Boiler Plant Sizing for Maximum Efficiency at Minimum First Costs: Measure First!

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Abstract: *This is* part one of a series of shameless “White Papers” on boiler plant design. The founders of Thermodynamic Process Control have been involved for more than 20 years providing clients with custom solutions for the issues of boiler plant design and control. Through the years we have been involved in every aspect of mechanical/boiler rooms. Without going into too much detail our careers have been spent designing, building, maintaining, and controlling boiler plants. In that process we have developed proprietary methods for each of these tasks. Today we are solely involved in design and control of these boiler plants. In part 1 of this series we wish to make the case for a better understanding of a building's load for comfort heating hot water boilers. We intend to show that current methodology is inadequate for determining the load for an existing structure that requires a retrofit of the boiler room. We will show how current methods can lead to increased installed costs. Further, we will show that there is no reason at all to make a mistake in boiler plant sizing for plant retrofits. Last, we will present TPC's solution to this largely unknown problem.

Current Methods For Sizing Boiler Plants For New Buildings:

When a new building is constructed nothings exists except a plot of ground. The Architect makes plans that include the heating of the structure. In the absence of an existing structure, estimation methodology must be used to determine the size of equipment to be installed. This design estimation, quite rightly, must be made with the worst case scenario in mind. Once this worst case is calculated, there is usually a factor of safety applied. After the factor of safety, then redundancy is added in the form of an additional boiler or boilers. This is an added measure in case there is a failure in one or more of the boilers.

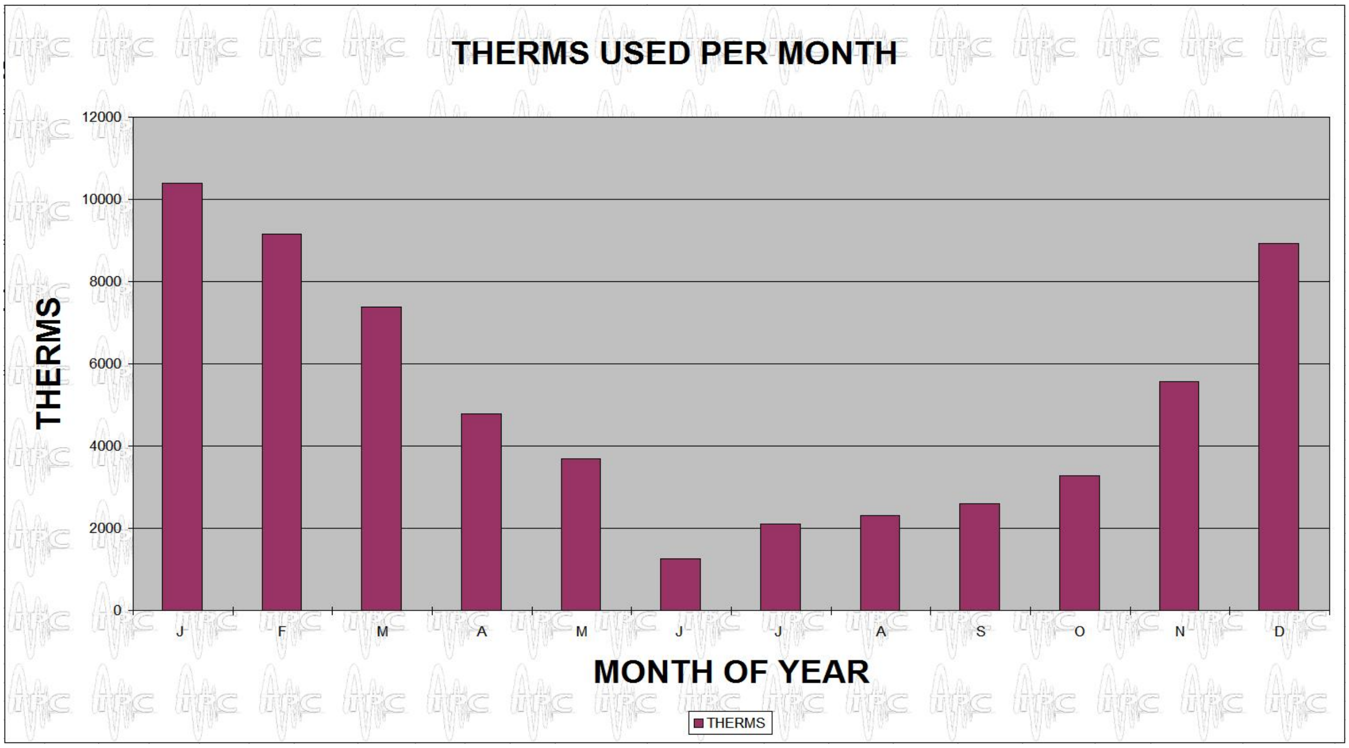
Over time these calculations have been amended to reflect current building methods and mechanical plant design changes. Estimated sizing methods are constantly improved and amended. In order to understand the retrofitting process for an existing building we must first understand how existing mechanical plants are designed. This paper will focus mainly on the existing building, boiler room retrofit.

Current Methods For Sizing Boiler Plants For Existing Buildings.

Existing structures provide new opportunities for boiler plant design. In retrofitting an existing structure, we have a distinct advantage over the Architect, since the building and energy use data exists. The question now is: How much will we press our advantage over the Architect with our analysis? Perhaps we should take a closer look at how, boilers sizing for plant retro-fits, typically happens in the real world. There are currently two main types of boiler plant sizing methods, one used by Salesmen, and one by Engineers. The Salesmen typically will not be the one sizing public works projects, so his method can be called the Business Estimation Model. The Engineer will be the person responsible for sizing boiler's in the public works arena, therefore we will refer to that methodology as the Public Estimation Model. Principle to this discussion of plant sizing models, is an understanding of the needs of the two distinct customer market verticals. We will discuss the business vertical first, then the public vertical will follow.

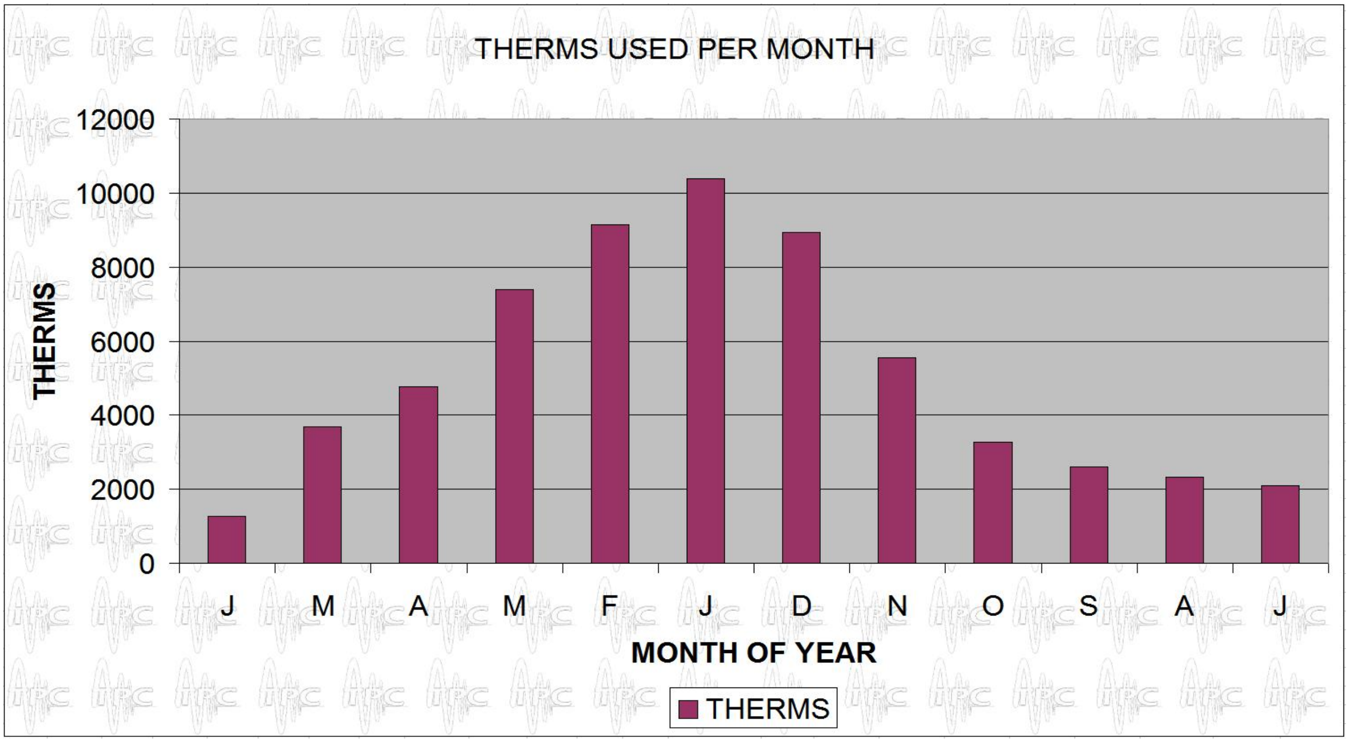
The Business Estimation Model:

To the business, how the project looks on a financial statement can be more important than the specification of equipment itself. The business is looking for a 10-15 year solution, that will have a simple pay-back in two years and show favorably on paper within a quarter. This is a pretty high hurdle, in fuel savings, for most salesmen to overcome. Those who attempt, typically start their analysis with an examination of total gas usage for the building for the previous two (2) to five (5) years. This billing is then averaged and graphed (example below) showing the average monthly usage.



(Chart 1: Example of annual average fuel usage by Month.)

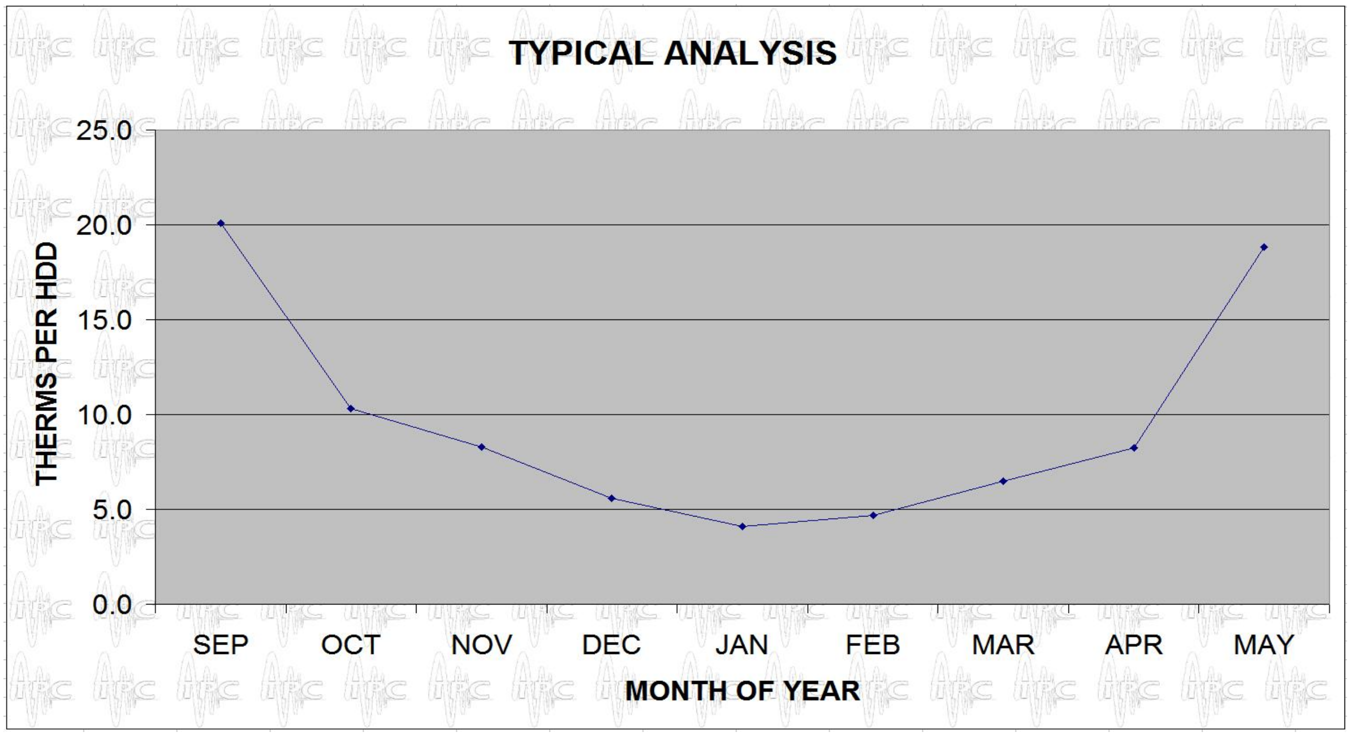
There is usually an inherent initial error in this chart. The chart created from the fuel bills accounts for the entire structure's gas usage. If the building has a kitchen with gas burners, a swimming pool, or a significant domestic hot water load from the kitchen or showers, this attempt to isolate the comfort heating system will have a substantial error. To further complicate this kind of analysis is a heating mode known as reheat. Reheat is essentially heating air that has been over-cooled by the chiller. The problem with combined reheat and heating in fuel bill analysis is it can lead to errors in energy savings predictions for a boiler replacement. Many erroneously assume that much of the gas used for reheating is wasted gas from boiler short-cycling. Without reliable data you are pretty much stuck with this kind of analysis. Looking at the graph above you can see that the winter months use the most energy for heating. You might also have noticed that if you were to change the graph and put January and December in the middle and June and July on the ends, you would end up with a nice bell curve shown below.



(Chart 2: Example of annual average fuel usage complied to show bell curve.)

Now that the usage is more or less established, an attempt to understand plant efficiency ensues. These salesmen are looking for a pattern in a particular graph that is an indication of boiler cycle efficiency. The graph is a manipulation of data that indicates the fuel used in a given month as compared to how cold it was outside. This is derived by examining the therms used per heating degree day (Therms/HDD). A heating degree day is an attempt to quantify how cold it is, as compared to a tipping point for needing heat. So if we applied 65F outside as our tipping point for needing heat, and for 24 straight hours it was 45F outside, the result would be 20 heating degree days for that day. If the next day the temperature were 55F all 24 hours we would accumulate 10 heating degree days. Of course the daily temperature rises and falls so each hourly average is accumulated and totaled by the National Weather Service and other outlets. Once the heating degree days are totaled, they are publicly reported free of charge in several places on the internet.

Something unexpected happens when this graph is complied (see example below). The nice bell curve we desire is the inverse of what we would expect. Even after attempts are made to account for the initial error of all gas being used in the analysis, instead of just the comfort heating gas, the graph is usually still the inverse. Jack McKeegan was the first to point this out to the industry. McKeegan correctly linked this inverse pattern to boiler over-sizing and poor boiler control theory that leads to boiler short-cycling. This is a very wasteful condition found in many boiler rooms.



(Chart 3: Example chart shows Therms/HDD analysis.)

Heating degree day analysis definitely shows that a problem exists. While other potential problems with efficiency may exist, it does at least indicate that short-cycling is an efficiency issue for this plant. This is the point where our ability to analyze stops and hypothesis begins. The analysis is typically used to add a smaller boiler to the plant. This data has been used by boiler salesmen and design build firms with just as many failure stories (that you will never hear) as success stories. Even the "successful" projects (the projects that saved energy) in many cases are left incomplete; the savings could have been greater!

The Public Estimation Model:

Since there is a good chance for a significant error in building load calculations, many boiler plant retro-fits are replaced BTU for BTU. In other words the current designer will rely heavily on the original designer's calculations. It is recognized by many that buildings are usually improved or modified over time. Building envelope changes with improvements in ventilation. Instillation of new windows may reduce air infiltration and thermal losses. Personal computers, copy machines and other electrical devices add heat to the structure. The understanding that a building's load profile will change over time leads us to the second methodology: the Public Estimation Model.

The public model may or may not start out with the same analysis as described above. If it does, it is not usually given as much weight in design as do the businesses. This is primarily due to the fact that engineers recognize that this jockey boiler "patch" will be incomplete to the needs of a public entity. The public entity is typically designing for a robust boiler room that will be a 20-30 year heating solution. Therefore the analysis must be made with this reality in mind. Most will start by adding up the total capacity of the end-user heating coils. This will tell the designer what the maximum output capacity of the user coils will be at design conditions. After this, a more modern technique for calculating building heating losses and gains may be applied to the calculation. Ultimately the value will be determined based on a total or partial plant replacement and may be a nod to the gas bills: in other words, an estimate. These efforts do not take into account how the heating process works. Not enough is known about when and how much energy is being used in terms of rate or, what effect how the heating system is operated plays in its own usage patterns. Therefore, this effort, just like fuel bill analysis, will not lead to a complete understanding of the building's load.

Heating is a process.

None of the techniques described above lead to an understanding of the heating process. The attempt to compare heating degree days to monthly gas data, as in the Business model, tells nothing about how, when and at what rate the energy was used. Attempting to understand the capabilities of the heating equipment, as in the Public model, will add nothing significant to how the energy was used either. Whether one is attempting a total boiler plant replacement or a partial plant replacement, this data is incomplete. Using this method alone cannot produce an understanding of the building's load that will lead to a design for optimum efficiency at minimum cost. This is because these methods, and any other estimation model used, will primarily focus on capacity of equipment and macro-usage of fuel. There is no data in these methods that will help to understand the *process* of heating your building. Understanding the *process* of heating your building will add critical information to the boiler plant sizing criteria. The sizing criteria should strive for optimum plant efficiency with respect to minimum equipment and cost. Therefore the R&D department at Thermodynamic Process Control (TPC) would like to present a new methodology for determining boiler plant size. We would like to suggest that plant sizing for efficiency is not well understood in the main. Not enough analysis goes into the effort on the front end to ensure that results are optimized and costs are minimized. The methods below have been developed, tested, and utilized by TPC in real world boiler plant design. The process should start with a feasibility study by the owners. This includes an attempt to measure and understand the load of a building and would ideally be started at least a year prior to project demolition.

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Measure First To Find A Building's True Load Profile:

Is any estimation methodology appropriate for designing boiler retro-fit plants? According to Merriam Webster to “estimate” is “to judge tentatively or approximately the value, worth or significance of”. Approximations, as we all know, are only as good as the person who makes them and the process they use to approximate. Let us take notice of a couple implications associated with what we are approximating: First, the cost to operate your plant over its use-full life will be many times the cost of the plant itself. Therefore, information gained now about what equipment to select for your plant will greatly influence future costs. Second, the cost of that plant will be greatly affected by the sizing of the equipment of that proposed plant. Therefore, information gained now about how to size your plant correctly will greatly influence initial costs. Knowing this, why would you estimate what can be measured, and known with certainty?

Data logging shows how building loads really happen.

Thermodynamic Process Control (TPC) has developed a boiler control that is also a data logger. The logger function data samples building loading conditions at 36,000 samples an hour and records with date and time stamp the hourly averages. This data is retained for at least five (5) years in the control's data memory storage. Further, this data is used to operate and optimize your boiler plant operation. The graph below shows the result of a six month data capture of natural gas input to the heating process. It shows the hourly average usage of a middle school at the hourly average outdoor air temperature. This graph, and others like it, was a little surprising at first. There are two distinct curves in the average line at the edges. This is the first bit of evidence that shows that the loading for and given outdoor air temperature is greatly influenced by other factors. Load, it seems, cannot be closely approximated with just one variable. The curve on the right (or warmer weather) is easy enough to explain. It is caused primarily by reheating. As the outside temperature increases, loading of the boiler plant will include re-heating for dehumidified air. This in turn causes an increase in energy used in the boiler plant to overcome this reality. Both curves are the result of the heating process and when the process happens. It is no secret that daily highs occur in the, well... daytime. Nightly lows, on the other hand, happen at night, as you might expect. There is something else that happens to coincide with these realities; occupied and unoccupied building operations. The graph takes its unexpected shape because in many buildings, occupied heating and cooling operations will take place during daily highs, (providing at least some of the upturn on the right). Unoccupied operations, on the other hand, take place during the nightly lows. This leads to the profile showing a drop in the average usage at colder temperatures. This graph alone does not produce an adequate understanding of the building's load. In fact it really causes more questions than answers. One thing is obvious, we need to dig deeper.

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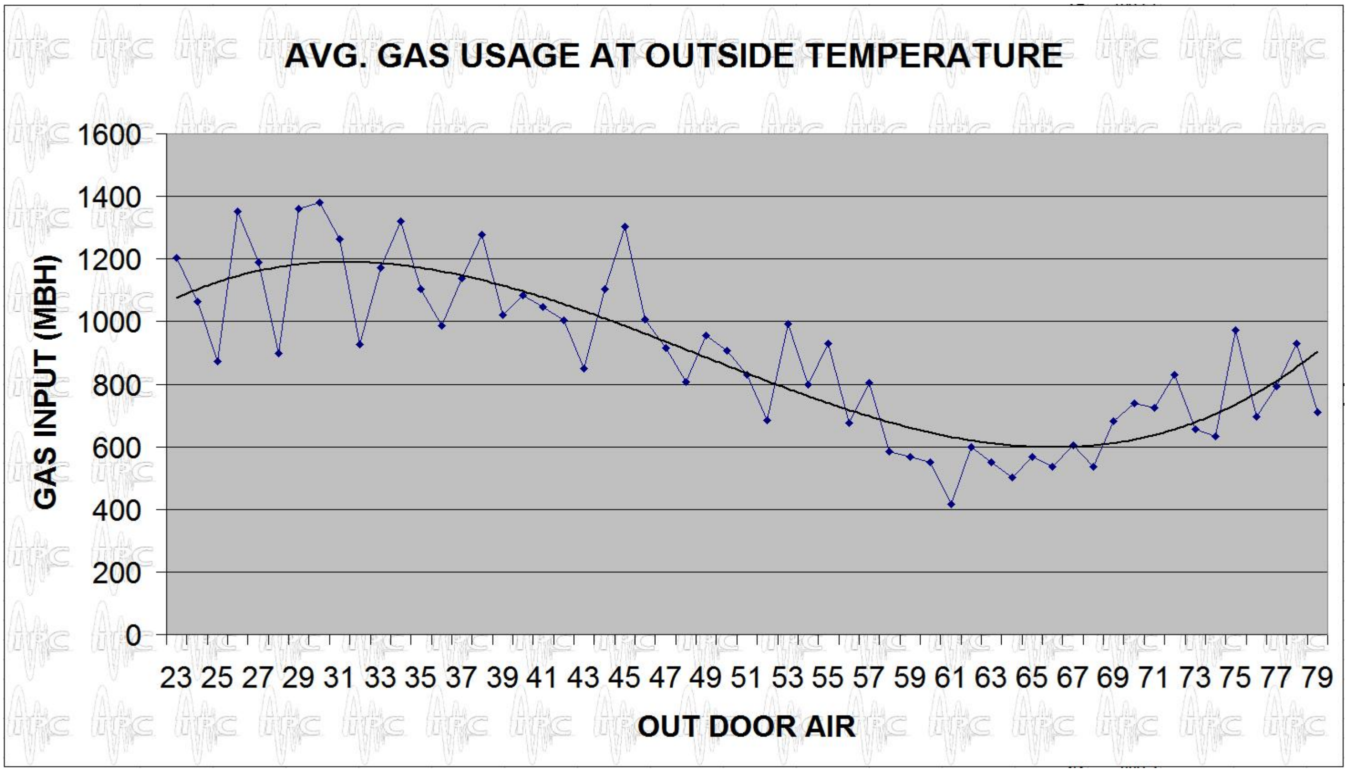

(Chart 4: Example of six (6) Month sample of building load profile.)

Outdoor Temperature Alone Is Not A Good Indicator Of Load.

What TPC has learned, through all of our building loading analysis, is that outside temperature is not a good indication of the load in buildings. The building's load will be affected by many conditions such as occupancy, night set-back, morning warm-up, humidity, sun loading, etc. Notice in the graph above the tendency for an increase in the deviation from the average line at the edges. Starting from the center the data is relatively tight. As the distance from the center increases, so too does the deviation from the average line. This is an obvious indication that something else is a driving factor in the data. The data used to compile Chart 5 below is from the same six month sample as Chart 4 above. That shows the total for all outdoor air conditions sampled. It is a subset of Chart 4 that shows every data sample of the load that was taken when the outside temperature averaged 40 degrees Fahrenheit. The chart below shows the effect of changing building conditions on the load at the same outside temperature. The data shows that the load at the same outside temperature can change ten fold with other conditions being primary factors. We now need to turn our attention to those other driving factors.

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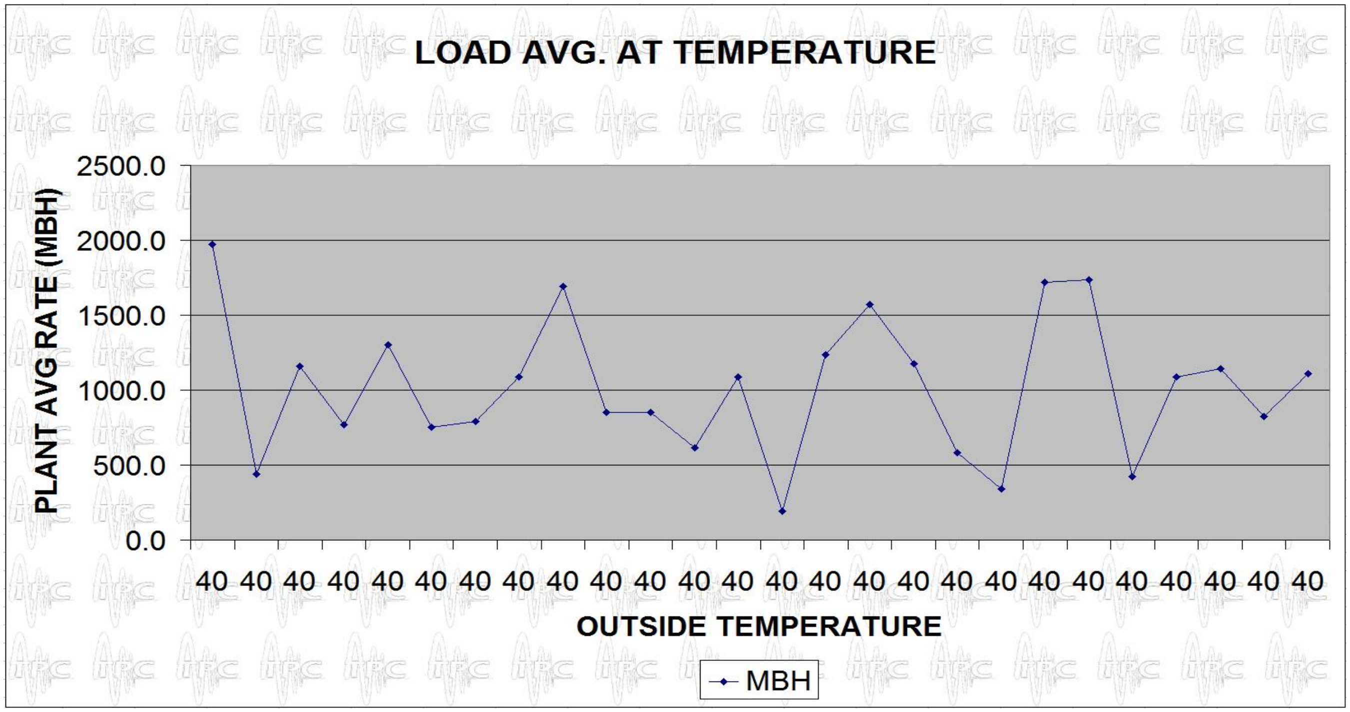
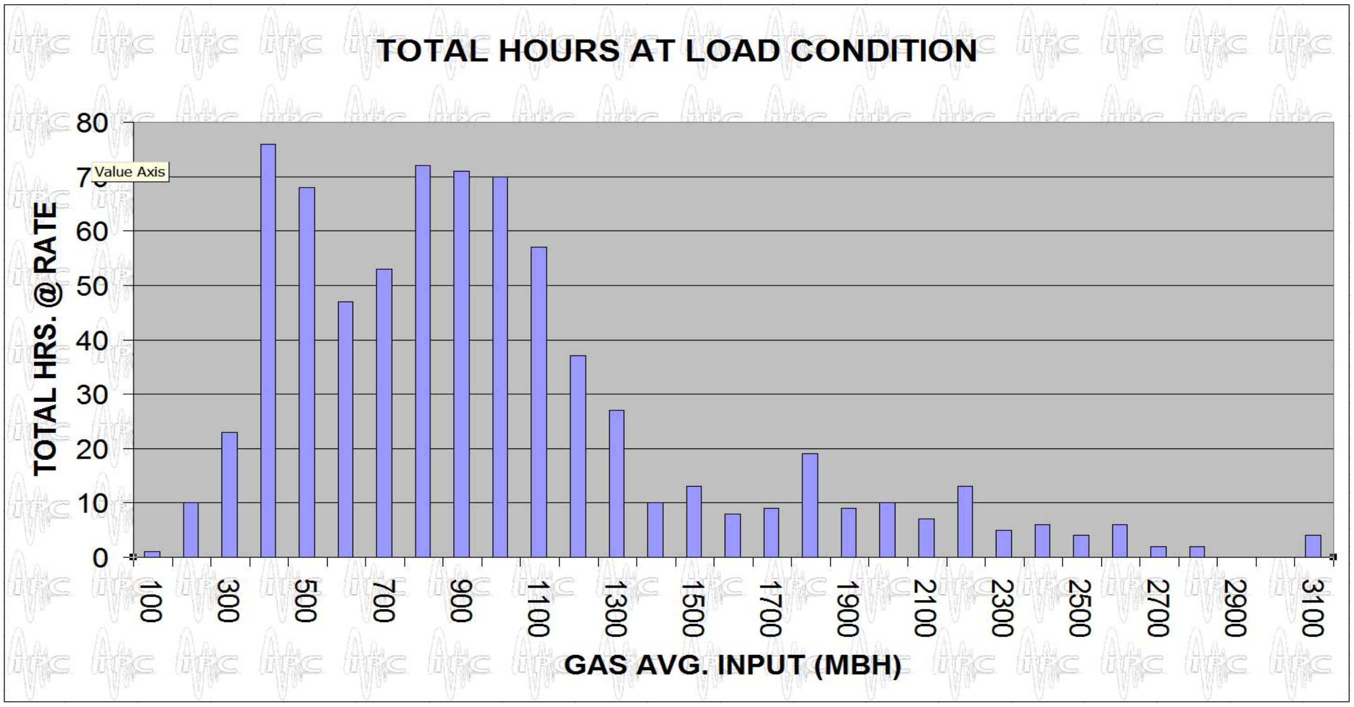


(Chart 5: Six (6) Month log of building loads at hourly avg. of 40F outside.)

Find The Hours Spent At Load Condition.

The question most designers want answered is: What is the maximum load? Another question that should be answered prior to publishing project documents is: How can we design a plant to be most efficient during all (or most) loading conditions? This question does not seem to occur to most designers. It is obvious from the data above that outside temperature analysis of a building's load will not tell the true story. Therefore we need to examine the load profile in new and better ways. First we propose that it is necessary to know what are the loading conditions and how often do they occur? This is particularly helpful in finding the low end of the building's load profile. Finding the low end of the profile allows the designer to size equipment with respect to light loads. Once light loads are known, boilers can be sized to reduce short-cycling. Short cycling is a common boiler room problem that reduces plant efficiency and increases wear on equipment. By understanding how small the loads can be for extended periods of time, it follows that short-cycling can be reduced by allowing for low end inputs from the boiler plant. When sizing a boiler plant for low end and top end efficiency, it is usually helpful if all the boilers are not the same size. This has to do with efficient turn-down of boiler plants. If one were to install two boilers in a plant retro-fit that required 6000 MBH, the designer will usually select two 3000 MBH boilers. A typical boiler turn-down ratio will be 5:1 yielding a minimum input of 600 MBH from a single 3000 MBH boiler. If however your hours at condition are such that you routinely operate your plant below the minimum input from a single boiler, your boiler plant can and will short-cycle.



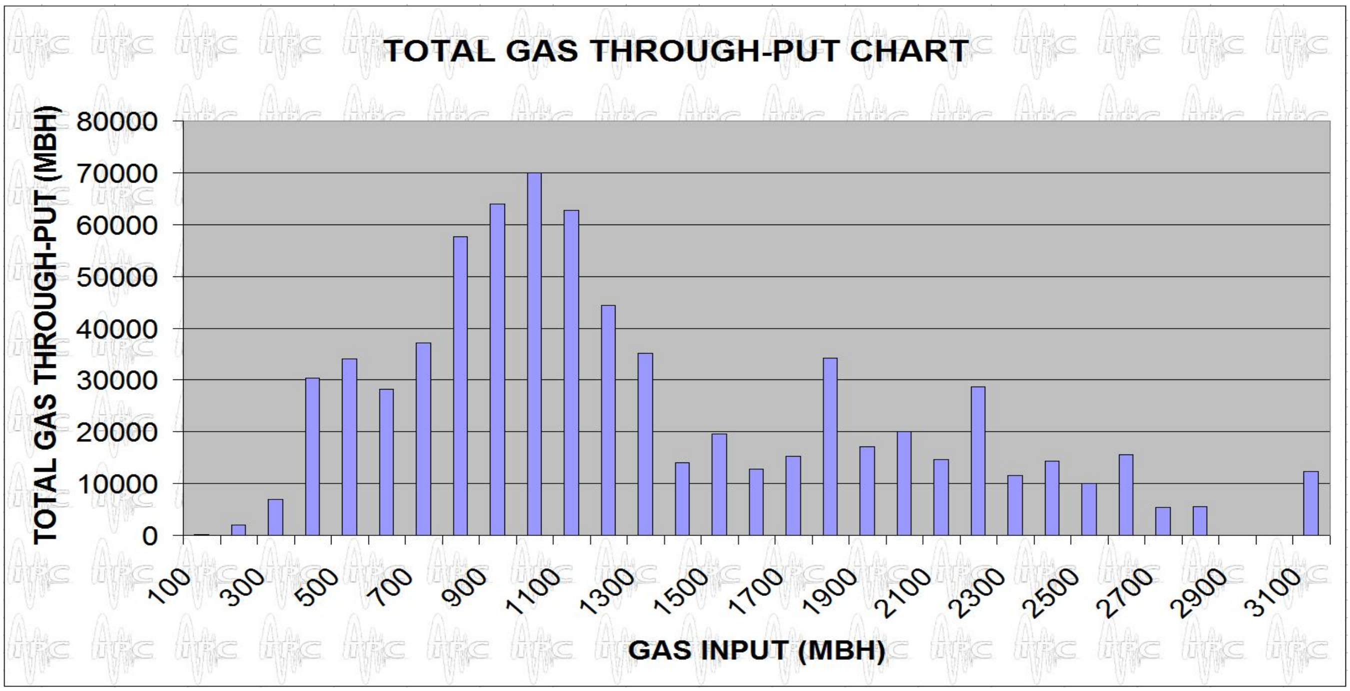
(Chart 6: Six (6) month log shows load conditions that occur most often)

A better solution will be to install a 1500 MBH boiler and a 4500 MBH boiler. With this plant you will get the same 6000 MBH, but your low end input will now drop to 300 MBH, accounting for many more hours of plant operation without short-cycling. It is important to note that this short-cycling cannot be eliminated by plant sizing alone. Short cycling is just as much a control issue as it is a plant sizing issue, therefore also having a TPC Real Time Load™ boiler control is the complete answer.

Develop A Gas Throughput Chart.

The next question that TPC proposes to answer is: How do we use this data to maximize the impact of a boiler's efficiency on the load? The next step we propose in the process is also entirely new for designing comfort heating and domestic hot water boiler retro-fit plants. We propose to find the loading conditions of the building that are concurrent with the maximum annual throughput of fuel. This is not to be confused with the maximum load on a building. Maximum loading conditions rarely occur. It is also not the weather conditions that occur most often, like outdoor air. What we need to know is: What are the plant loading conditions, (in terms of rate

MBH) that are occurring when most of the fuel is being burned? By finding the throughput of fuel at every given rate of plant output, we find the load conditions of a building that use the most fuel. Knowing this data allows a designer to size a boiler plant to be at optimum plant efficiency during these maximum throughput loading conditions. This kind of analysis is never completed today prior to commercial boiler retrofit projects. We all know however, that the bar is constantly being raised by someone and what is considered exceptional today will become standard due diligence tomorrow.

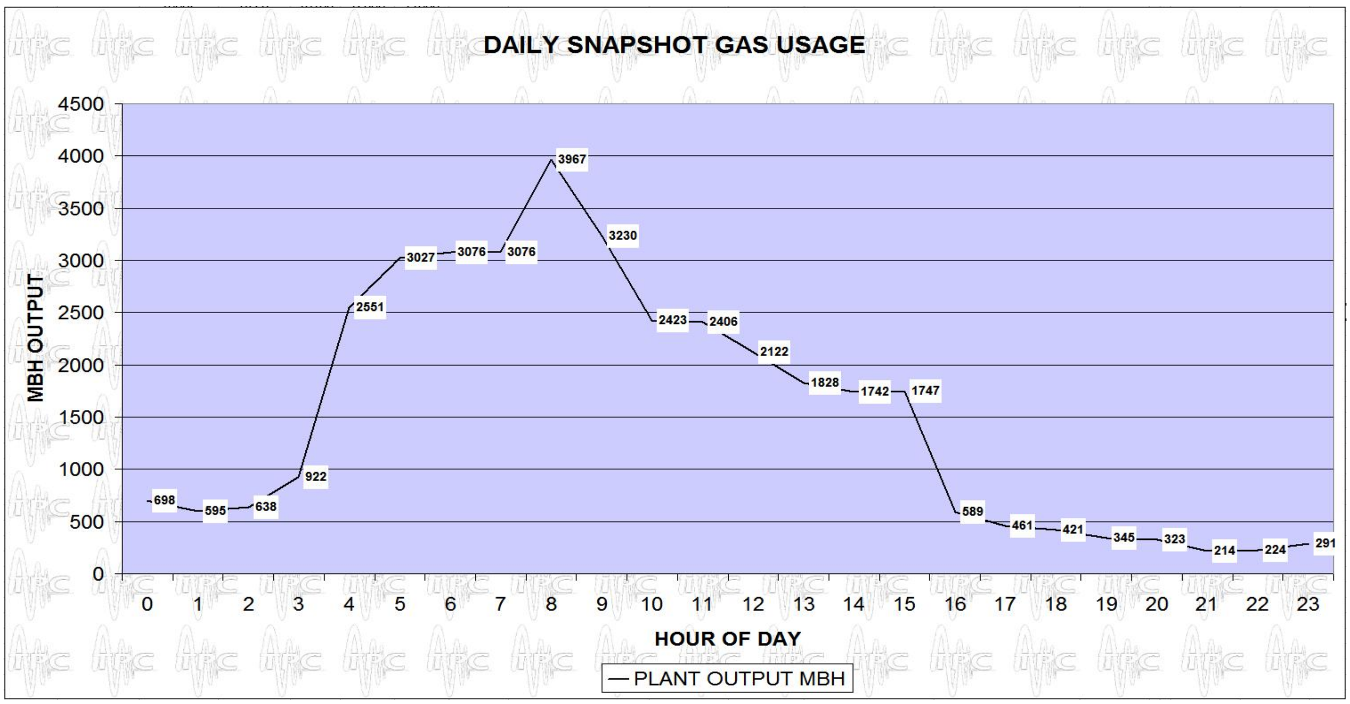


(Chart 7: Throughput load profile shows that there is a difference between conditions that occur most often and conditions that use the most fuel.)

The chart above depicts a new way to analyze fuel usage in your boiler plant. It answers the questions of how to size your plant for maximum desired efficiency at minimum first costs. The designer and the owner are now in total control of the outcome for this project. The data can be used to make a decision to size the plant to account for 100% of the fuel throughput. Collecting this data will most likely already result in first cost savings in equipment purchases for full plant replacements, as boiler sizing estimates are notoriously high. The data can be used to make decisions that take into account the law of diminishing returns. Let’s say that the owner or designer is trying to make a decision between buying two or three boilers. Upon examining the load data in this format they might find that two boilers will cover 95% on the fuel throughput. They could then decide to save tens of thousands of dollars by not buying the third boiler, thus decreasing the payback period of the entire project.

Find The Peak Loading Condition.

A building's load profile will range widely due to type of space, internal heat gains, occupancy schedule, end user heating equipment, percent of outside air and other weather related loading. These ever-changing conditions imposed on a building cause radical changes in loading. It is important to understand that static loading never happens. The load is a moving target. In order to size and design a plant effectively, one does need to know the largest loading condition. This information however, cannot be found on your heating bill.



(Chart 8: Graph shows worst case snapshot of loading conditions.)

Turn Your Mechanical Room Into An R&D Lab.

What is needed in boiler plant sizing, is boilers that are not too big, nor too small at the maximum usage and throughput conditions. One could say that boilers need to be sized in the “Goldie Locks Zone” for efficiency. Boilers should be sized so that they do not short-cycle in light load unoccupied times and efficient with consideration to the maximum through-put of the plant. Once your Project is complete, you will have before and after results. Your TPC system Administrator will continue to act as a data logger while it optimizes your process. Knowing the Input of natural gas and the boiler output energy using Real Time Load™ you will know your before and after boiler plant efficiency! This ongoing data is invaluable to determine if you are reaching your organizational goals for energy savings and carbon reduction.

For These and More Great Ideas Contact TPC:

TPC's data logger is designed with these first costs in mind. The design of the logger has no wasted parts. All of the equipment utilized in the data logger becomes the Administrator of the BEST boiler mechanical room plant controller available. New devices are added to the network as required to control the rest of the plant, but all original parts of the data logger are integrated into that design. Further, TPC is uniquely qualified to control these plants. TPC has a patented boiler control with Real Time Load™. Knowing the Real Time Load™, TPC controls make the correct decision as to what boiler or boiler(s) to operate and how to modulate them using Real Time Load™.

Upon hearing of TPC's control platform, one industry professional remarked:

> One of the most powerful capabilities of the TPC control platform is its ability to collect and store up to five years of hourly average performance data. This data-set includes outdoor temperature, the load in BTUs, system flow, supply and return temperatures (and therefore system temperature differences) and so on... It may perhaps be surprising, but it does not appear that anyone has ever gathered such data for buildings. We think that having such data may also be valuable in its own right. It may, for example, give you an objective and empirical basis for evaluating future boiler plant designs, and it may help you establish guidelines for future energy management practices. Most of what we know about heating loads is based on heating load *estimates*. Imagine having heating load *measurements* for buildings. We believe that this is game changing information.

We believe he is right!

TPC would encourage all who attempt a plant retro-fit to contact us. All boilers are not created equal. Significant differences exist between a boiler's rated efficiency and the actual efficiency your plant can achieve. Sophistication of control aside, some boilers are more difficult to get to the maximum than others. You need a partner that understands this data. Knowing how to use this data is the key. In the right hands, data logging answers the question of maximum benefit for minimum initial costs for boiler retro-fit projects.

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