison.

Like other ALM controllers, the *M2G* uses water temperatures within the primary loop to estimate and anticipate the heating load pattern of a building. Sometimes referred to as "indoor reset controllers," ALM controllers differ from OTR controllers in that the heating load at the boiler is directly measured as opposed to inferring the heating load using a proportional relationship the outdoor temperature, a relationship determined *a priori*. In particular, the *M2G* measures the return and supply water temperatures every 10 seconds, observing and recording patterns and comparing real time temperature change to onboard memory of past cycles. With this data analysis, the *M2G* "decides" when and for how long to hold off the boiler from firing following a call for heat. Greffen Systems confirms that the controllers will never hold the boiler for more than 15 minutes at a time. Thus, during perceived low load conditions the controller could limit the boiler to fewer than 4 cycles per hour.

In this study, just like ALM controllers, because the datasets contain the supply temperatures and state loggers, inferring the boiler set point is possible, even if it is changed over the course of the study (see Figure 19). ALM controllers act to dynamically change the boiler differential, increasing it from the baseline during periods of low demand, thus inferring what the differential was critical (see Figure 20 and Figure 21). What proves difficult is determining the impact of the controllers' memory of past cycles on its "decision making", however the goal of this is not to reverse-engineer this particular ALM controller.

In the case of on/off sites (such as Cary), this was achieved during the "off" days, where the cut-in return temperature is observable. This can be seen in Figure 25 and Figure 26, with the last half of an *M2G*-off day followed by the first half of an *M2G*-on day at the Cary Site. While the "common supply" temperature reading within the primary loop indicates cycling, the boiler return and supply temperatures are steady, indicating a fixed differential of about 25°F. After the *M2G* is activated at midnight and following a morning heat up until 8:30 a.m., the loop temperatures are allowed to drop below their set points as the *M2G* holds off fire for period of time until the return temperature drops more than 5°F. Ultimately, the boiler is released to fire shortly thereafter, but if sudden call for heat is not received this reduces this firing cycle by a little less than 10 minutes.

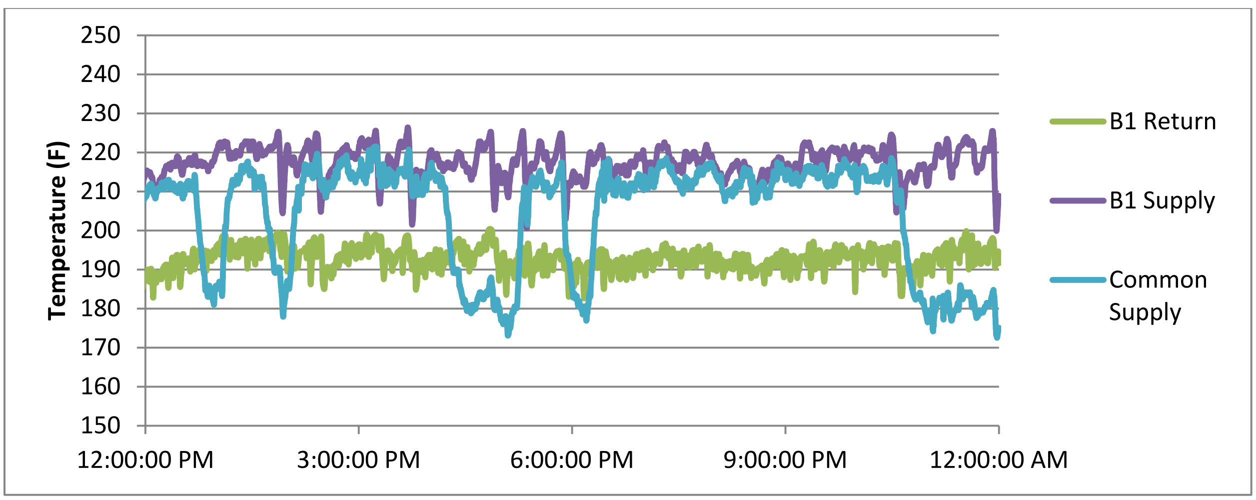

Figure 25. Boiler return, supply, and primary loop supply temperatures with *M2G* off—1/21/13

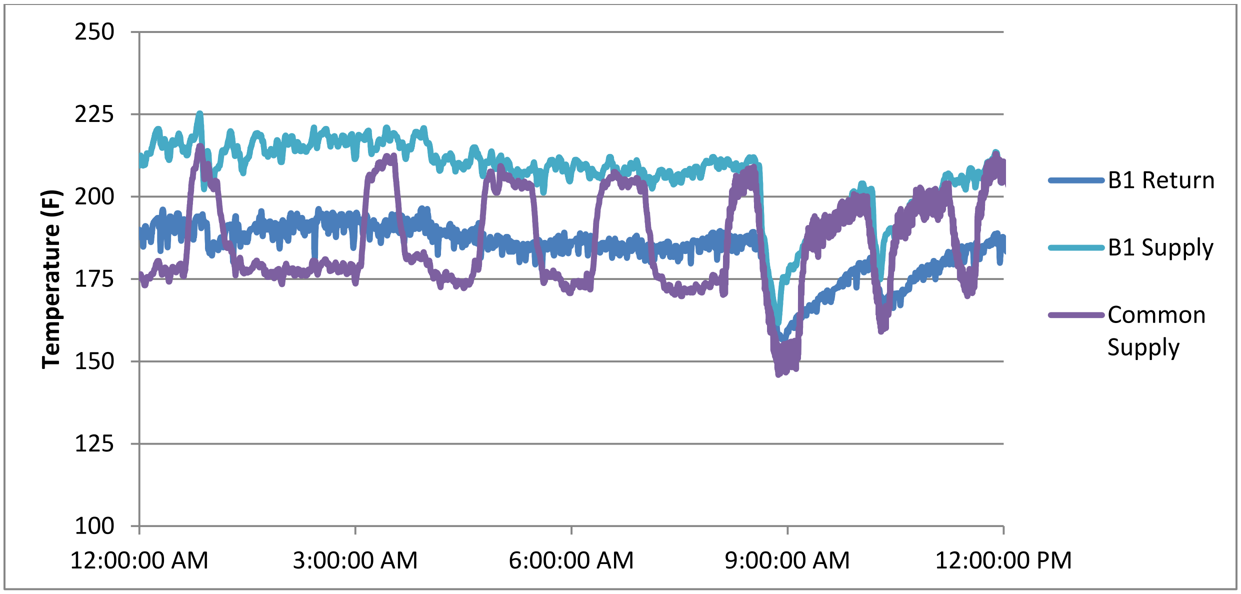

Figure 26. Boiler return, supply, and primary loop supply temperatures with *M2G* on—1/22/13

This method of holding off the boiler, until the return or supply temperatures drop below the prescribed values, appears to be the most common for Cary site boilers (operating individually or in parallel). As the boilers have high utilization factors, indicating the low degree to which they are oversized for their load (Figure 15), the long boiler runtimes and subsequent sharp drop of loop return water temperatures of 3°C (5.4°F). This also is a common method for the boilers at the Chicago site, with approximately 48% of cycles fitting this category. Roughly 26% of cycles do not meet these criteria, wherein the *M2G* holds off a boiler cycle by 15 minutes, then releases it to fire. The remaining cycles at the Chicago site are some combination of these modes and the proprietary "memory-based" method of determining when to release the boilers to fire.

4 Conclusion

Datasets from this field evaluation of an ALM controller (when able to operate with wider boiler differentials) suggest that this technology may be a reliable retrofit measure for multifamily housing, provided that the application meet certain criteria, those seen at the Chicago site though not at the Cary site. The primary criterion for viable applications is a high oversize factor, indicated by high boiler cycling rates (>100 cycles/day) or low utilization rates (50% and below on average). This was not the case for the Cary site that had high utilization rates and thus, low reductions in cycles during ALM controller operation. For the Chicago site, extrapolating annual savings from the brief period monitored is tenuous, however at almost 0.4 therms/HDD saved, the payback during the 2013–2014 Chicago Winter (October 1, 2013 to April 1, 2014) would be less than 4 years for an average natural gas price of $1.03/therm. For multifamily sites of an appreciable size, in which the therm savings potential would be larger, this may be an attractive solution even for buildings in which an OTR system is present. Throughout this limited study, a focus was placed on gaining insight into the performance of this class of retrofit technology for suitable multifamily buildings:

- Multifamily buildings evaluated have wider supply loop to return loop temperature differentials than is recommended for the *M2G* ALM controller. It is recommended that *M2G*-equipped boilers operate with a differential of less than 15°F, over which the *M2G* is not designed for optimum performance (unless a modified chip is supplied custom by the vendor). The Chicago and Cary field sites both had differentials in excess of 20°F.
- The degree that boilers are oversized for their heating load is proportional to the anticipated savings with ALM controllers. This oversize factor is a fixed condition, given the specified boilers, and more importantly a variable condition where opportunities for ALM controller energy savings are greater during shoulder season months, as shown by laboratory testing of an *M2G*-equipped boiler under conditions simulating a hotel and secondary school. Also, upgrading the envelope of a multifamily building would result in greater ALM-controlled savings versus a baseline boiler for this same reason.
- As the *M2G* does not require calibration, it infers the operating conditions of the boiler (e.g., aquastat setting) dynamically, it can be paired with OTR-equipped boilers or other temperature-based setback controllers. The two controllers paired together do not necessarily have additive benefits, however based on the operating strategy of the *M2G*, it is not expected to have a negative impact on performance. All boilers equipped with *M2G*s during this study were operated with OTR controllers as well, which act to change the primary loop temperatures as a function of outdoor temperature, which impacts the demand on the system in the form of dry-cycling losses (in which standby losses are a component) and will likely reduce the simple payback of the ALM controller.

Concerning the research questions, those which can be definitively answered are as follows:

- Do the savings differ from those observed for commercial and industrial field evaluations? If so, what is unique about the low-rise multifamily sites to cause this?

  Yes, this is due primarily to the variability in the boiler differential, which can be in excess of 20°F. Commercial and industrial boilers are controlled with finer differentials, often less than 5°F, which are enabled in part by the greater thermal inertia of the heating system. Based upon laboratory testing with a larger differential, multifamily applications of ALM controllers can expect reduced levels of savings for similarly oversized systems.

- Under what conditions does this ALM controller "decide" to hold the boiler from firing and when does it allow the boiler to fire?

  Outlined in Section 2.3, the three primary means in which this ALM controller releases a boiler to fire are: if the monitored water temperatures drop a prescribed amount following a call for heat (indicating a demand), the prior cycling behavior based on recorded memory appears to be a demand, or a period of 15 minutes elapses. For the *M2G*-equipped boilers in this field study, the most typical scenario is the first, a temperature drop exceeding a prescribed value. During laboratory testing, the most typical scenario was the third, 15 minutes elapsing.

- What is the minimum temperature that the ALM controller allows the return water to drop?

  While laboratory simulated testing of an *M2G*-equipped boiler operating with its prescribed 5°F differential did not allow the return water to drop more than 11°F from baseline, the field boilers operating with much larger differentials exceeded 15°F below the return temperature following a call for heat, during which a differential of up to 35°F was observed.

- What energy savings are realized over a heating season by an *M2G* equipped hot water boiler in a low-rise multifamily building? How does the energy savings potential for intelligent boiler load control compared to other competing products that use OTR to produce energy savings? When added to an existing outdoor reset or scheduling control system, what is the additional energy savings associated with this product?

  During "shoulder season" operation, with daily HDD of less than approximately 40°F-day, the Cary site showed 7.1% therm savings with a 16.5% reduction in cycles and the Chicago site showed a 14.4% therm savings with a 31.8% reduction in cycles (adjusted for HDD), with annual savings expected to be less. These were all observed for systems equipped with OTR controllers. Baseline performance of OTR versus non-OTR controllers was outside of the scope; however, the vendor of the OTR controllers suggests that 5%–30% annual savings are to be expected.

  As an "indoor temperature reset" solution, the potential for savings from ALM controllers is impacted by the presence of OTR controllers, as it indirectly reduces dry-cycling by varying the primary loop temperature with ambient conditions. However, results from this study show the savings from ALM control in parallel with OTR control, may be predictably normalized to HDD. Savings in retrofitting OTR-equipped boilers with ALM controllers are not expected to be additive from the performance of individual systems, however data from this study suggest that the degradation is nominal with simulated "shoulder season" performance in a laboratory study on the same order as that observed at the Chicago site.

- Is there a perceived change in thermal comfort from heating with and without an ALM controller?

At the both sites the maintenance staff has not fielded service calls or complaints due to loss of thermal comfort due to the *M2G*. In the case of the Cary site tenants have offered unsolicited comments to the opposite that comfort is enhanced compared to past years. This is unlikely to be directly attributable to the *M2G*, which did not have a significant effect on cycling during the winter peak months at the Cary site.

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