Effects of equipment cycling and sizing on Seasonal Efficiency

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ABSTRACT

This paper reviews the effects of seasonal weather variations on heating system performance in multi-family buildings. By investigating 14 months of actual operating data from 30 occupied sites, the research has been able to document and clearly illustrate some previously held assumptions regarding seasonal efficiency of these systems.

The paper presents the results of a New York State Energy Research and Development Authority sponsored research study on fuel consumption and single pipe steam heating/DHW systems operations. As part of the project, the buildings were instrumented for monitoring apartment, outdoor, boiler and DHW temperatures, burner on-off times, stack temperature, oil & boiler make-up water flows, and DHW temperatures at various points on the system.

The focus is on the portion of the research that delved into the vast amount of heating related data in the database. The effects of seasonal efficiency have been analyzed by examining daily fuel use vs. boiler runtime at different outdoor temperatures, and during the various seasons. Also, time of occurrence and duration of burner on-and-off cycles have been studied to determine the trends and potential effects of system cycling. These data are presented in such a way as to illustrate real-time operations and show the negative effects of system oversizing, (an all to common practice in this stock of buildings). In addition to the heating data analyses, calculations (based on this project and prior DHW research) are presented that allow for a more accurate treatment of seasonally varied DHW consumption.

The research is currently evaluating how we may use this better understanding of the effects of seasonal efficiency to create a Seasonally Adjusted Degree Day Methodology (*SADDM*). Such a *SADDM* will assist energy professionals and facility managers in evaluating shorter term increases or decreases in consumption, that are currently only apparent with annual analyses.

Data Monitoring

Data Collection

Instrumented monitoring of heating plants and DHW was conducted for 14 months in 30 multi-family buildings in New York City in association with an existing monitoring system operated by Langsam Property Services. Nine buildings were instrumented to provide detailed DHW consumption data.

The buildings selected ranged in size from 17 to 103 apartments, and have either 5 or 6 above-ground stories. These buildings were constructed pre-1902 or between 1902 and 1928. All the boilers are combination heat and hot water units, steel tube boilers, and (primarily) air atomizing No. 4 or 6 oil burners, with DHW generated by a tankless coil.

The data for this research were collected by Heat Computers that monitored the following data points on all buildings: internal apartment temperatures, outdoor temperature, burner on-off-times, boiler water (aquastat) temperature, and DHW temperature. The nine upgraded buildings (ID #s 1-3 and 5-10) had additional data monitoring equipment installed to record stack temperature, boiler make-up water flow, DHW flow in 5 and 15-minute increments, oil flow, and DHW temperature before and after mixing valve and on the return line. Measurements from these devices were recorded periodically (every 5 minutes, 15 minutes, hourly, or daily depending on the particular device) by the heat computer, which then stored the data in memory.

Via modem, the building management firm's staff called each building every third day to download the data onto disks that were delivered to the investigator, Energy Management & Research Associates (EMRA). The data were then put through a custom-designed data translation program which rearranges the data to a data base readable format, as well as performing a number of preliminary calculations. The data were then loaded into a specially designed data base where macros perform a second level of calculations. The database environment was then used to perform specific analyses and output smaller data sets to spreadsheets for graphical analyses and presentations.

Project monitoring examined operational conditions, which should be distinguished from monitoring building thermal characteristics, such as heat loss.

Data Set

The data set includes all of the data collected by the building monitoring devices (in all 30 sites), building operational and tenant information requested from superintendents and property managers via questionnaires and interviews, and equipment and building condition data obtained through energy audits (performed by the author and colleagues). This information amounts to a data base containing about 12 million data points.

Additionally, a second subset of data from the Association of Energy Affordability's "Multi Family Research Project" (MFRP) was used to check the validity of some of the analysis methodology and the findings by comparing them to a different building set in a different weather year, (the 1995-96 heating season).

Analyzing Usage: "Know Your Baseline"

In analyzing a facility's energy usage against a controlling variable, such as weather or units of production, we attempt to remove consumption attributable to factors other than the main variable. This 'other' portion of consumption referred to as the facility's baseload usage is then removed as an adjustment from the total consumption before analysis against the controlling factor. All too often professionals conducting such evaluations assume that if they can find a period during which only the baseload consumption is occurring, that level (of consumption) can be used to make adjustments across the entire year. Examples of this might be lighting during the winter (in a building with electrically driven air-conditioning and a non-electric heating system), or the summer domestic hot water (DHW) load in a fossil fuel driven heating/DHW system.

It is important to investigate what is actually occurring with the assumed baseload across the full year. One should not assume that it is an even load throughout the year. In multi family buildings such as those in the monitored study, the industry standard has been to consider the DHW load as the base. In evaluating a building's fuel use, it is customary to take the summer fuel bills and project that level of consumption out evenly through 12 months. The argument being that during the summer period the heating plant is operating solely to provide DHW and therefore all fuel use during this period can be attributed to that function. Also until recently it had been assumed that the DHW use, while variant between sites, was within a building constant from month to month. Results from earlier research into this database have revealed the constant level assumption to be incorrect (Goldner 1994).

Analysis of the seasonal DHW consumption levels reveals a pattern, as Figure 1 illustrates, the average consumption in the summer rose by 10% in the fall and then by 13% during the winter period. The consumption then fell by 1% in the spring and fell 19% during the second summer period.

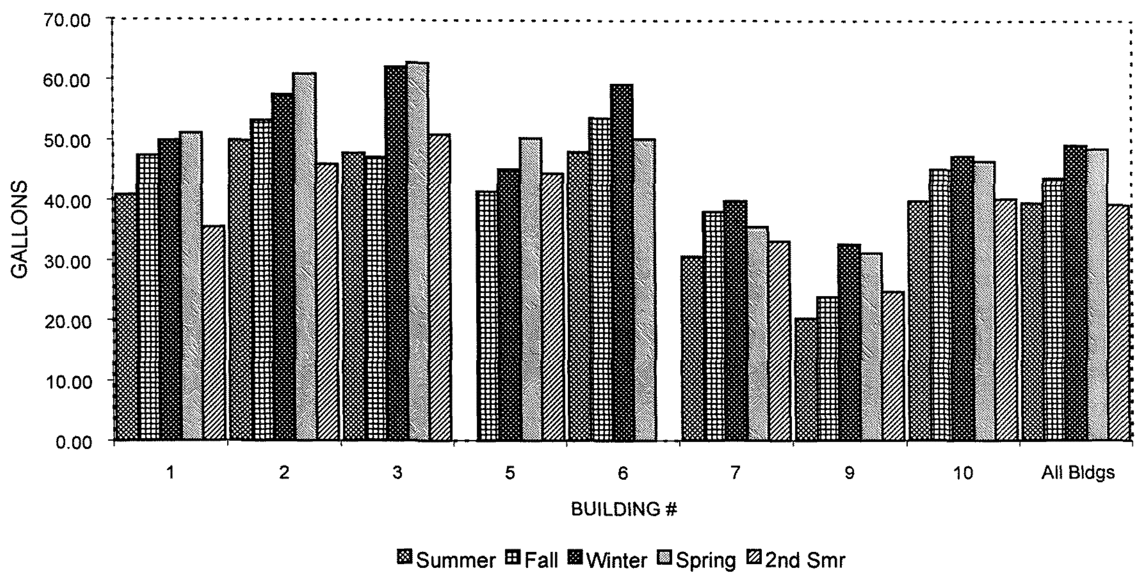

Figure 1. Seasonal Comparison of DHW Consumption Average Gallons per Capita per Day

In order to compensate for the higher levels of DHW being used during the non-summer months it is necessary to adjust the baseline fuel consumption. This is done by multiplying the average daily units of fuel, (gallons of oil in the study buildings), by the number of days in each season and by the multiplier for increased DHW consumption.

As an example, Figure 2 illustrates the fuel use for study Building #7. We can clearly see that there is a constant base level of fuel consumption during the summer months, for providing DHW. Once this baseload has been determined, the fuel use for the other seasons are reduced by an amount equal to this level adjusted upward by the appropriate factor, (of 1.1 in fall, 1.25 in winter and 1.23 in spring).

When investigating factors that effect the DHW load, two other potential issues arise. First, supply water coming into the DHW system is colder during the non-summer months. Manual spot measurements show a delta T of -20^{O}F during the winter as compared to the average summer city water supply temperature. Calculating this against a typical 60^{O}F temperature rise (for DHW heating) results in approximately 30% more energy needed to heat the water during the colder months. Secondly, as is described in the following section, the boiler/burner unit operates considerably more efficiently as the outdoor temperature drops. An analysis of the system's operations during the summer reveals that they are delivering DHW at an average efficiency of 42%[1]. The second issue tends to have an inverse effect of the first; so for the purposes of this analysis these have been considered self negating.

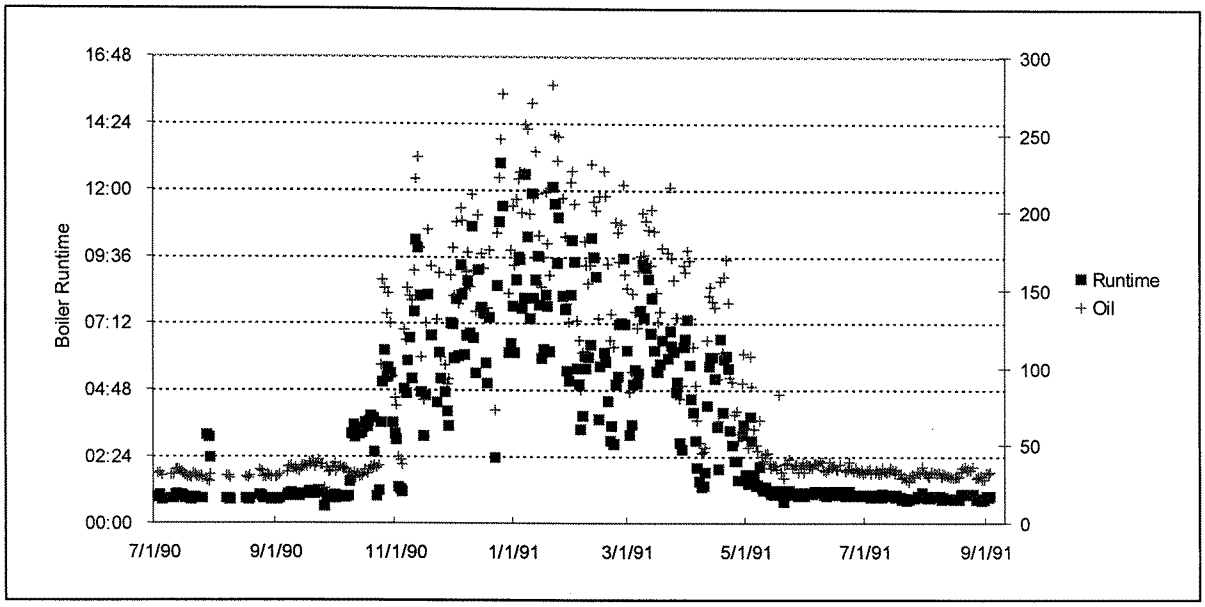

Figure 2. Boiler Runtime vs. Fuel Used, Building 7

Systems Operations & Generic Methodology

Once the baseload has been broken out from the overall consumption, the remainder of the energy use can then be evaluated against the controlling variable. Before using even some of the most accepted methods, it is advisable to re-evaluate both your facility's operation and the underlying suppositions of the method to be employed.

In the case of a space heating application the most commonly used methodology is to calculate the fuel used per heating degree day (HDD). The initial daily fuel consumption evaluation of gallons of oil per HDD (Gal/DD) resulted in a relatively flat level across the heating season, (see Figure 3). This appeared to contradict the widely held assumption that equipment is more efficient when it is operating at closer to full load. Upon further review of the buildings' operation and control strategy it became apparent that some of the basic principles behind standard HDDs were not correct for this stock of buildings. A HDD (those published by the National Climatic Data Center) is equal to 65° minus the average of the high and low recorded temperatures for a day. HDDs are calculated for any day on which the

[1] The analysis compared total BTU OUT to BTU IN. With BTU OUT = Gallons of DHW consumed * 8.33 lb/gal * ((Average of temperature leaving the mixing valve and temp. of return water) - temp. of inlet supply water) * 1 BTU/lb/$^{\circ}$F, and BTU IN = gallons of oil burned * BTU/gallon.

average (mean) temperature falls below 65^{o}F[2]. The assumption being that during the heating season, whenever the outdoor temperature falls below 65^{o} the heating system will act to keep the interior space at 65^{o}. In this stock of buildings that hypothesis differs from the algorithm employed by the heating plant controls. New York City's Housing Maintenance Law requires that when the outside temperature falls below 55^{o}F the building must provide an interior temperature of not less than 68^{o} F[3]. The various controls used throughout this stock of over 120,000 buildings are set up to comply with this code. Thus it is apparent that the underlying theory of a 65^{o} based HDD does not hold true and should not be employed in calculating the energy use indices for these facilities.

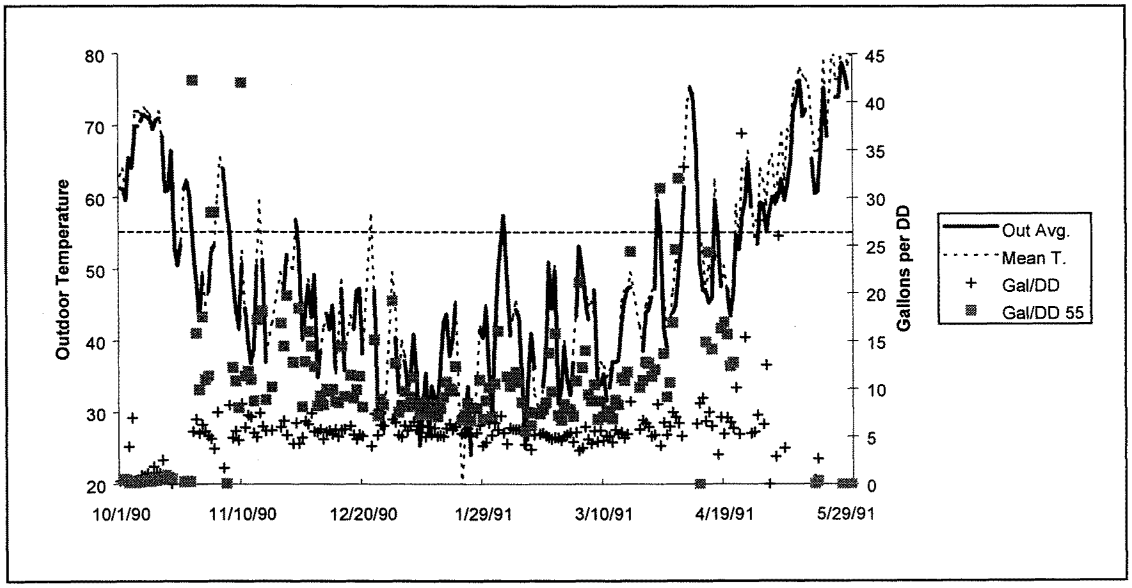

Figure 3. Temperature vs. Gal/DD – Adjusted for 55, Building 7

Given the data collected in this project it was possible, however, to calculated a new HDD set based on the control strategy. The new 55^{o} base HDD (DD_55) tables were compiled by employing the condition that HDDs are computed only for days in which the mean temperature for a day fell below 55^{o}F. On those days the mean temperature for the day was subtracted from 68. This then gives us a more accurate model upon which to evaluate the buildings' performance.

Included in Table 1 is a breakdown of the yearly totals of DD_55 and DD_65 (the commonly available 65-degree-based figure) for 1991 through 1996. Note that the difference between the annual pairs of degree day figures vary significantly from year to year. This

[2] Note that it is possible to get weather data (from NCDC and other sources) in other formats, such as average daily or hourly temperatures. These can be utilized to compute/create the DD base most appropriate for your application.

[3] In fact, the law states that between Oct. 1 and May 31 during the hours from 6 am to 10 pm when the outside temperature falls below 55^{o} F the building must provide an interior temperature of not less than 68^{o} F, and from 10 pm to 6 am when the outside temperature falls below 40^{o} F the building must provide an interior temperature of not less than 55^{o} F. As most generally available data is for average daily temperature, the case above and DD_55 data presented later have been simplified and calculated using only the daytime control temperature settings as a parameter. It should be noted that a more exacting representation would be obtained by calculating the degree hours against the two different, 'daytime' and nighttime', regulation levels.

further proves that use of the traditional 65-degree-based degree days as a method of calculating energy use and savings can result in misleading conclusions, (when making year-to-year weather-adjusted usage comparisons). Further examination of individual date DD_55 and DD_65 degree day figures reveals that, while on cold days, e.g., 1/2/91, the DD_55 base system accumulates three more degree days, whereas on warmer days, e.g., 4/6/91, the normal 65-degree-based system (DD_65) can accumulate an even greater number of "false" degree days. That is, degree days are calculated, when in fact no heating is being called for. This then exaggerates to an even greater extent the misleading results that can occur from use of the 65-degree-based system as compared to the DD_55 ("Degree Day 55") methodology.

Table 1. Degree Days for a Sampling of Periods

Year	DD_55	DD_65	
1991	4840	4589	105.5%
1992	5198	4862	106.9%
1993	5188	4749	109.2%
1994	4864	4663	104.3%
1995	5003	4724	105.9%
1996	5337	5029	106.1%
Date			
1/2/91	26	23	
4/6/91	0	7	

Figure 4. EXAMPLE OF HOW TRADITIONAL DD_65 METHODOLOGY INTRODUCES ERROR

Examination of a 30-unit apartment building reveals a consumption of 27,090 gallons of number 2 fuel oil in 1993. As a result of an energy audit, the building management installed energy conservation measures and implemented new operating procedures during 1994. In 1995 the consumption was 23,615 gallons. In the following example the consumption has been weather-adjusted with both the 55 Degree Day base (DD_55) and the 65 Degree Day base (DD_65). The results illustrate the error (or overestimation in this case), that exists when employing the traditional DD_65 methodology.

1993 - 27,090 gallons total consumption
8,127 gal for DHW
18,963 gal for heating

Weather adjustment with 55 degree day base:

$$18{,}963_{\text{gal}} / 5188_{\text{DD\_55}} = 3.655_{\text{gal/DD\_55}} \times 5072_{\text{6 yr avg DD\_55}} = 18{,}539 + 8{,}127 = 26{,}666 \text{ gallons}$$

Weather adjustment with 65 degree day base:

$$18{,}963_{\text{gal}} / 4749_{\text{DD\_65}} = 3.993_{\text{gal/DD\_65}} \times 4769_{\text{6 yr avg DD\_65}} = 19{,}043 + 8{,}127 = 27{,}170 \text{ gallons}$$

The building then installed ECMs during 1994

1995 - 23,615 gallons total consumption
7,085 gal for DHW
16,531 gal for heating

Weather adjustment with 55 degree day base:

$$16{,}531_{\text{gal}} / 5003_{\text{DD\_55}} = 3.304_{\text{gal/DD\_55}} \text{ X } 5072_{\text{6 yr avg DD\_55}} = 16{,}758 + 7{,}085 = 23{,}843 \text{ gallons}$$

Weather adjustment with 65 degree day base:

$$16{,}531_{\text{gal}} / 4724_{\text{DD\_65}} = 3.499_{\text{gal/DD\_65}} \text{ X } 4769_{\text{6 yr avg DD\_65}} = 16{,}688 + 7{,}085 = 23{,}772 \text{ gallons}$$

Summary:

	DD_65	DD_55	Difference
1993	27,170	26,666	
1995	23,772	23,843	

Savings:

gallons	3,397	2,823	574
Dollars	$3,228	$2,682	$546
% cost			20%

We see in this example how use of the traditional DD_65 methodology introduces a 20% error factor in the computed cost savings. A run of other site evaluations, comparing the DD_55 and DD_65 methodologies, reveals that while the level of error may vary both in magnitude as well as in direction (in some cases overestimation and others underestimation), the traditional 65-degree-based method always results in an incorrect appraisal in the change of (weather adjusted) energy consumption. This takes on even greater importance in the soon-to-be-deregulated environment, as even more energy projects will be instituted under some type of performance contracting (such as shared savings).

The analyses were then rerun against the DD_55 values. In Figure 3 we see that in fact the efficiency of the heating system increases (lower Gal/DD 55, solid squares) as the outdoor temperature drops, and the boiler is operating at closer to full load. Then as we approach the shoulder months of spring the efficiency drops resulting in a higher Gal/DD 55. It is also interesting to note on this graph that the mean temperature (Mean T.) of the day, computed as [high – low] / 2, is almost identical to the average outdoor temperature (Out Avg.), computed by averaging the 24 hourly readings collected each day. (The only notable differences appearing toward the upper right hand corner of the graph.) It was initially thought that this mean temperature, (averaging of high and low temperatures), was not properly representing the true condition of a day.

Figure 5 more clearly illustrates how, as the load on the heating plant increases, the system operates more efficiently to fulfill this demand. Each point on the graph represents the amount of fuel used on a given day to provide heat to the building. The load is represented by be number of degree days (DD_55) for a given day. We can see that at higher load levels, e.g., colder days with more degree days (when more heating is needed), system efficiency increases.

As all of the monitored (heating system) data for this study was collected (as part of another study) in the 1990-91 heating season, we felt that it was important to see if this observation of increased efficiency with increased load held true under different weather conditions. To this end, data from the MFRP research project, collected during the 1995-96 heating season was examined. Figure 6 illustrates that the phenomenon of increased efficiency at closer to full loads holds true as projected.

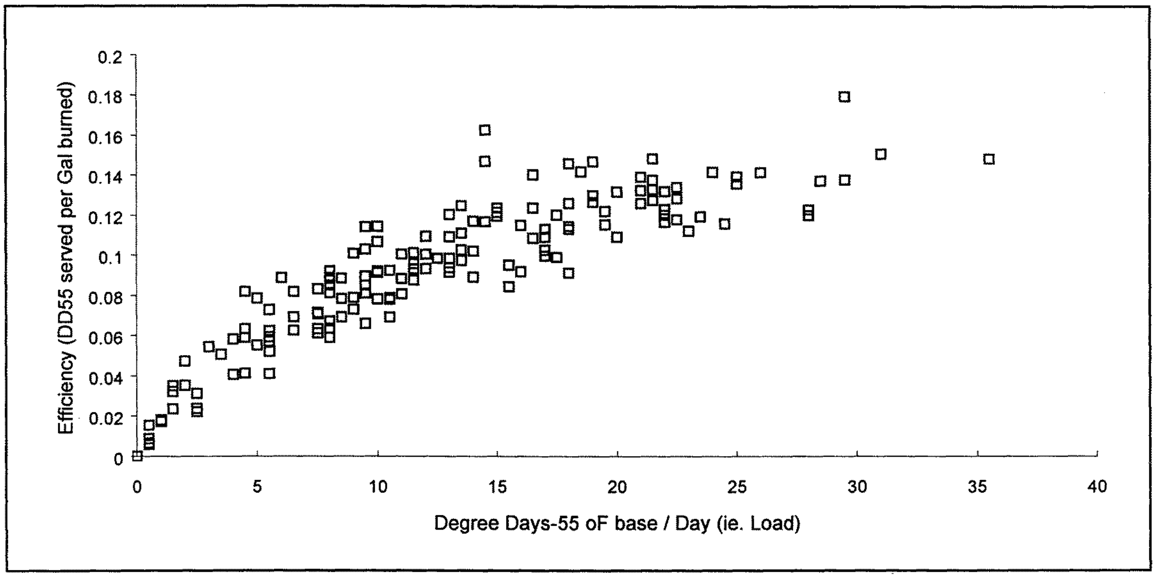

Figure 5. Heating Production Efficiency vs. Load, Building 7

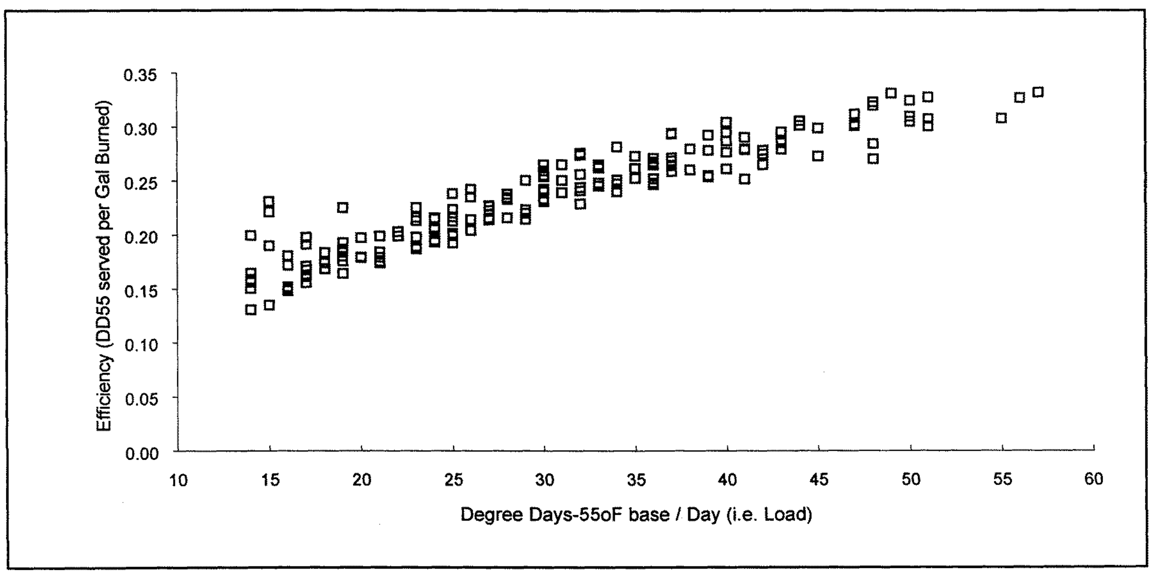

Figure 6. Heating Production Efficiency vs. Load, Building MFRP-2

Following similar analyses (to those presented for Building 7, illustrated in Figures 2, 3 and 5) for all eight sites for which detailed data was available, individual site data was compiled to produce Figures 7, 8, and 9. Figure 7 examines fuel use for heating vs. outdoor temperature. We can clearly see that as the outdoor temperature decreases there is a resultant increase in fuel use efficiency, delineated as a lower gal/HDD (using the 55 DD base). The explanation of why this greater seasonal efficiency is occurring comes to light in Figure 8, as we see that there is a direct correlation between the decrease in Gal/HDDs as the daily burner runtime increases. Some smaller portion of the increase in the runtime is also contributable to the higher DHW loads during these seasons. Examination of the consumption data on a seasonal basis suggests that the buildings are operating approximately 30% more efficiently during the winter as compared to the fall and spring.

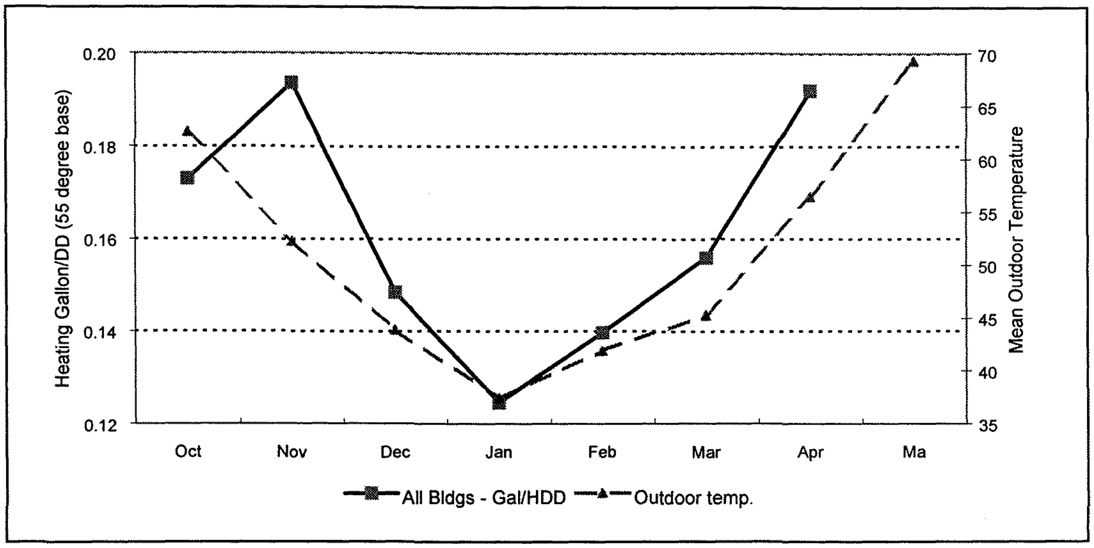

Figure 7. Seasonal Efficiency, Average Gallons/HDD – Adjusted for Baseline

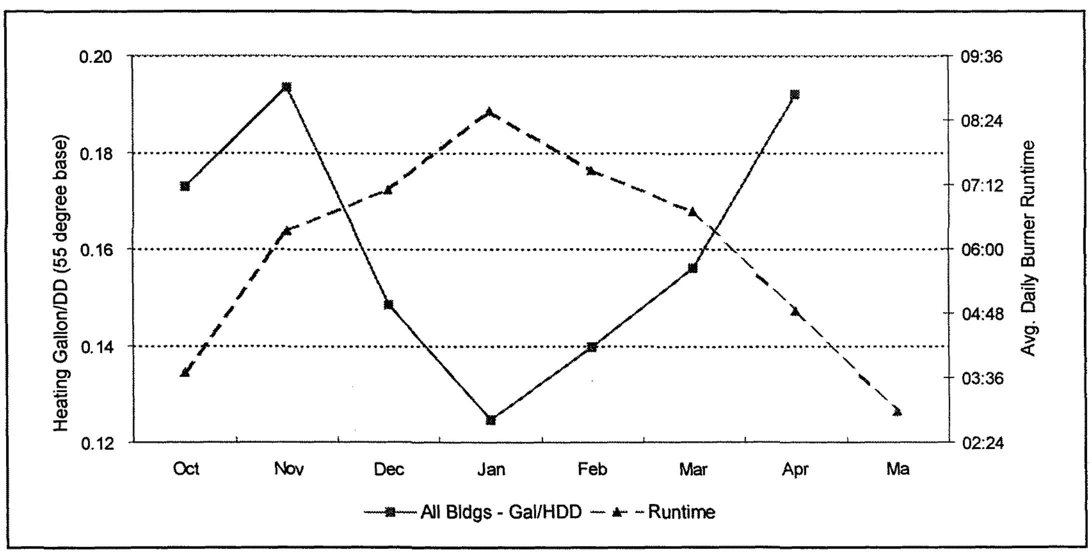

Figure 8. Seasonal Efficiency, Average Gallons/HDD – Adjusted for Baseline

Figure 9 documents that the trend of increasing burner runtimes is occurring stock wide, and is not limited to the sites with more detailed level of data collection. We see that the highest average daily burner runtime of 8:32 occurs in January, and is 3.2 times longer than the lowest average daily runtime of 2:39 which occurs in August.

While total daily runtime begins to explain the increase in operating efficiency during the colder months, as the boiler is running at closer to full loads, it does not shed light onto all the pertinent issues. To gain greater insight, time of occurrence and duration of burner on-and-off cycles were studied to determine the trends and potential effects of system cycling. As shown in Table 2 the day was broken down into 3 periods. Period 1, midnight (00:00) to 5:30 AM, represents the overnight time during which little to no DHW is used (Goldner 1994) and the system comes on only to maintain minimum boiler water temperature (during the summer period), and/or to satisfy heat calls. Period 2, 5:30 to 9:00 AM, represents a peak DHW demand period as well as the early morning heating boost period. Period 3, 9:00 AM to midnight (23:59), covers the rest of the day representing a mix of high and low demand times.

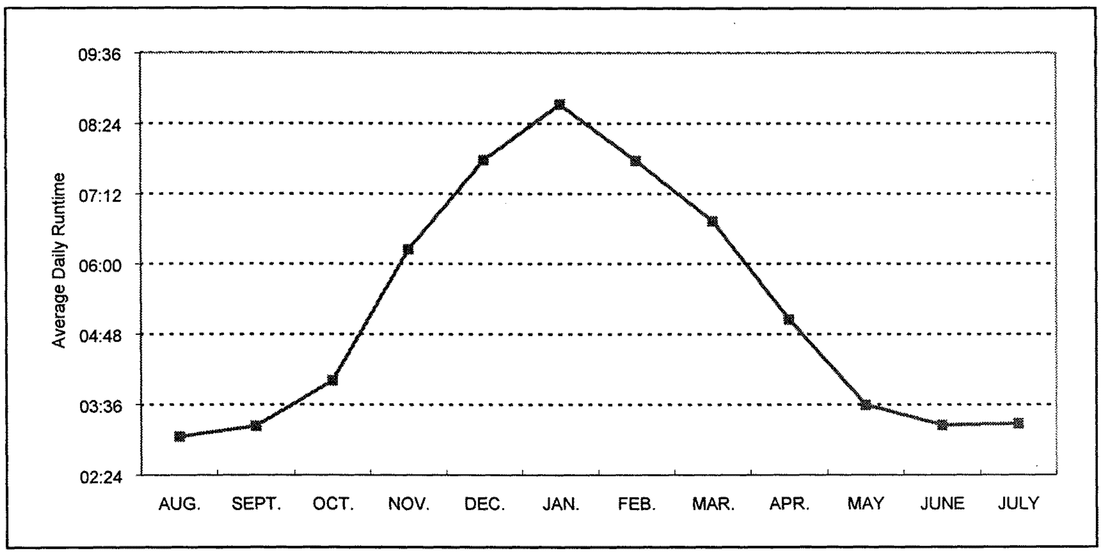

Figure 9. Burner Runtime, (Mean of All 30 Sites)

A significant amount of energy is lost from the heating plant each time it cycles, due to shut down and start up losses. Examination of Table 2 illustrates the occurrence of longer duration runtimes during the colder periods, which reduce the system inefficiencies attributable to cycling.

Trends Towards An Alternative Methodology

The data analysis has documented some of the previously held beliefs regarding improved seasonal efficiency at higher loads. One of the more interesting relationships revealed by this project is between seasonal efficiency (measured in Gal/DD 55) and the number of HDDs for the period. A month-by-month analysis of consumption suggests that there may be a direct correlation between degree days in a period and the efficiency level for that period. A potential next step would be further testing of this hypothesis on a larger group of buildings during other (weather pattern) years to refine the mathematical relationship. This could provide a valuable new energy use targeting/ tracking methodology. Such a methodology would assist energy professionals and facility managers in evaluating shorter-term increases or decreases in consumption, that are currently only apparent with annual analyses.

Table 2. Boiler Cycle Time Lengths

	00:00 to 5:30		5:30 to 9:00		09:00 to 23:59		
SEASON	ON TIME AVERAGE	OFF TIME AVERAGE	ON TIME AVERAGE	OFF TIME AVERAGE	ON TIME AVERAGE	OFF TIME AVERAGE	SEASON
Summer	00:05:00	01:03:14	00:05:07	00:36:19	00:05:21	00:36:13	Summer
Fall	00:06:35	00:54:08	00:13:03	00:24:15	00:09:57	00:33:07	Fall
Winter	00:09:22	00:38:57	00:22:21	00:15:29	00:14:31	00:26:19	Winter
Spring	00:05:12	00:58:34	00:08:50	00:25:48	00:06:08	00:30:31	Spring
AVERAGE	00:06:32	00:53:43	00:12:20	00:25:28	00:08:59	00:31:32	AVERAGE

** NOTE: Times are in HOURS : MINUTES : SECONDS (HH:MM:SS).*

SUMMARY OF SIGNIFICANT ISSUES

- It is necessary to understand and adjust properly for what is actually occurring with the assumed baseload across the full year.
  - For DHW in a multifamily building, the summer baseload level should be adjusted upward by a factor of 1.1 in fall, 1.25 in winter, and 1.23 in spring.
- When combination heating/DHW systems are just generating DHW in the summer, the average heating plant system efficiency was found to be only 42%.
- In evaluating energy use, it is necessary to understand both facility operation and the underlying suppositions of the energy indices method to be employed.
- The mean temperature of a day (computed as high - low / 2) is almost identical to the average outdoor temperature (computed by averaging the 24 hourly readings each day), and is therefore a good representation for weather conditions.
- As the load on a heating plant increases toward (closer to) full-load conditions, the more efficiently the system operates. This phenomenon is a result of the boiler needing to

operate for longer periods (increased daily burner runtime at closer to full capacity conditions) to supply larger heating loads at lower temperatures, as well as less cycling, due to longer duration of each cycle runtime.

- All degree days are not equal. A degree day on a 50° F day requires a different amount of fuel to satisfy related heating load than does a degree day on a 25° F day. Therefore it is not possible to compare energy consumption of a building in the fall to, a winter period. A potential solution to the need to evaluate energy usage on a shorter-term (less than annual) basis is the development of a Seasonally Adjusted Degree Day Methodology (SADDM).
- In multifamily buildings the conventional 65-degree-day base system may result in misleading conclusions when making year-to-year weather-adjusted energy usage and savings comparisons, (in buildings where the heating plant control algorithm differs from the assumptions of the conventional basis for calculating degree days).

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