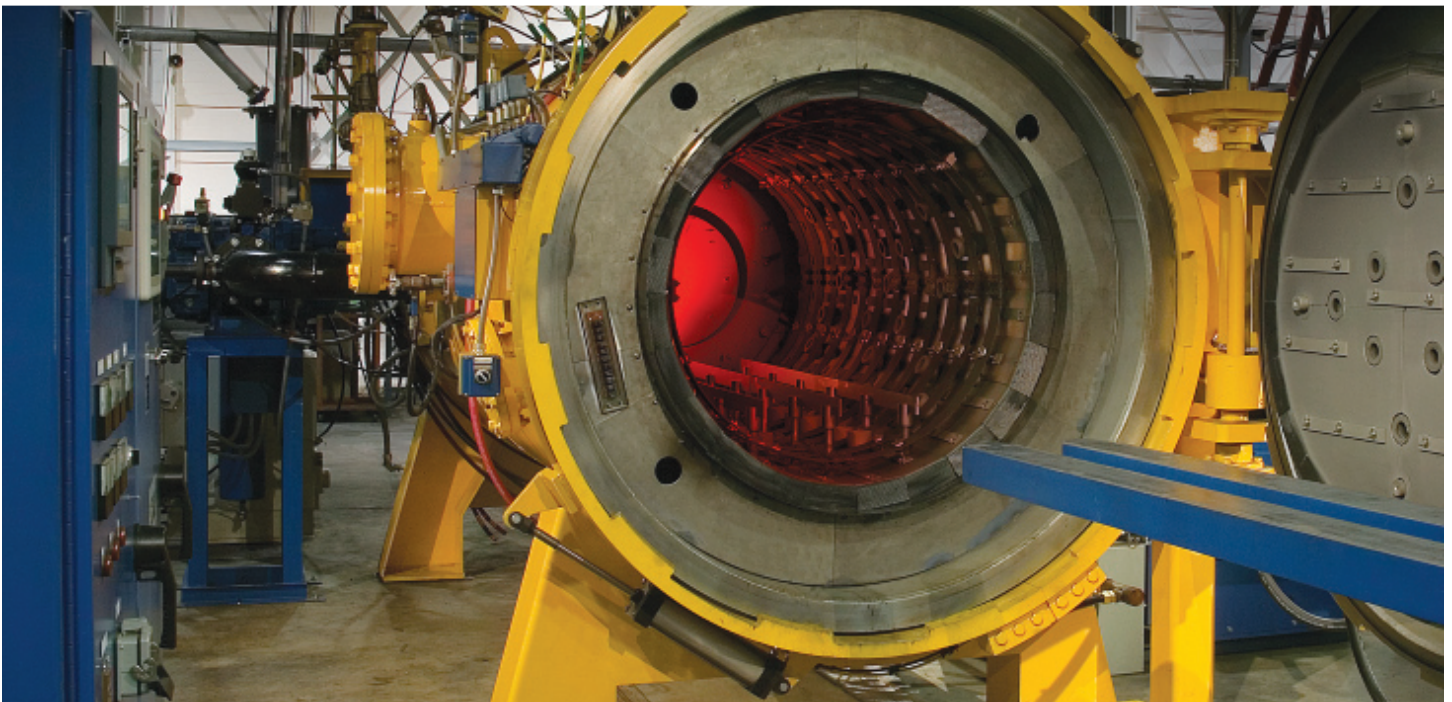# Understanding Power Losses in Vacuum Furnaces

SOLAR

Understanding Power Losses In Vacuum Furnaces

Since the early development of the vacuum furnace, engineers and thermal experts have continually tried to improve the insulating characteristics of the furnace hot zone. Several materials have been used for different applications with varying success. However, all designs must still deal with the heat losses penetrating through the insulation materials and the need to minimize these losses. This is especially important today with the continual escalation of electrical power cost.

This paper will review the different types of hot zone insulation materials used, the projected losses of the different designs, the impact relating to furnace cycle heating rates and cycle times, and the projected cost advantages of one design over another.

A) Hot Zone Designs

Most of the early designs of vacuum furnaces used an all-metal shielded approach for the hot zone. This consisted of a stack of thin metallic sheets spaced approximately .25" apart. Usually, the first two or three layers consisted of a high temperature material (molybdenum, tantalum, or tungsten – depending on the upper temperature requirement) backed by additional layers of stainless steel sheet. Over the years, furnace manufacturers began to realize that as vacuum furnaces became an important production tool, other types of hot zone designs must be developed. This led to the use of fiber type material such as ceramic fiber, graphite felt, graphite board, and graphite foil. All of these materials have been tried in various combinations with significant advantages and disadvantages of each different structure.

Considerations in selecting a particular type of hot zone include maximum temperature range of operation, types of cycles to be performed, expected holding times at elevated temperatures, peak power concerns and overall operating power costs. All of these factors relate to hot zone construction and its related power losses.

1) All-Metal Designs

Although the insulated type hot zone is now used in most vacuum furnaces, the all metal design is still used on specific applications where the use of Carbon components is unacceptable to the process. This is especially true in the aircraft engine manufacturing industry where an extremely clean processing system is required to negate the possibility of product contamination. However, all-metal design hot zones are the most inefficient when considering power losses and should only be considered when absolutely necessary.

2) Ceramic Fiber Included Designs

Early versions of insulated hot zones included the use of ceramic fiber board or blanket. Ceramic fiber definitely proved to be an excellent insulator in terms of minimizing power losses, but introduced the distinct disadvantage of moisture absorption when applied to the vacuum furnace. This resulted in greatly extended vacuum pump down times which caused dissatisfaction to the furnace end user. In addition, at elevated temperatures, ceramic fiber did demonstrate a shrinkage problem over short time use, which proved to be detrimental to most furnace applications. Although some users have tried to use ceramic fiber as a backing material to graphite felt and board where it would mainly see lower temperatures, moisture absorption continued to be a negative factor. Therefore, its use is basically restricted to soft vacuum and lower temperature types of furnaces.

### 3) Graphite Type Insulated Hot Zones

The most acceptable types of hot zones manufactured today use graphite in the form of sheets, felt, and board in varying combinations and thicknesses. These combinations offer the end user a wide selection of what would be best for a particular vacuum furnace application.

Some of the most widely used graphite combination hot zones incorporate laminated graphite sheet like graphite foil backed by layers of graphite felt in varying thicknesses. Others include a front facing of graphite board backed by layers of graphite felt. This combination is more widely used in furnaces incorporating high pressure type quenching where gas velocity and turbulence might cause problems to designs not capable of withstanding these violent dynamics.

B) Defining Hot Zone Losses For Different Hot Zone Configurations

Many studies and tests have established a baseline for losses using different combinations of all-metal and insulated designs. Figure 1 below defines these losses that can be expected from different designs as watts per square inch of the hot zone surface area. These graphical values can be extended to calculate projected power requirements for a given furnace size. Figure 1 compares the losses for an all-metal design using (2) molybdenum and (3) stainless steel shields, an insulated design using 2" of graphite felt with a graphite foil hot face, an insulated design using 1.5" graphite felt with a graphite foil hot face, and an insulated design using 4 inches of ceramic fiber faced with a molybdenum sheet. As is reflected in the graph, a significant difference in losses is revealed between each design.

- Please note that the 1.5" graphite felt design equates in losses to an insulated design consisting of 1" of graphite board backed by 1" of graphite felt.

Power Losses Vs. Hot Zone Type
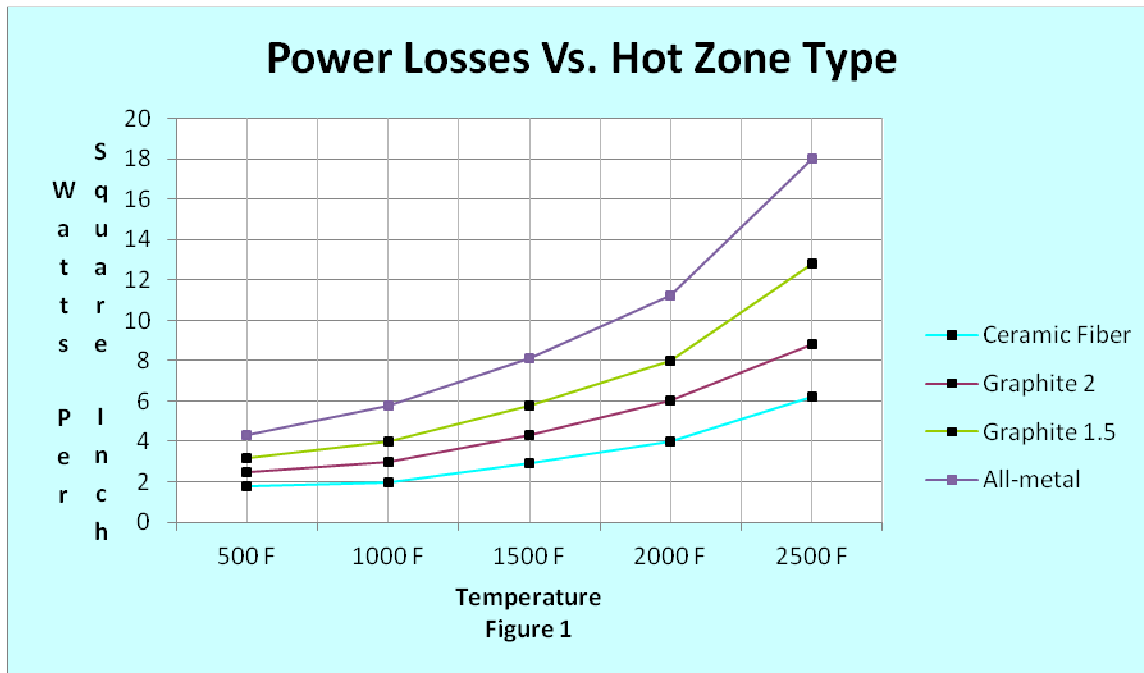
Figure 1

As illustrated in Figure 1, a significant difference exists for each design consideration. However, as stated previously, unless absolutely required, we prefer not to use the less efficient all-metal design or the moisture absorbing ceramic fiber configuration due to vacuum pumping concerns. Therefore, most of our following data will be concentrating on various graphite combinations.

1) Calculating Power Losses For A Given Size Furnace

One of the most popular size vacuum furnaces used in the heat treating industry is a horizontal loading furnace with a work zone measuring 36" wide x 36" high x 48" deep. The furnace is defined as a Solar Model HFL-5748 horizontal type and we will use this model going forward in our analysis. This furnace will be used as a basis for most of the following discussion. However, any size furnace could be used by simply calculating its appropriate hot zone surface area.

The internal hot zone surface area of this furnace amounts to approximately 17,350 in^2. Multiplying this figure by the projected losses at various temperatures shown in Figure 1, makes it possible to plot Figure 2. As stated above, we are primarily interested in the graphite designs but have included the all-metal design on this chart to demonstrate its true inefficiency.

Power Losses Vs. Hot Zone Materials
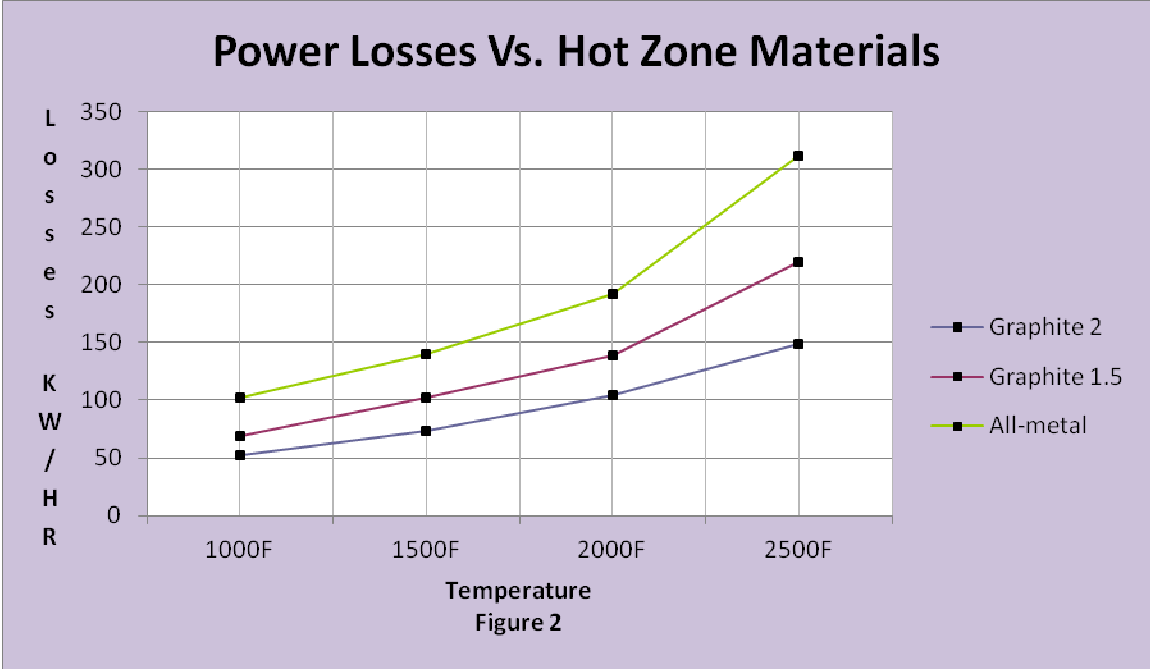
Figure 2

As is illustrated in Figure 2, there is a significant difference in losses per hour for the three designs at the various temperatures. These losses are continually increasing as the temperature rises and become especially important when holding the furnace at temperature for an extended time. Putting the values into a chart for better analysis, we have the following:

Losses - KW /HR			
Temperature	HZ – Graphite 2.0	HZ – Graphite 1.5	HZ – All-Metal*
1000F	52 KW	69 KW	102 KW
1500F	73 KW	102 KW	140 KW
2000F	104 KW	139 KW	192 KW
2500F	149 KW	220 KW	312 KW

Chart 1

* All-metal design will become even more inefficient as the reflective shields become oxidized and dirty over time and long term use.

Chart 1 demonstrates the significant difference of holding for one hour at a given temperature. At $2000^{o}F$, the Graphite 2.0 construction uses 35 less KW than the Graphite 1.5 and 88 less KW than the all-metal design. Converting this into dollars, this becomes very important and will be discussed in greater detail later in this paper.

2) Effect Of Hot Zone Losses On Heating Rates and Peak Power

When analyzing the power required to heat a given load to a specific temperature, basically three components are involved. These are the power (kWh) to heat the load, the power (kWh) to heat the furnace hot zone and the power (kWh) to overcome furnace losses. The heating power for the load and hot zone become fixed values while the power for the losses becomes a variable based on the overall cycle time. The profile of a typical heating power curve might look like Figure 3.
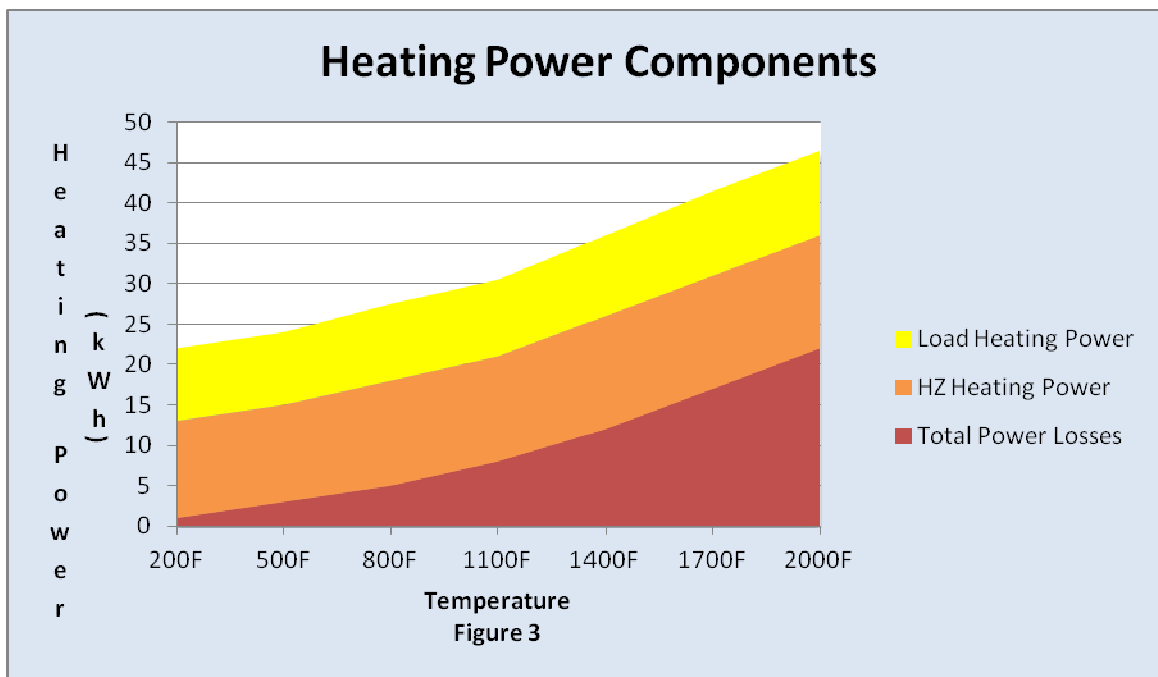

Figure 3 illustrates the various Heating Power Components and the significant impact of furnace losses with the increase of temperature. This becomes most important when overall heating rates and total cycle time are considered. Obviously, this reflects on the importance of a more efficient hot zone versus cost factors over time. This will be discussed later with the objective of selecting the most acceptable design.

The heating rate of a load will dictate the total energy required to heat that load at that heating rate. Heating as fast as possible is not often the best solution to the application.

Another area of heating concern has to do with Peak Power demands. Generally, all electrical power companies now charge a supplemental amount based on peak usage over a given time frame adding even greater cost to the furnace operation.

The faster a load is heated, the greater the peak demand to reach desired final temperature. Prior tests (Figures 4 & 5) were performed in our Model HFL-5748 furnace heating a 1000 pound load show total energy needed and peak power demand for different heating rates.
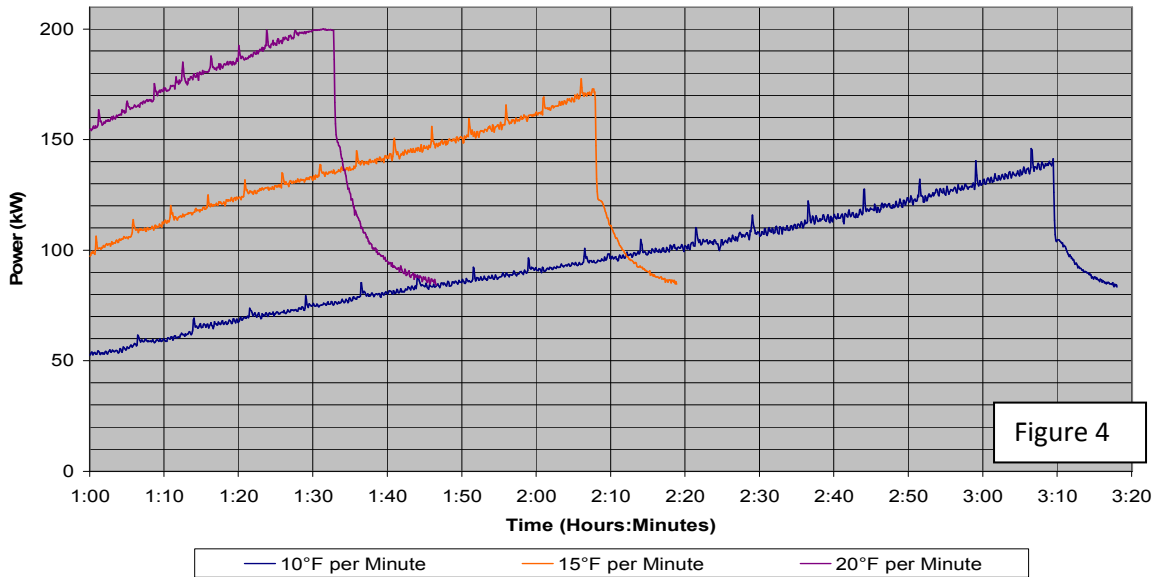
Furnace Hot Zone Demand Power
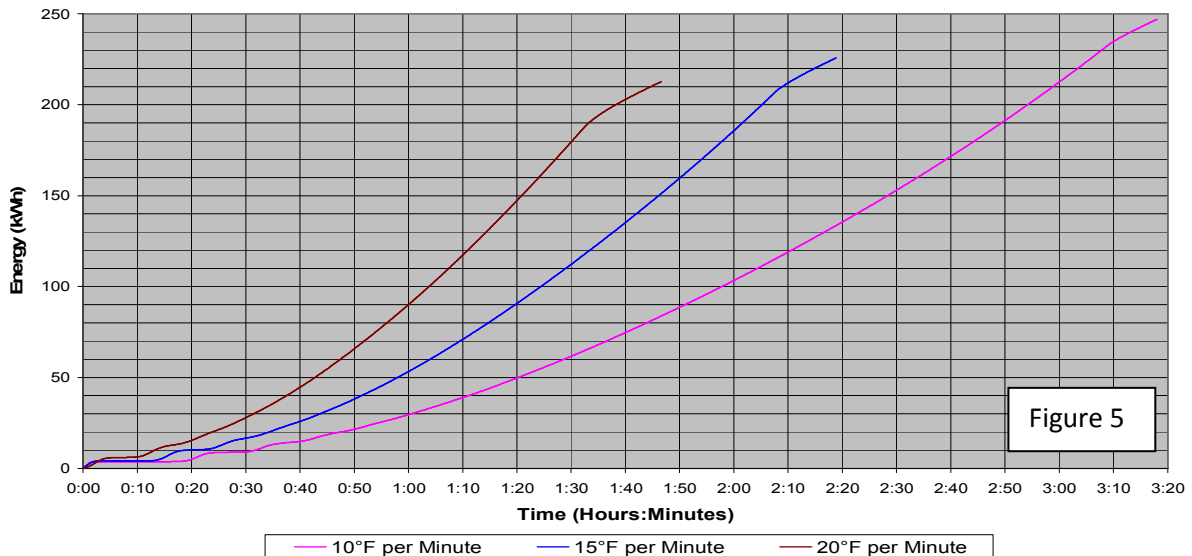

Figure 4

Furnace Hot Zone Energy Usage

Figure 5

The results from Figures 4 & 5 are summarized in Chart 2.

Heating Rate	Heating kWh	Average KW/HR	Peak Demand KW
10 Degrees/Min	247	77	140
15 Degrees/Min	225	105	174
20 Degrees/Min	212	132	200

Chart 2

By using the above chart to calculate the KW required to heat a 1000 pound load and the furnace hot zone to $2000^{o}F$, we reach the following conclusions regarding furnace losses:

a) Heating a load of steel materials to $2000^{o}F$ requires approximately 72 kWh of power.
b) Heating the hot zone and its various components and materials to their respective temperatures (these vary based on the component location) requires approximately 97 kWh of power.
c) Extending these calculations against the time required to achieve the final results, we can calculate the cycle losses for the given furnace as reflected in chart 3. Notice that the losses do increase in total value the slower the heating rate.

| Heating Rate	Total kWh Used	Load & Hot Zone kWh	Loss kWh
10 Degrees/Min	247	169	78
15 Degrees/Min	225	169	56
20 Degrees/Min	212	169	43

Chart 3

Reflecting on Charts 2 & 3, we can see the relationship of hot zone losses as they relate to peak demand and cycle heating time. The end user must determine whether a faster heating rate, allotting for added peak demand costs, is better than a longer cycle with lower peak costs but more overall total power consumed due to increased hot zone losses. All furnace users should base the final decision on their particular application. Also, most important to a furnace user is hold time at elevated temperatures which will greatly impact total losses. The best solution to many of these various situations hopefully will be answered by what follows regarding insulation thicknesses and designs.

C) Effect on Power Losses With Various Insulation Layers and Thicknesses

As we have demonstrated in Figure 1, the number of layers of graphite felt used on the hot zone greatly impacts the final losses expected from a given design. A graphite felt hot zone with (4) layers of ½" graphite felt is significantly better than a hot zone using (3) layers of ½" graphite felt or 1" of graphite board backed by (2) layers of ½" graphite felt. One would conclude from this comparison that adding additional layers of graphite felt should continually improve losses at a rapid pace. However, the percentage of improvement continually decreases as layers are added and the true cost for additional layers versus expected savings must be properly determined.

Based on many tests and actual power studies, we are able to plot Figure 6.
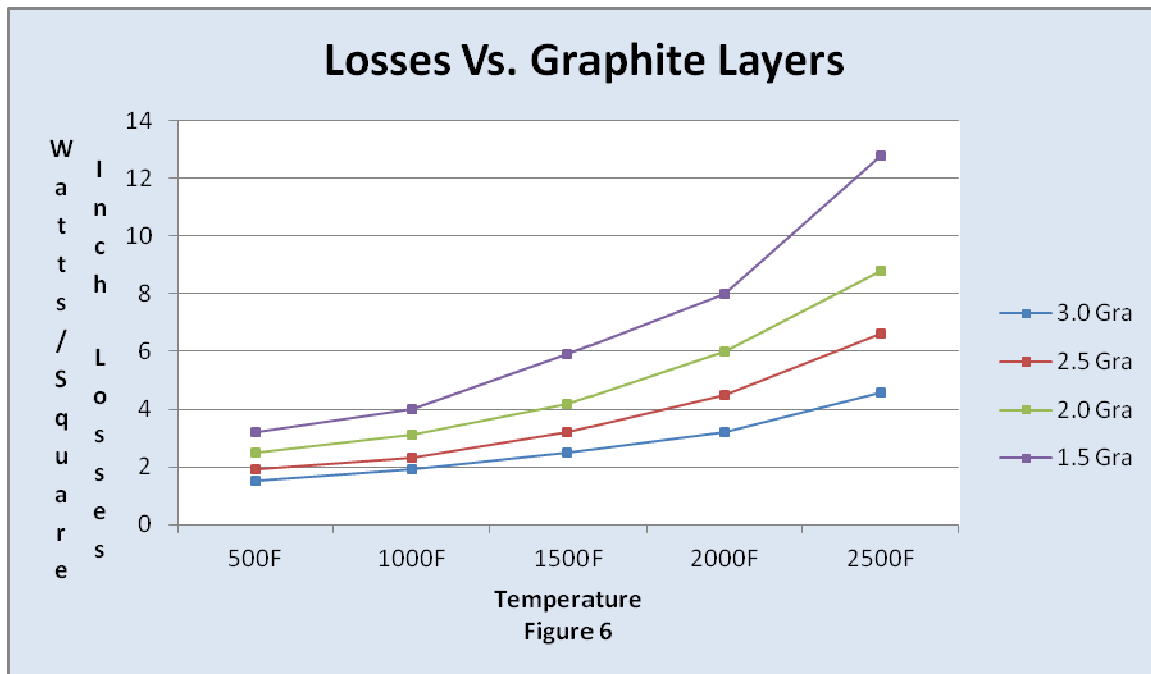
Figure 6

From Figure 6, we are able to plot the power loss ratio that can be expected of a 2" felt insulation design versus other felt thickness designs. This is shown in Figure 7. The ratio shown would be reflective of relative losses at $2000^{o}F$.

Power Loss Ratio

Felt Thickness
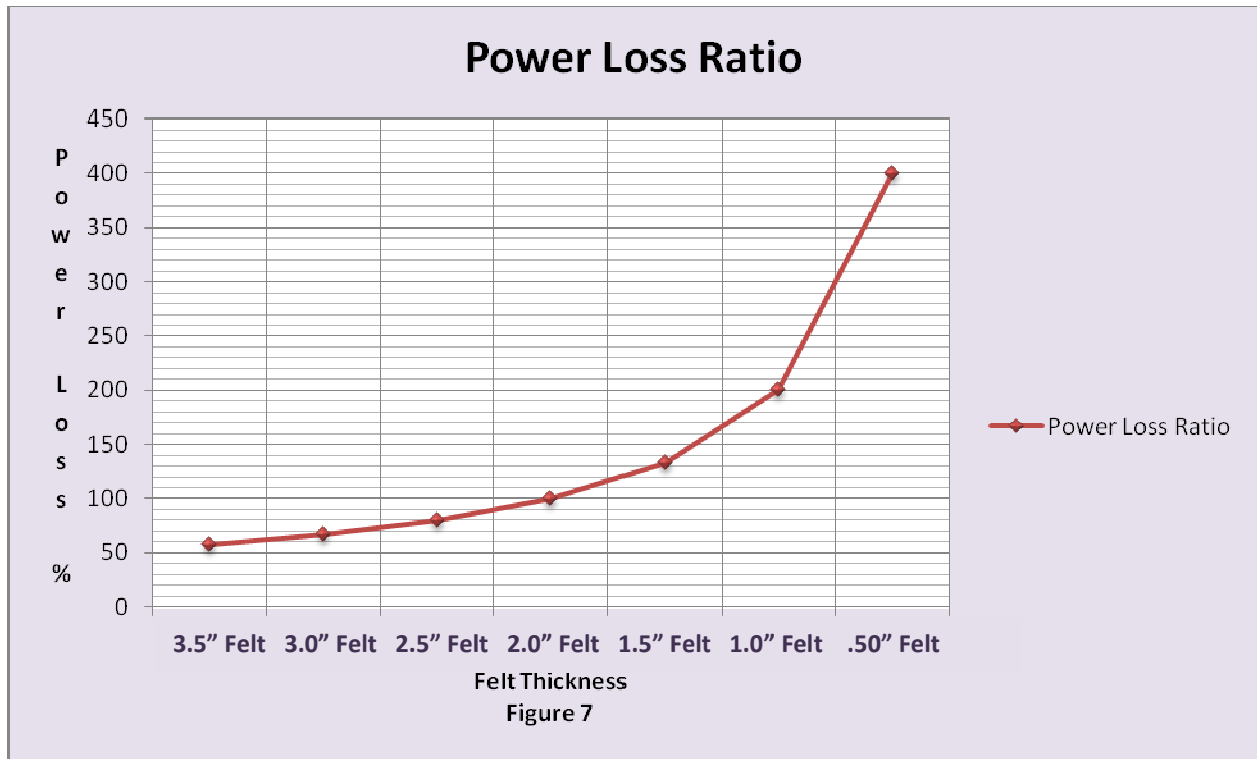
Figure 7

1) Projecting Relative Losses Versus Felt Thicknesses

Using factors from Figure 7 and preliminary data from Chart 1, we are now able to predict losses for each hot zone when holding each hour at a given temperature. These numbers will be used later to outline the importance of each hot zone design versus actual power cost and projected saving of one design versus the other.

Losses – KW/HR				
Temperature	3.0" Graphite	2.5" Graphite	2.0" Graphite	1.5" graphite
1000 F	36 KW/HR	44 KW/HR	53 KW/HR	69 KW/HR
1500 F	49 KW/HR	58 KW/HR	73 KW/HR	100 KW/HR
2000 F	68 KW/HR	83 KW/HR	104 KW/HR	139 KW/HR

Chart 4

The data from Chart 4 has been plotted in Figure 8 to better illustrate losses from different hot zone configurations.

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Losses Per Hour At Temperature
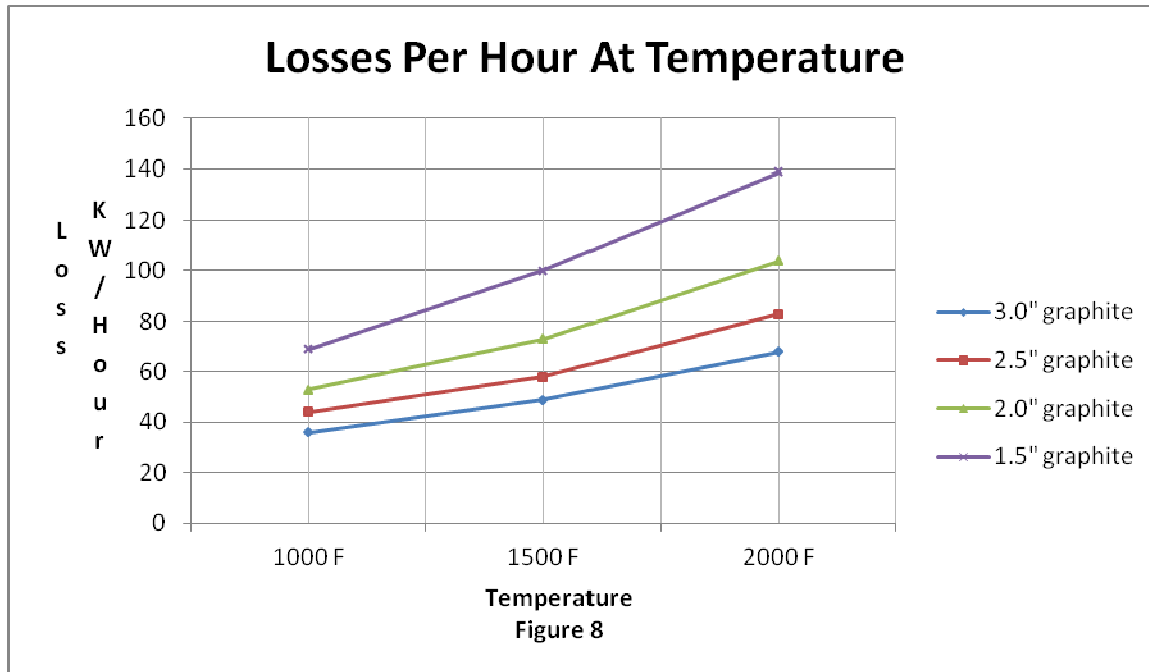
Figure 8

Using Figure 8 above and our information from Chart 3, we can now project the total power required to heat a 1000 Lb. load to 2000°F for different insulation packages.

D) Equating Insulation Designs To Actual Power Usage

As we have stated above, cost of electrical power varies for any given area of the country. We can cite three different locations with significant variations in their power pricing structure. These differences are shown in Chart 5.

Power Location	Peak Power Costs	Cost Per Hour Operation
Area One	$ 2.30 / KW	$ 0.08 / kWh
Area Two	$ 11.00 / KW	$ 0.10 / kWh
Area Three	$ 29.00 / KW	$ 0.11 / kWh

Chart 5

Since losses are most significant at maximum temperature for a given cycle, we will illustrate the added cost per holding hour for the various areas of operation and for the different hot zone structures. If we assume holding at 2000°F for one hour and using Charts 4 & 5, we have the following costs for each given design:

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Area	Rate/KWH	3.0" Graphite Total Costs/Hr	2.5" Graphite Total Costs /Hr	2.0" Graphite Total Costs/Hr	1.5" Graphite Total Costs/Hr
One	$ 0.08	$ 4.48	$ 6.24	$ 8.32	$ 11.12
Two	$ 0.10	$ 5.60	$ 7.80	$ 10.40	$ 13.90
Three	$ 0.11	$ 6.16	$ 8.58	$ 11.44	$ 15.29

Chart 6

As illustrated above, there exists a significant difference in operating costs based on the layers of graphite used which should become a factor when specifying the furnace hot zone for a given application. However, the cost for the increasing layer of insulation must be compared to the projected saving based on the cycles expected to be processed.

1) Projecting Cycle Costs For Different Areas Of Operation

All of the above curves and charts highlight that the cost of operating a vacuum furnace has two very specific concerns. The first is how the furnace is insulated to minimize losses and the second is how fast the product is heated. Both become very significant depending on your specific electrical cost structure.

Based on our charts, we are now able to create the following table for heating the 1000 lb. load in our test furnace.

Heating Rate	Heating Energy (kWh)	Pumping System Energy (kWh)*	Total Energy (kWh)	Peak Power Demand (kW)	High 15 Min kW Average
10°F/Min	247	33	280	140	135
15°F/Min	225	23	248	174	168
20°F/Min	212	18	230	200	194

Chart 7

*This value represents how much energy was consumed by the pumping system operating in a Solar Manufacturing conservation mode. It would be higher without this feature.

Using the above chart, we can now calculate cost for geographical areas, based on several different electrical service billing rate structures as shown in chart 5. Using the electrical data obtained from the three heating rate tests, we can calculate and compare the total cost per cycle for the different billing rate structures. Please note that our calculations are based on processing 50 production cycles per month and a minimal hold time after achieving final temperature.

Heating Rates For Different Cost Areas	Total Energy Cost	Peak Demand Cost	Total Cycle Cost
Cost for $.08/kWh & $2.30/kW			
10°F/Min	$22.40	$6.21	$28.61
15°F/Min	$19.84	$7.73	$27.57
20°F/Min	$18.40	$8.92	$27.32
Cost for $.10/kWh & $11.00/kW			
10°F/Min	$28.00	$29.70	$57.70
15°F/Min	$24.80	$36.96	$61.76
20°F/Min	$23.00	$42.68	$65.68
Cost for $.11/kWh & $29.00/kW			
10°F/Min	$30.80	$78.30	$109.10
15°F/Min	$27.28	$97.44	$124.72
20°F/Min	$25.30	$112.52	$137.82

Chart 8

As can be seen by the above comparisons, the first example reflects very little variations in cycle cost. This would mean that the user should process his work as fast as the load can be processed to optimize throughput. The second example begins to reflect the impact of peak demand cost to total cycle cost (between 50% and 65%) and the overall cycle cost based on the different heating rates. The third example illustrates how critical peak demand impacts total cycle cost and must be seriously considered when trying to establish the best heating rate for optimizing furnace production.

Using the 15°F/Min heating rate as an average, we can now look at the impact of peak demand pricing on total cycle cost.

Peak Demand Rate	Peak Demand Cost	Total Cycle Cost	% of Total Cycle Cost
$2.30/kW	$7.73	$27.57	28%
$11.00/kW	$36.96	$61.76	60%
$29.00/kW	$97.44	$124.72	78%

Chart 9

2) Impact of Hot Zone Type on Total Cycle Cost

If we select a nominal heating rate of 15 degrees per minute, we can project the relative cost of operating a furnace for different insulation types. Based on the above data and assuming a one hour hold at temperature, we can create Chart 10.

Hot Zone Type	Cycle Heating Energy (kWh)	Pumping System Energy (kWh)	Holding Energy for one hour (kWh)	Total Cycle Energy (kWh)
1.5 " Graphite	244	23	139	406
2.0" Graphite	225	23	104	352
2.5" Graphite	214	23	83	320
3.0" Graphite	207	23	68	298

Chart 10

Using our data from Chart 10 and the given rates for the different areas, we are able to compare total cycle cost for the different hot zones excluding peak demand.

Cost Area	1.5" Graphite	2.0" Graphite	2.5" Graphite	3.0" Graphite
Area 1	$ 32.48	$ 28.16	$ 25.60	$ 23.84
Area 2	$ 40.60	$ 35.20	$ 32.00	$ 29.80
Area 3	$ 44.66	$ 38.72	$ 35.20	$ 32.78

Chart 11

If we now assume roughly 50 cycles per month and extend that to one year usage, we can demonstrate the various year cost for the different hot zones excluding the added cost of peak demand.

Cost Area	1.5"Graphite	2.0"Graphite	2.5"Graphite	3.0"Graphite
Area 1	$ 19,488	$ 16,896	$ 15,360	$ 14,304
Area 2	$ 24,360	$ 21,120	$ 19,200	$ 17,880
Area 3	$ 26,796	$ 23,232	$ 21,120	$ 19,668

Chart 12

Although Chart 12 does not include added peak demand cost, it does illustrate the yearly cost difference that can be expected on the various graphite layer thicknesses. Also please remember that this is based on our test furnace size and will certainly change for other sizes. However, it does illustrate a significant difference in the different designs and the impact of hot zone losses.

E) Summary And Conclusions

1) How a Vacuum Furnace is insulated has a major effect on furnace losses and resulting operating costs.
2) When focusing on optimizing production in vacuum furnace operations while trying to minimize electrical power costs, it is essential to review and understand your current electrical power billing structure.
3) Peak power demand costs represent a substantial part of electrical billing.
4) Hot zone losses can be projected and reduced by considering more efficient designs. Initial capital investment may be quickly recovered based on the resulting electrical cost savings.
5) Peak power demand costs are mainly dictated by furnace heating rates but more efficient hot zones will also impact final peak demand costs.
6) Overall peak demand costs will normally help to establish the best heating rates for different size work-loads.
7) Graphite felt insulation with 4-5 layers of ½" blankets appears to be the most economical and best performing hot zone based on losses and overall power costs. Additional layers might be considered for furnace applications requiring long hold times at elevated temperatures.
8) Hot zone designs and internal supports and hardware need to be designed with consideration to low mass and specific heat wherever possible to avoid hot zone energy absorption.
9) Maintaining a furnace hot zone in good operating condition will continue to minimize hot zone losses during processing.

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