01 Jan 2005

Efficiency in Steel Melting: Opportunities and Progress

Kent D. Peaslee
Missouri University of Science and Technology

Semen Naumovich Lekakh
Missouri University of Science and Technology, lekakhs@mst.edu

Von Richards
Missouri University of Science and Technology, vonlr@mst.edu

Jay Triplett

Recommended Citation

Efficiency in Steel Melting: Opportunities and Progress

Kent D. Peaslee[1], Simon Lekakh[1], Von Richards[1] and Jay Triplett[2]

[1]Department of Materials Science and Engineering
University of Missouri-Rolla, Rolla, MO 65401

[2]Monett Metals, Inc., Monett, MO 65708

Abstract

This paper summarizes the findings from a study of melting efficiency in steel foundries and provides examples of material and energy savings from improvements in technology and melting practices. This study is based on information gathered at 19 Steel Founders Society of America member foundries and includes a combination of historical data and industrial measurements by the research team. Information and data were collected on the type of melting equipment, melting practices, energy use and ladle practices. The data was statistically analyzed using STATGRAPHICS commercial software. A multiple regression analysis allowed evaluation of the influence of the melting furnace (type, size, age, and transformer power) and operating parameters such as tap temperature, tap to tap time, and furnace productivity on the energy consumption for melting steel.

Also included in this paper are results from one industrial partner's site, Monett Metals, where a concerted effort was made to improve the melting operations with a goal of decreasing energy consumption and melting costs. Melting practices and equipment changes are reviewed and the results are evaluated by comparing heat balances and statistical analysis of the chemistry and energy data before and after the changes.

Present State of the US Foundry Industry - Statistical Analysis

Melting furnace statistics. The types and age of melting furnaces used in steel foundries are summarized in Table 1 and Figure 1. The average foundry furnace is 28 years old. Electric arc furnaces (EAF) are generally significantly older installations than induction furnaces (IF). EAFs used in steel foundries average 45 years in age with the oldest installation built in 1938 and the newest installation in 1977. Older EAFs are typically less energy efficient than newer furnaces, especially in the area of electricity distribution and control. Coreless induction furnaces used in steel foundries are typically newer installations averaging just over 10 years in age with several furnaces installed within the last five years. Many IF-based foundries have installed new furnaces with the newest generation of power supplies which are more energy efficient than previous generations of equipment.

Table 1: Type and age of melting furnaces

Furnaces	Number	Average	Standard deviation	Minimum	Maximum
All	58	1977	18.3	1938	2003
EAF	24	1960	12.5	1938	1977
IF	34	1992	5.4	1976	2003

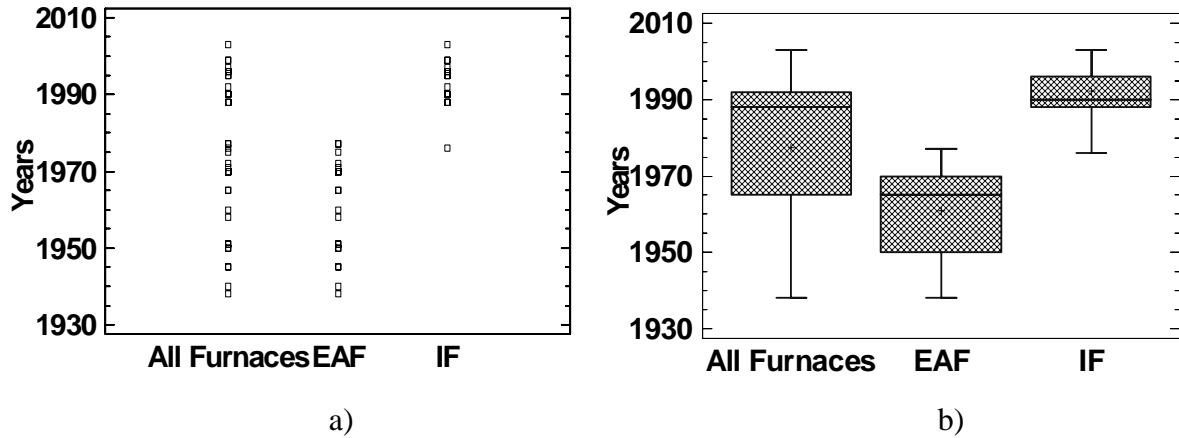a)   b)

Figure 1. Ages of melting furnaces: a) scatterplot and b) box-and whisker plot

Figure 2 compares the current production volume of castings versus the full production capacity of each of the furnaces evaluated. Based on this plot, steel foundries are operating at an average of 63% of full capacity. However, induction furnaces are operating significantly nearer to full capacity (72%) on the average than electric arc furnaces (57%). In both cases, this indicates large percentages of downtime (scheduled and unscheduled). In contrast, wrought steel producers typically exceed the furnace design capacity driving energy efficiency to high levels. Foundries operating below production capacity reduce energy efficiency based on frequent start-ups, shutdowns and increased heat transfer losses during delayed operations. Induction furnace data is closer to a linear fit than the electric arc furnace data with values of R-Squared of 0.959 versus 0.727 for EAFs. This shows that there is a greater variation in the production percentage of capacity in EAF operations than in induction furnace operations.
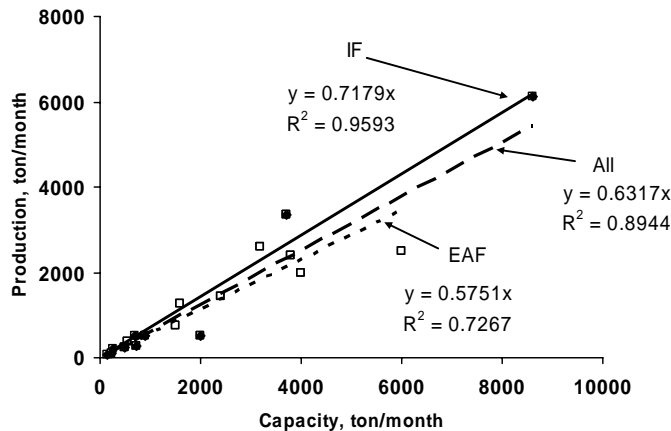

Figure 2. Plot of steel castings production versus full melting capacity of steel foundries

Table 2 summarizes the capacities of the different types of melting furnaces in steel foundries. EAF capacity averages over ten times the capacity of the average IF. The average EAF has a 13 ton capacity with the largest furnace in the survey at 55 tons capacity. The average IF capacity is 2440 lbs with the smallest IF reported at 400 lbs capacity. The scatterplot and the box-and whisker plot for furnace capacities are given in Figure 3.

Figure 3c compares the types of refractory linings used in the various furnaces. IFs use alumina-based refractories exclusively. EAFs are split with nearly 2/3 using basic refractory linings (magnesia) and 1/3 using acid refractory linings (silica). The steel foundry industry has made some progress in moving towards basic refractory from a previous survey completed five years ago when just over 50% of the EAFs in use were basic lined. All of the wrought industry's EAFs are lined with basic refractory to take advantage of the steel quality, productivity, and energy benefits associated with basic practices.

Table 2. Capacities of melting furnaces (lb)

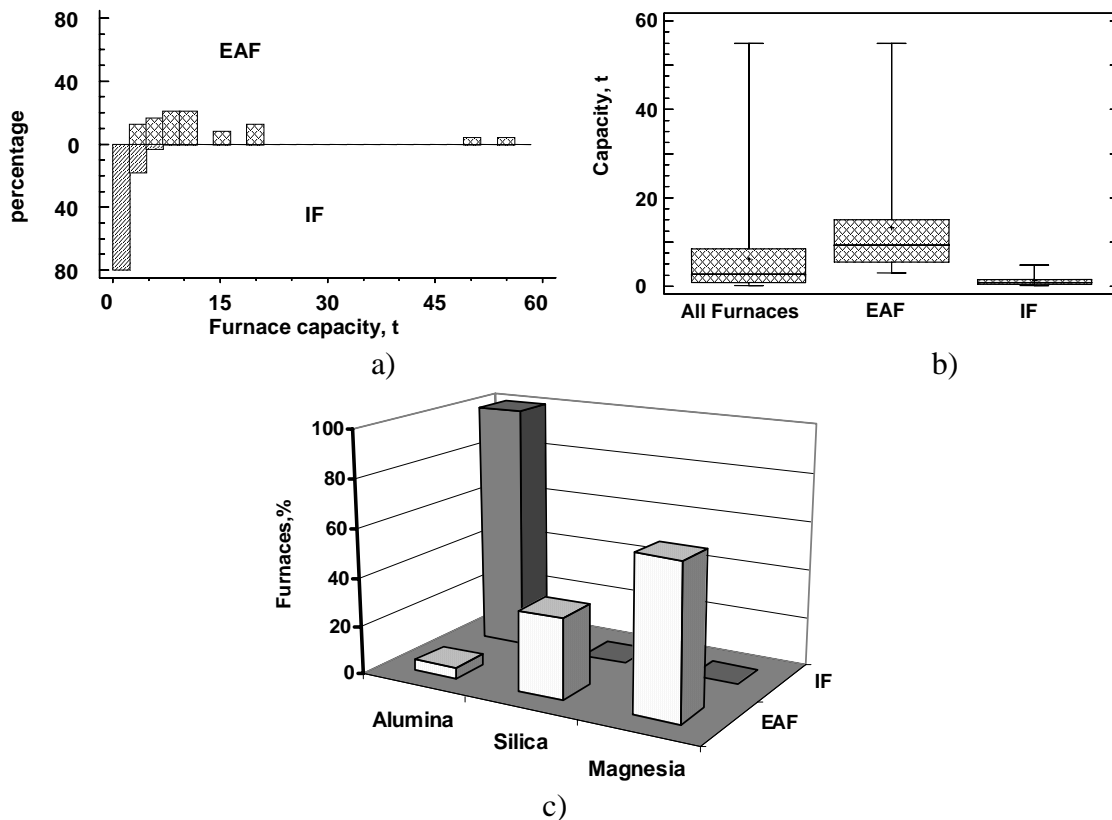| Furnaces	Number	Average	Standard deviation	Minimum	Maximum
All	58	12368	20570	400	110 000
EAF	24	26433	26259	6000	110 000
IF	34	2440	2190	400	9 500

a)

b)

c)

Figure 3. Statistics of melting furnaces: a) capacity distribution,
b) box-and-whisker plot of capacity and c) lining type

Figure 4 is a plot illustrating the furnace capacity by installation year. There is a general trend in steel foundries towards smaller capacity furnaces. The largest capacity furnaces (EAFs) were installed over 30 years ago. Recent furnace installations have been smaller capacity IFs. Although a trend line (linear regression line) and 95% confidence limits (dashed line) are shown on the figure, there is considerable scatter in the data (correlation coefficient K= -0.39).
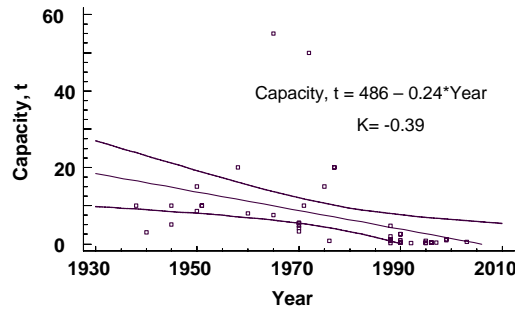

Figure 4. Trends in furnace capacity of new installations since 1930

Statistical data for the furnace power supply (transformer KVA capacity) per ton of furnace capacity is shown in Figure 5a. The KVA/ton is generally higher for induction furnaces than electric arc furnaces. There has been a general trend towards increasing the furnace transformer capacity per ton with time (Figure 5b).
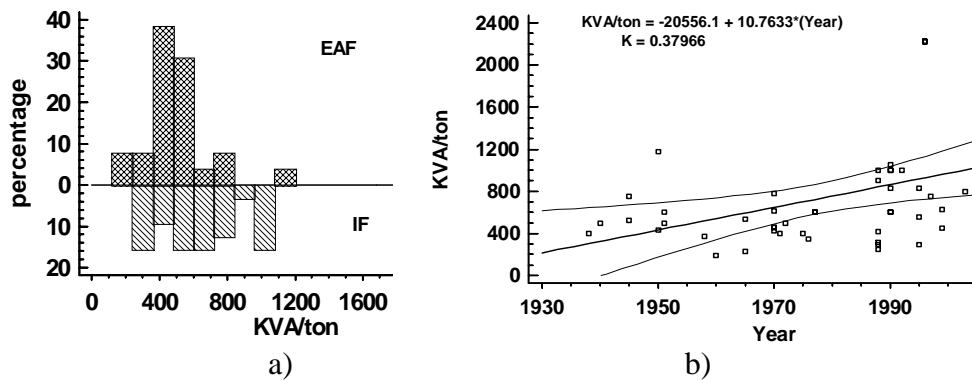

Figure 5. Statistics of specific transformer capacities (KVA/ton) for EAF and IF

Energy consumption for melting steel. Statistics of energy consumption in steel foundries is given in Table 3. Reported energy consumption varies between 350 KWH/ton to 700 KWH/ton with an average of 527 KWH/ton. Figure 6 illustrates the large variations in energy consumption between the various steel foundries.

Table 3. Statistics of energy consumption (KWH/ton) for steel melting

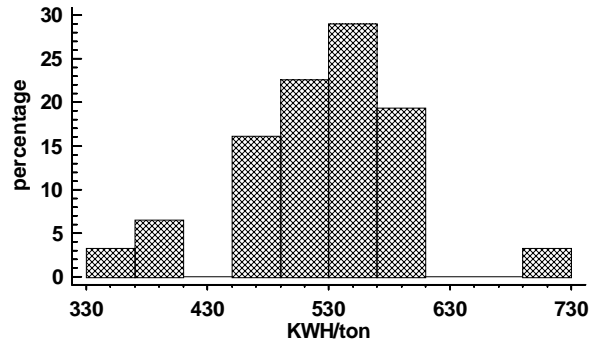| Average	Standard deviation	Minimum	Maximum
527	65	350	700

Figure 6. Histogram of energy consumption for melting steel

Multiple regression analysis was done for the purpose of determining how operating practice variables and equipment type (independent variables) influence the energy consumption for melting steel (dependent variable). Figure 7 is a graphical analysis of the component effect which shows the relative magnitude of the influence of individual independent variables (furnace type - induction furnace or electric arc furnace, tap temperature, tap-to-tap time, year of installation, specific transformer power and furnace capacity) on the value of the dependent variable (energy consumption).

The P-values, which statistically characterize the relationship between the variables, are given in the ANOVA Table 4. In determining whether the model can be simplified, high P-values on independent variables indicate a lack of statistical significance. Therefore, the high values of "furnace capacity" and "specific transformer power" indicate that these variables cannot be shown to be statistically related to the energy and can be removed from the model. Using the four remaining independent variables, the following equation for KWH/t was calculated using multivariable linear regression:

$$KWH/t = 1364 - 169*(EAF=1; IF=0) - 1.3*Year + 0.91*Tap\ to\ tap\ time,\ min + 0.57*T_{tap}, °F$$

The R^2 for this equation was 0.54, indicating fairly good correlation of the data with this equation.

The multiple regression analysis showed that the following independent variables had an influence on the energy consumption for melting steel (from strong to weak influence):
- increasing "tap temperature" increased energy consumption (strong influence)
- increasing "tap to tap time" increased energy consumption (strong influence)
- "EAF" has lower energy consumption than "IF" (strong influence)
- newer equipment ("Year of installation") decreased energy consumption (strong influence)
- increasing "specific transformer power (KVA/ton)" decreased energy consumption (weak influence)
- increasing "furnace capacity" decreased energy consumption (weak influence).

Higher tap temperatures increase the driving force (thermal gradient) resulting in higher energy. Longer tap-to-tap times increase the time of maximum heat transfer resulting in

higher energy use. EAFs consume less electrical energy because they use a combination of electrical and chemical energy for melting.
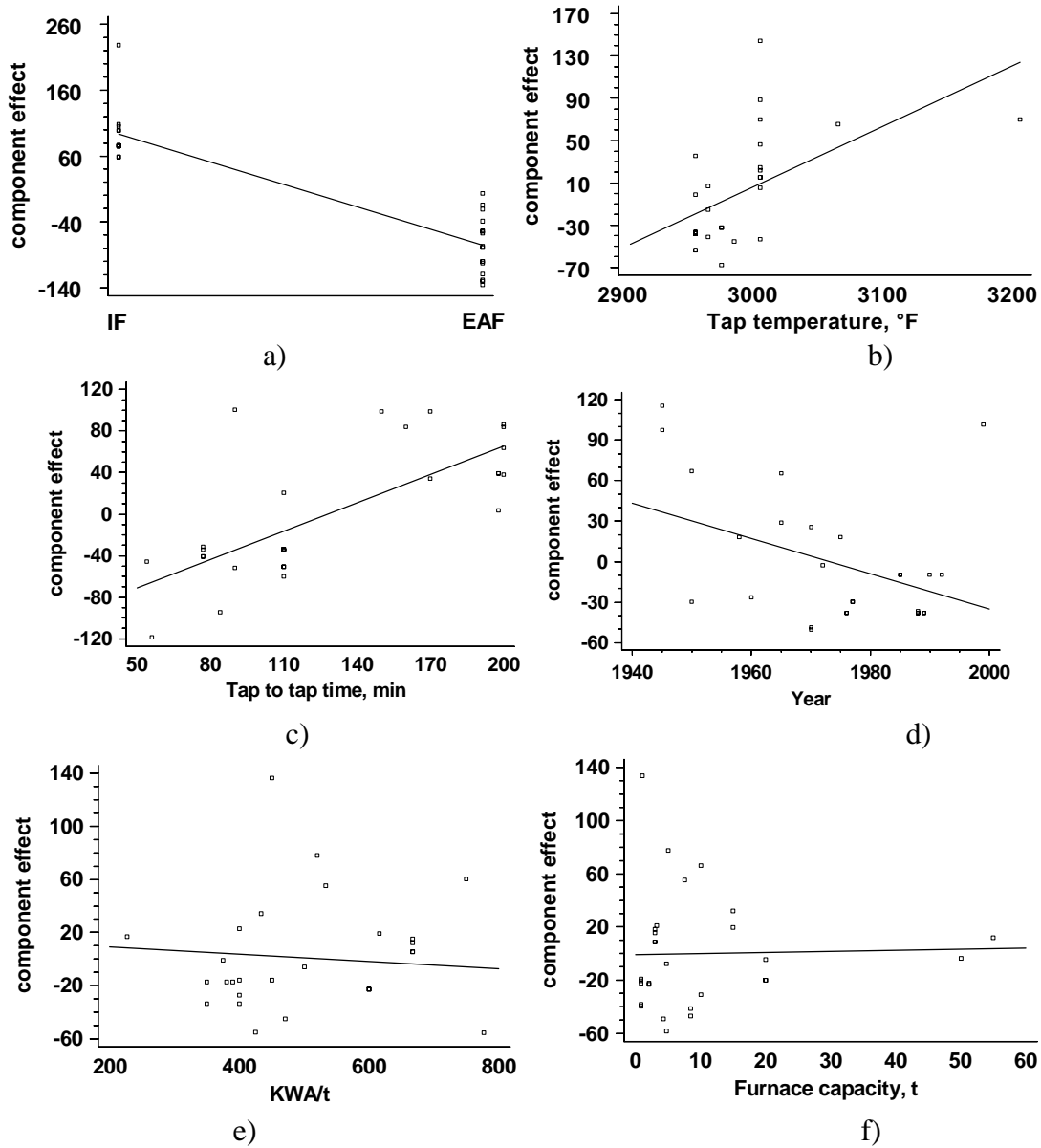

Figure 7. Component effect of a) "IF versus EAF", b) "Tapping temperature",
c) Tap to tap time", d) "Year of installation", e) "Transformer power",
and f) "Furnace capacity" on energy consumption for melting steel

Table 4. ANOVA analysis of multiple model for energy consumption for melting steel

	Independent Variables					
	Tap temperature	IF versus EAF	Tap to tap Time	Year of installation	Furnace Capacity	Transformer KVA/ton
P-Value	0.035	0.004	0.013	0.178	0.93	0.58

Analysis of melting parameters. This analysis was performed to evaluate the factors that influence tap to tap time and melting time which were both shown to have a significant influence on energy consumption. Single-variable linear analysis of the effects of "furnace capacity", "year of installation", and "specific transformer power" on the "tap to tap time" of melting furnaces is shown in Figure 8. This shows that larger capacity furnaces tend to have longer tap to tap times. New furnaces have an advantage in generally reducing tap to tap time. The value of specific transformer capacity was shown to have little influence on "tap to tap time". The results of ANOVA analysis of "tap to tap time" also indicated that the effects of increasing the power supply could not be proven statistically to have an effect on the "tap to tap time" in foundry practices. This means that scheduling plays a more important role in determining foundry melting tap-to-tap practice than the transformer size.
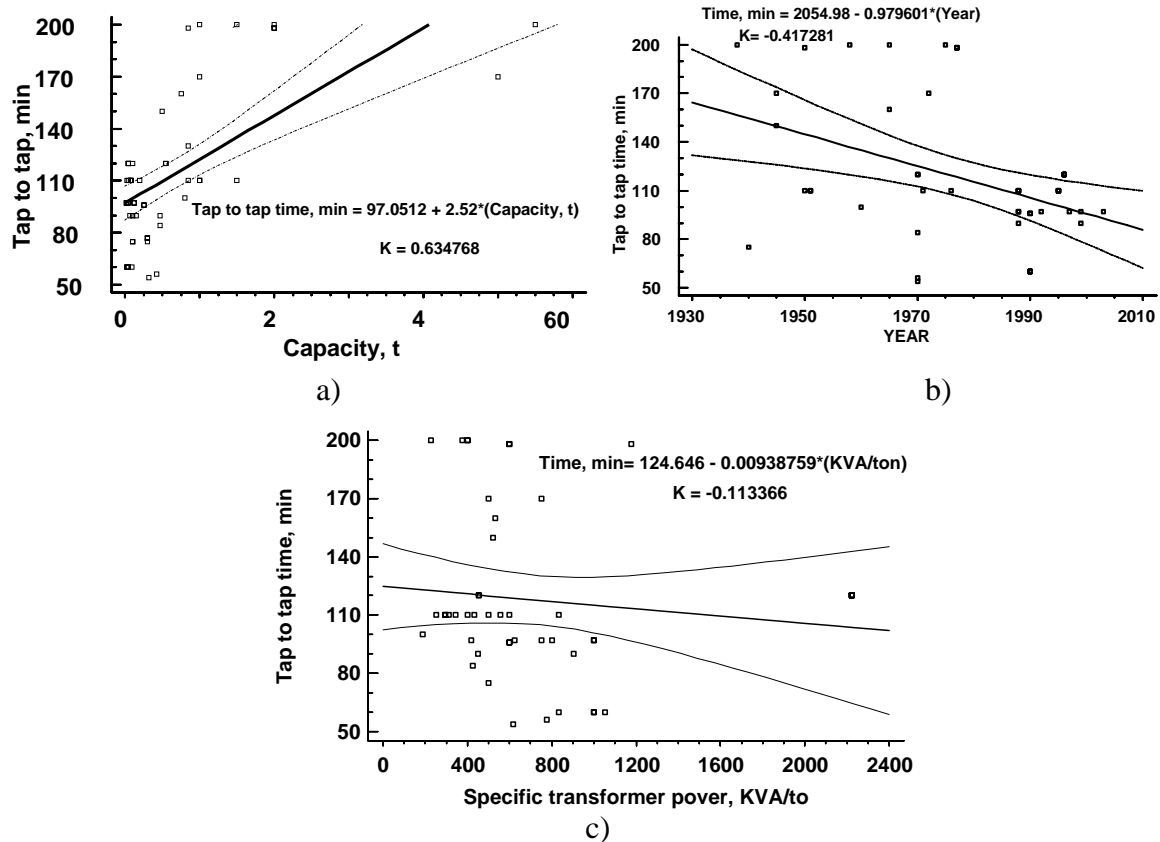
Figure 8. One-variable analysis of the influence of a) Furnace capacity, b) Year of installation, and c) Specific transformer power on tap to tap time of melting furnaces

The tap temperature has a significant influence on energy consumption for melting steel. One-variable analysis, two sample comparison, and multi regression analysis were performed for statistical evaluation of the tapping temperature. Histograms of the tapping and the pouring temperatures, as well as a box-and-whisker plot, are given in Figure 9.
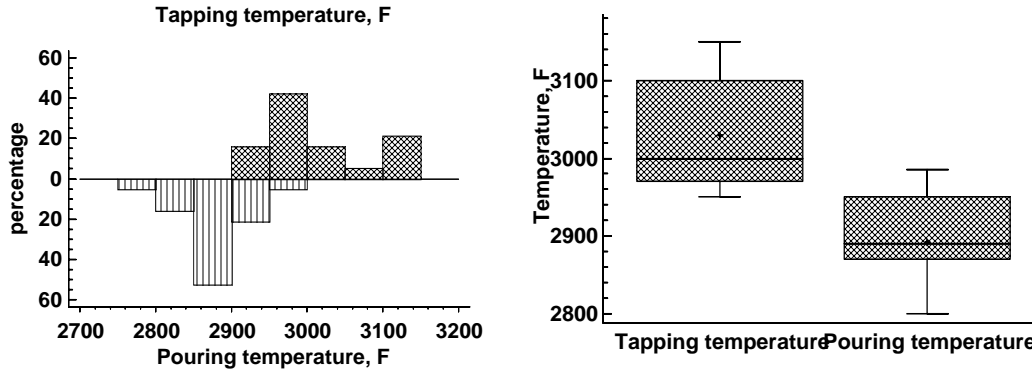
Figure 9. Comparison of tapping and pouring temperatures

The influence of "pouring temperature" and "heat weight" on the "tapping temperature" were analyzed using multi-regression analysis (Figure 10). As expected, the tap temperature is directly proportional to pouring temperature. Larger heats typically require lower tap temperatures which could be attributed to the lower surface area to volume ratios of the furnaces and ladles. The equation of the fitted model is:

(Tapping temperature, °F) = 464 + 0.89*(Pouring temperature, °F) – 1.94*(Heat weight, t)
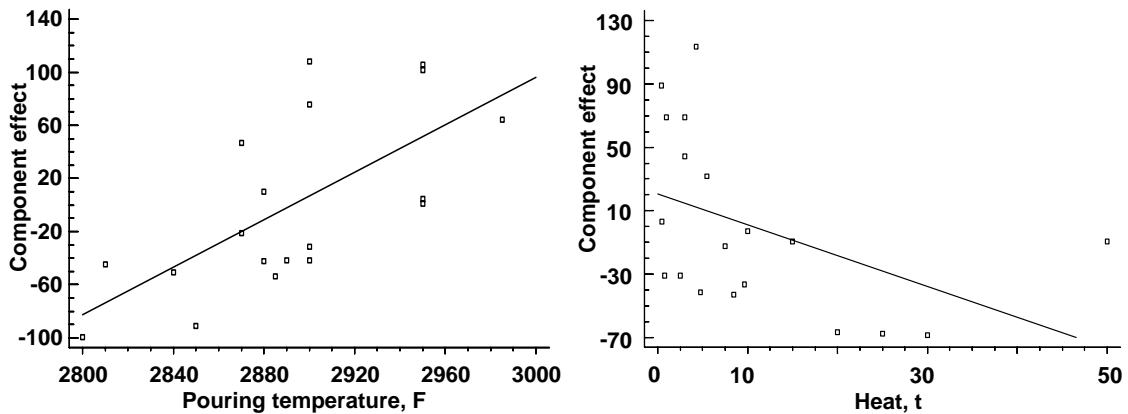R-squared = 54.6%

Figure 10. Multiple regression analysis of the effects of a) pouring temperature and b) heat size on tap temperature

Miscellaneous. In addition to the statistical data collected at foundries, foundry operators were asked to report on what they considered to be the major factors with the greatest influence on energy losses during melting at their facilities. The three major factors most frequently cited in the survey (see Figure 11a) were "refractory" (75% of surveys), "scheduling" (70% of surveys), and "casting yield" (25% of surveys). Figure 11b indicates the wide variation in casting yield.
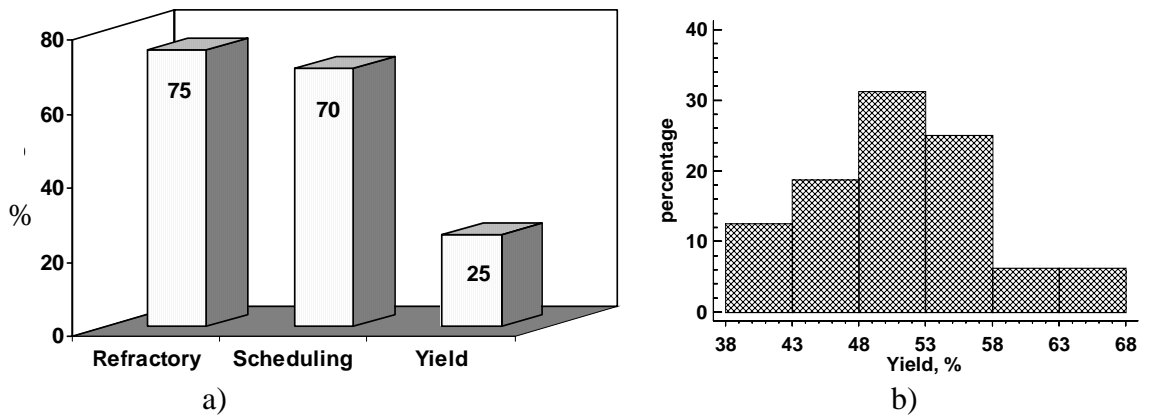
Figure 11. a) Major sources of energy losses according to survey results and b)
casting yield statistics

Successful energy management in steel foundries is difficult without monitoring energy consumption. Unfortunately, this is an area that the steel foundry industry is poorly equipped. Only 38% of the electric arc furnaces and 15% of the induction furnaces in operation are equipped with electric meters for monitoring electric consumption (Figure 12). Over one-third of the plants surveyed have no way of monitoring their energy consumption during steel melting.
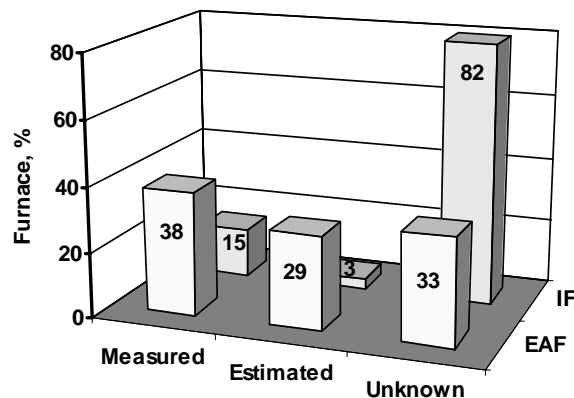
Figure 12. Energy consumption monitoring for melting steel in foundries

According to the survey (summarized in Table 5), most U.S. steel foundries have introduced melting improvements including new equipment (furnaces, power supply, PLC), processes and materials (low density and thermal conductivity linings, alloy wire, argon stirring) and new off-gas cleaners.

Table 5. The major improvements implemented in 19 steel foundries during last 15 years

Number (%)	Major improvements, number								Bag-house
	Melting furnaces				Ladles				
	New furnaces	Power Supply	PLC	Water Cooling	Lining	Preheat	Alloy Wire	Ar stirring	
17 (90)	9	5	4	3	7	2	2	1	2

Trials to Improve Energy Efficiency During Steel Melting

The first section of this paper summarized the types of furnaces and practices used in the steel foundry industry and the resulting wide variation in energy consumption. Measurements done by UMR researchers in previous industrial trials[1,2] showed that even in individual foundries, energy consumption varied by as much as 50% within the same melting furnace. This presents opportunities for individual foundries to save energy through improved production controls and process management techniques that provide for more consistent melting. In addition, there are melting technological improvements that do not require significant capital investments but are capable of saving significant energy and materials. Studies of heat balances during melting, evaluation of operation melting efficiency and thermal measurements are necessary to make improvements in melting efficiency because they allow numerical evaluations of the energy losses in existing practices. One practical example is illustrated in this section where an energy study in 2004 by UMR led to technological improvements together with new management directives that resulted in significant energy and material savings.

Monett Metals, Inc. melts low, medium carbon and stainless steel in medium frequency induction 500 KW furnaces of 2000 lb capacity. During UMR's 2004 study, energy consumption averaged 500 and 666 KWh/ton for melting on hot and cold linings, respectively. The main heat losses during steel melting were attributed to heat accumulation by the cold lining as well as radiation and conduction of heat during the 30-45 minute final chemistry correction period (see Figure 13a and 14a). Operational energy efficiency was found to reach a maximum of 70 to 80% while melting solid charge materials but decreased dramatically to nearly zero (just enough energy to maintain temperature) during the final chemistry correction period. The energy efficiency was between 30 and 50% during heating of the molten bath to the tap temperature under an open surface (Figure 15). Statistical analysis indicated a wide variation in the total energy consumption with the lowest observed values of the total energy consumption per ton being near to the best practices observed in other foundries equipped with induction furnaces. However, the wide variation in energy efficiency between heats resulted in an average electrical energy consumption that was higher than the average of other induction foundries utilizing best practices. In addition to the electrical energy consumed, an additional 300,000 – 400,000 BTU of natural gas was used during the 1.5-2.5 hours of ladle preheat for each heat. Total temperature losses measured during tapping and pouring ranged from 110°F to 150°F.

In 2005, Monett Metals made a number of management and operating changes in an attempt to increase productivity, reduce energy consumption, save operating costs, and increase quality and safety. Recommendations for energy savings from UMR's 2004 industrial trials were implemented at the same time as other plant wide operating improvements. These improvements were made without an increased capital investment. Some of the changes included:
- optimize scheduling to minimize the number of heats melted at less than full furnace capacity (reducing scrap and decreasing energy)
- improve production schedule to decrease the number of cold heats on a lining

- gas preheat the induction lining prior to the first heat (minimize thermal shock to the refractories and reduce energy requirements of first heat)
- change alloying practice to minimize alloys added to charge and only add alloys immediately after deslagging the furnace
- rewrite melting practices and train employees to consistently melt the same way (improve consistency in hitting chemistries, decrease final chemistry correction period and reduced tap-to-tap time)
- decrease radiation losses by using covers during melting and pouring
- instituted an effective preventive maintenance program
- trained employees to adhere to a 5 S program on the melt floor for production efficiency
- revamped the quality system to retrain employees and make sure they understand their personal responsibilities, institute better accountability and frequent audits
- instituted safety/housekeeping bonus systems

Energy improvements: After implementation of these improvements, Monett Metals was revisited in 2005 and a series of industrial trials performed to evaluate the effects of these changes. Example comparisons of energy consumption in trial heats observed before and after the improvements are shown in Table 6. Electrical energy was reduced by an average of 15% during the first heat on a furnace due to the improved preheat practices that were employed. Electrical energy was reduced by 5-10% on heats melted in hot linings. A comparison of the energy requirements is illustrated in Figure 13 (first heat on a lining) and Figure 14 (heats melted in a hot lining). Figure 15 illustrates the improvements observed in energy efficiency due to the changes made in 2005 during the different melting periods of heats on hot and cold linings. The effects of optimizing the scheduling in 2005 decreased tap to tap times and the percentage of first heats to 11.6% (Table 7).

Table 6 Observed heats in 2004 and 2005 years

Year	Steel	Lining	Charge	Corrections, #	Melting Time, min	KWH/t
2004	WCB	Cold	Solid	1	207	653
2004	WCB	Hot	Solid + 200 heel	1	120	545
2005	WCB	Hot	Solid	1	114	519
2005	WCB	Hot	Solid + 200 heel	1	104	517
2005	CF8M	Preheated	Solid	2	130	562
2005	CF8M	Hot	Solid +350heel	2	106	534

Table 7. Statistics of heats in 2005 years

Parameter	First heat (cold lining)	Hot lining
Heats, %	11.6	88.4
Average heat time, min	159	108
Standard deviation of heat time, min	72	18
Minimal heat time, min	95	65
Maximal heat time, min	360	167
Average heats per day	1	7.48
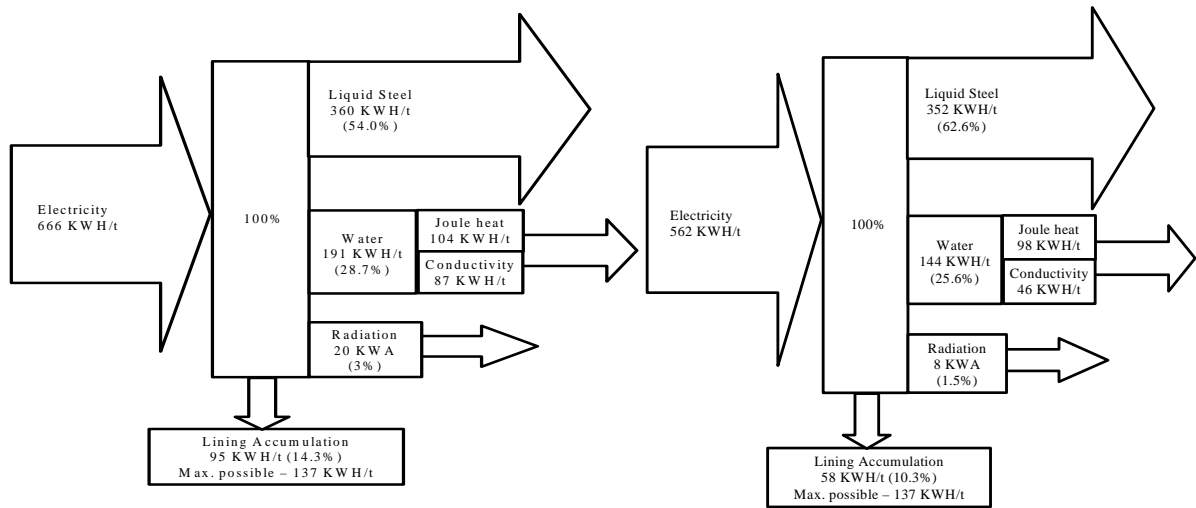
a) 2004 "cold" practice   b) 2005 "gas preheated" practice

Figure 13. Comparison of modified Sankey-diagram (energy flow) for first daily heats
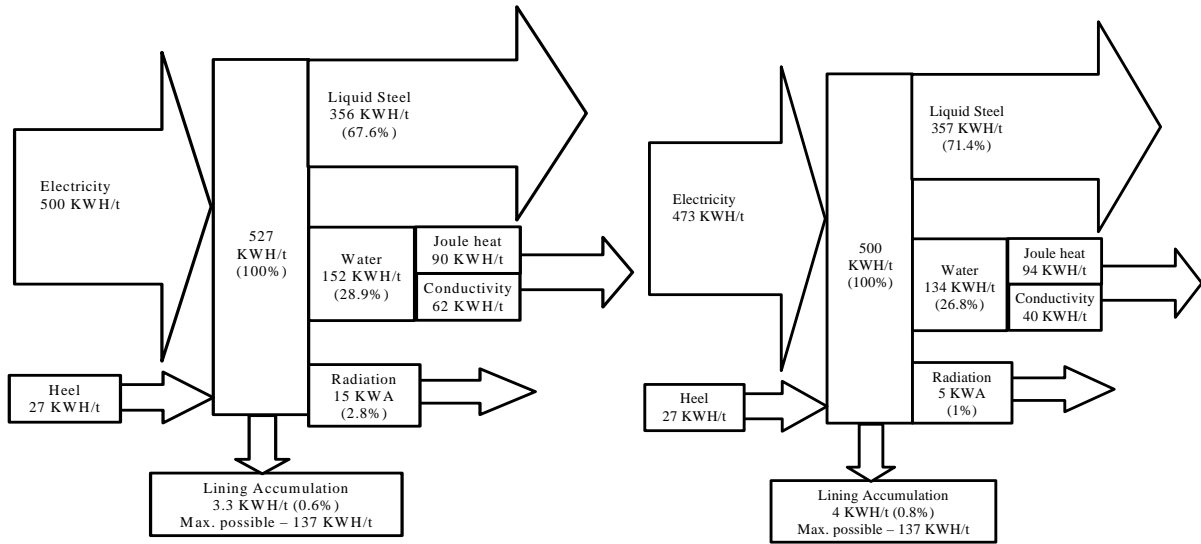
a) 2004 practice   b) 2005 practice

Figure 14. Comparison of modified Sankey-diagram (energy flow) of heats in
hot lining with 200 lb heel

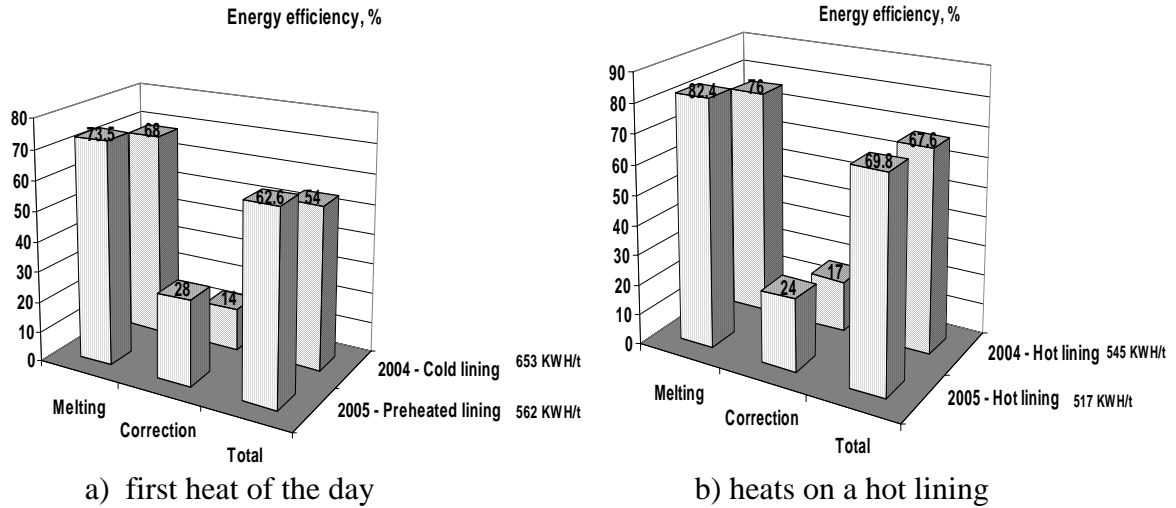a) first heat of the day   b) heats on a hot lining

Figure 15. Comparison of operational melting energy efficiency for 2004 and 2005

Figure 16 illustrates the new practice of gas preheating the IF lining before the first heat. Increasing the average temperature of the lining to 1550°F before melting significantly decreased the lining accumulation heat losses (nearly 100 kWh/ton reduction). In addition, this practice helps minimize the thermal shock to the refractories improving refractory wear. This improvement coupled with reducing the percentage of heats melted on a cold lining and other melting improvements have resulted in a 20% reduction in refractory usage in 2005 compared to 2004. The decrease in labor required for refractory provides more time to the operators to do other preventive maintenance.

Label	Average, °F
A1	1554

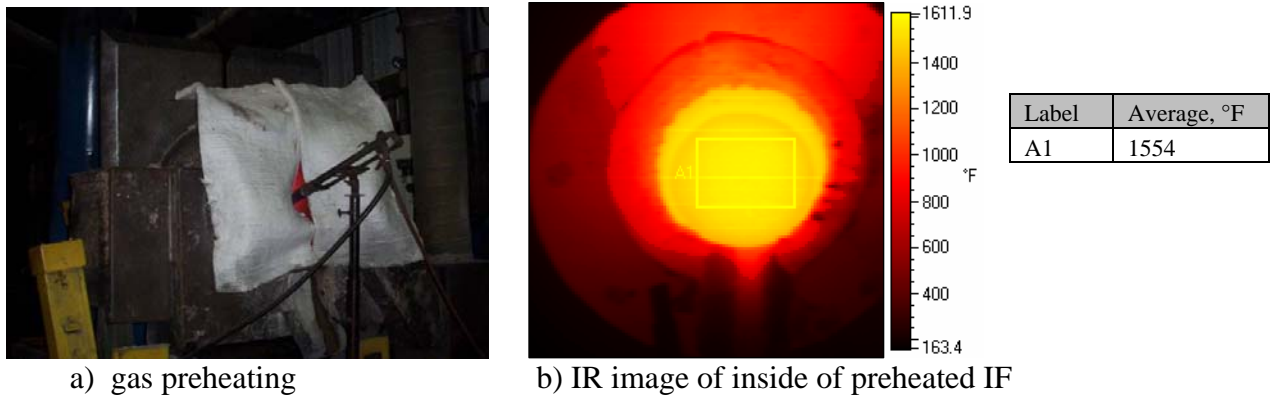a) gas preheating   b) IR image of inside of preheated IF

Figure 16. Gas preheating of IF for first heat of the day (2005 improvement)

Covering the bath during melting and the ladle during pouring decreased the radiation heat losses (see Figure 17) and stabilized pouring temperatures.
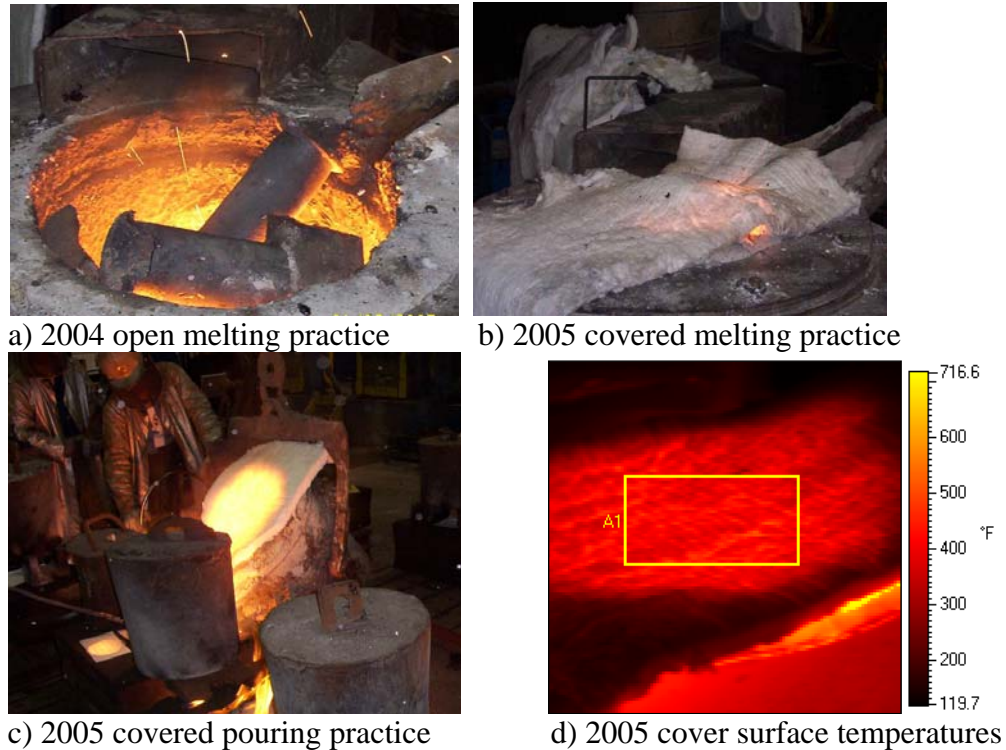
| a) 2004 open melting practice | b) 2005 covered melting practice |
| c) 2005 covered pouring practice | d) 2005 cover surface temperatures |

Figure 17. Comparison of melting and pouring practices in 2004 and 2005.

Alloying Improvements: In the 2004 study, the alloy recovery variation was evaluated for a series of three special trial heats and also statistically evaluated for 155 historic heats. The alloy recovery was found to be lower for ferroalloys added to the charge because of the greater potential for oxidation during the melting process. Also, the recoveries of *Mn* and *Si* added to the melt were inconsistent, some heats had high recoveries and others were much lower than expected. In observing alloying, variations were found to be caused in some cases by ferroalloy additions into a melt surface covered by slag. The distribution of the final chemistries by alloying element characterizes the consistency of melting practices. The ratio of the standard deviation (SD) for individual elements in the final chemistry to the specification range (SR) shows the capability of staying within the specification and also whether or not the element aim range can be reduced to save alloying costs. From a statistical basis, a SR/SD ratio of 4.0 or more indicates that 95.5% of the heats would be within the specification range based on a normal data distribution. In 2004, only the carbon distribution was above the critical ratio (SR/SD=5). Both *Si* and *Mn* were below with a ratio of 3.4 and 2.1, respectively (see Table 8). This indicated that alloying practices needed to be changed to result in more consistent practices and to save alloying costs.

In 2005, the melting practices were rewritten and operators retrained to minimize the alloys added to the charge, sample melts more consistently and avoid adding alloys through slag. Table 8 and Figure 18 illustrate the improvements in Mn recovery and improved consistency that were achieved through the new melting practices.

Table 8. Comparison of final *Mn* distribution in 2004 and 2005

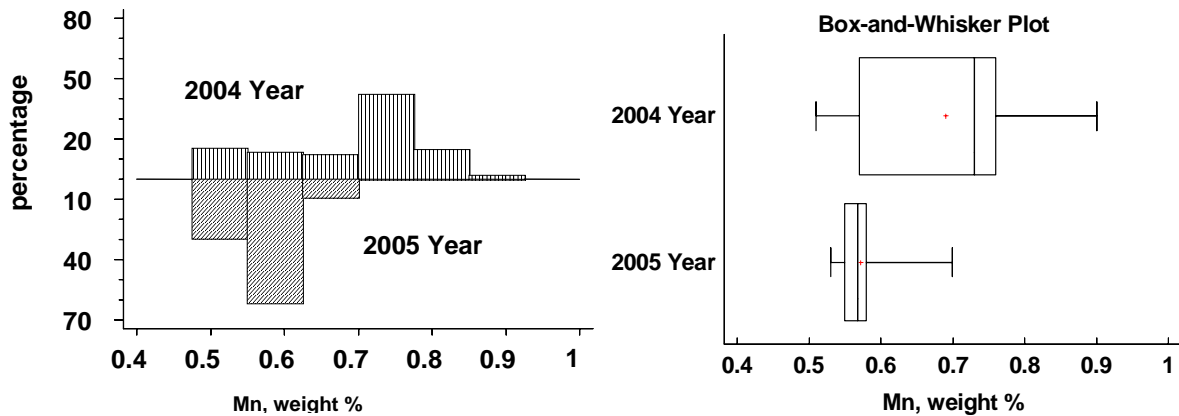| Parameter	2004	2005
Average	0.69	0.57
Standard deviation (SD)	0.097	0.031
Specification Range (SR)	0.4-0.6	0.4-0.6
SR/SD	**2.1**	**6.4**

Figure 18. Comparison of *Mn* variation in WCB steel produced in 2004 and 2005

In summary, these results show that changes in the melting operation can result in significant energy and cost savings without having to spend major capital. The combination of improved melting and management of a foundry can make significant productivity and cost savings. There were cost savings resulting from this combination of changes in nearly every measurable area of the plant (productivity, energy costs, scrap generated, refractory wear, quality rejects, maintenance, etc.).

Summary

A melting efficiency survey has been completed and the results evaluated from 19 different steel foundries to evaluate the efficiency of energy usage for melting steel. The following summarizes some of the findings from this project:

1. The average foundry furnace is 28 years old with EAFs generally significantly older (45 years in age) and IFs generally newer (just over 10 years old). Older furnaces are typically less energy efficient than newer furnaces, especially in the area of electricity distribution and control.
2. Steel foundries are operating at an average of 63% of full capacity with IFs operating at closer to full capacity (72%) than EAFs (57%). This is significantly lower than wrought steel production where actual production is consistently at (and in many cases above) designed capacity driving energy efficiency higher. Operating at low levels of production reduces efficiency based on frequent start-ups and shutdowns and the associated energy inefficiencies.
3. EAF capacity averages 13 tons, over ten times the capacity of the average IF (just over one-ton). In fact, the survey has shown a trend in reducing furnace size over the

years. All large capacity EAFs were installed over 30 years ago and recent installations have been small capacity IFs.

4. EAFs are split with nearly 2/3 using basic refractory linings (magnesia) and 1/3 using acid refractory linings (silica). The foundry industry has made some progress in moving towards basic refractory. However, all EAFs used in the wrought industry are basic-lined refractory because of the associated quality, productivity, and energy advantages.

5. Power supplies (transformer, KVA) have shown a trend towards more power with newer installations. Overall, the average value of KVA/ton is significantly higher for IFs than EAFs.

6. Many steel foundries do not have energy monitoring equipment available making energy conservation in melting difficult.

7. Reported energy consumption varies between 350 KWH/ton to 700 KWH/ton with an average of 527 KWH/t. A multiple regression analysis showed that the following independent variables had an influence on the energy consumption for melting steel:

- Increasing the tap temperature increases energy consumption
- Increasing the tap to tap time increases energy consumption
- EAFs have lower electrical energy consumption than "IF"
- New installations have lower energy consumption than older furnaces
- More powerful transformers (KVA/ton) decrease energy consumption
- Larger furnaces decrease energy consumption

In summary, the steel foundry industry uses a wide variety of equipment in terms of age, capacity, and melting practices. With this diversity comes a wide range of energy efficiency in melting and many challenges as well as opportunities for energy improvements and optimization. This paper showed how one company, Monett Castings, Inc. was able to significantly improve their melting efficiency, increase productivity and decrease costs by technological and management improvements without major capital investment.

Acknowledgments

References

1. Peaslee, K.D., Webber, D.S., Lekakh, S., and Randall, B., "Recovery and Control in Steel Melting," *58th Technical and Operating Conf. Proc.*, SFSA, 2004, paper 4.1, pp. 1-13.
2. Peaslee, K.D., Lekakh, S., and Randall, B., "Thermal Efficiency of Steel Melting," *58th Technical and Operating Conf. Proc.*, SFSA, 2004, paper 4.7, pp. 1-22.