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Kent D. Peaslee

Missouri University of Science and Technology

Semen Naumovich Lekakh

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

Edith Martinez

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Improvements in Steel Melting Efficiency – Industrial Trials

Kent Peaslee, Simon Lekakh, and Edith Martinez

Department of Materials Science & Engineering, Missouri University of Science and Technology, Rolla, MO
65409-0330, United States

^aCorresponding author: Ph: (573) 341-4714; Fax: (573) 341-6934; E-Mail: kpeaslee@mst.edu

ABSTRACT

Industrial trials were completed to improve energy efficiency in steel melting. First, the benefits of increased chemical energy from an oxyfuel burner and a Co-Jet system in a basic 20 ton electric arc furnace (EAF) were studied. Observations and measurements were made during production before and after the installation of the two systems. The additional chemical energy improved energy efficiency and resulted in increased production. In addition, production using a basic EAF practice was compared to the traditional acid EAF practice. Second, an industrial trial using a 750 lb ladle with a combination of a lightweight alumina castable refractory and an insulating board was compared to a standard alumina castable ladle. The new material also showed a potential for significant energy savings.

1. Background on Oxyfuel and Co-Jet Operation

Increasing and highly volatile energy prices make energy efficiency of steel foundry operations extremely important today and in the future. In a previous article¹ it was shown that supplemental chemical energy is a promising way for decreasing electrical energy consumption and increasing the efficiency and productivity of melting steel in foundry electric arc furnaces (EAFs). Both preheating the charge and oxy-fuel burners have the potential of increasing the melting efficiency of the solid scrap charge as illustrated in Figure 1a. During the scrap melting period, electrical energy is input at a fixed rate determined by the electrical transformer settings. Heat losses occur through the furnace sidewalls and roof with some additional losses through sensible heat in the off gas. The addition of chemical energy through the introduction of an oxy-fuel burner or multiple oxy-fuel burners can significantly decrease melting time by eliminating “cold” spots such as the area near the charge door which melt slower than the rest of bath. The reduction in melting time results in a reduction in electrical energy. The overall energy efficiency improves because the reduction in melt time results in less convection and radiation heat losses through the walls and roof.

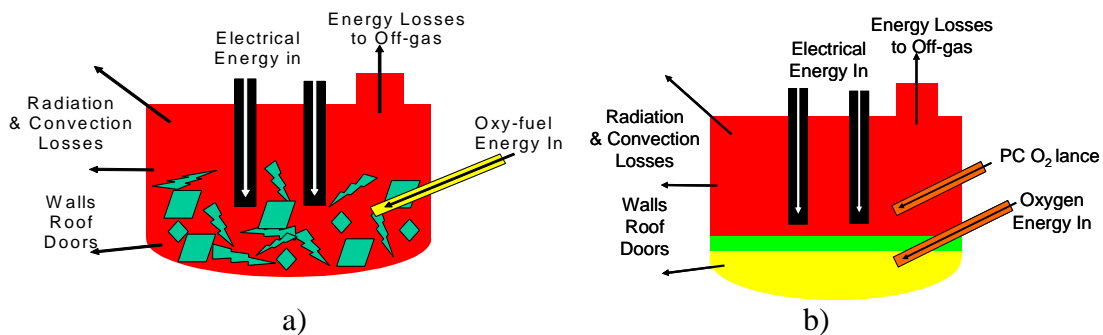


Figure 1. Energy use and losses in an EAF (a) during charge melting and (b) in flat bath periods¹.

Once the scrap has melted and the electrodes are operating on an open bath in air (see Figure 1b), the electrical energy efficiency drops significantly because a significant portion of the arc energy is reflected from the arc and bath surface to the sidewalls and roof where the energy is lost in heating (and often melting) refractory rather than steel. Therefore, opportunities to increase the energy efficiency are greatest during this period. Figure 2 from an earlier study illustrates the efficiency differences during the different production periods with ~85% electrical efficiency during the melting period dropping to ~30% when arcing on a flat bath (shown as correction period in Figure 2). Supplementary chemical energy in the form of additional oxygen can: a) combust C to CO, b) post-combust the CO to CO₂ in the furnace and c) recover the exothermic heat from the oxidation reactions. This decreases the time the steel is in the furnace reducing the energy losses and the electrical energy consumption. In addition, injecting small amounts of fine carbon with oxygen into the slag forms a foamy slag which blankets the arc and bath decreasing the losses to the side walls and roof. This provides the potential of further increases in electrical arc efficiency by utilizing more energy efficient long arcs (higher voltage and lower current) on a flat bath. Co-jet technology provides a supersonic oxygen jet with the opportunity of adding carbon directly into the jet providing a foamy slag effectively increasing chemical energy and decreasing radiation losses to the sidewalls. This paper will evaluate the effectiveness of the Co-Jet system on productivity and efficiency.

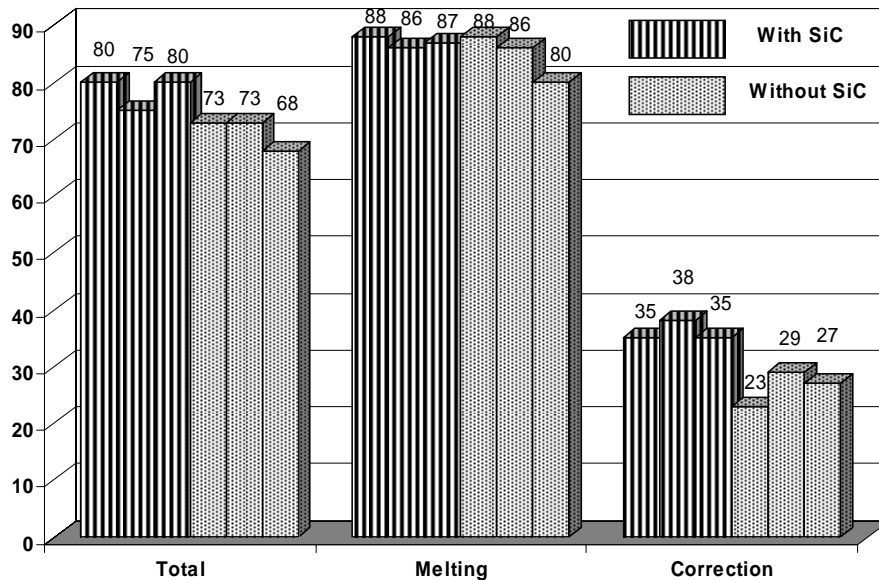


Figure 2. Comparison of total and operational energy efficiency for heats with and without SiC¹.

2. Oxy-fuel and Co-Jet Industrial Trials - Observations and Results

The participating foundry made several technology improvements to one of their EAFs (EAF #4):

- installed basic lining (6/11/2007)
- installed oxyfuel burner and Co-Jet (10/23/07)
- increased transformer power by 5% (12/27/07).

Detailed heat observations were made after the oxyfuel burner and Co-Jet installations and heat balances were calculated according at the same methodology described in our previous publications^{1,2}. Heat A followed the regular melting practice, Heat B had a crane repair delay of nearly 1 hour, and Heat C had a 10 minute delay to repair the oxy-fuel burner. So, it was possible to evaluate scheduling effect on melting parameters. The following components of energy input were considered:

- electrical energy
- chemical energy from natural gas
- chemical energy from oxidation of C and Si in charge during melting and oxygen boiling.

The maximum possible energy associated with carbon oxidation assumes that all of the carbon is oxidized to carbon dioxide based on the carbon charged, carbon added during the heat, and the final carbon after oxygen boiling. The sequence of electrical energy input and energy generated through chemical reactions is shown in Figure 3 for Heat A. The total heat balance is given in Table 1 and the operational efficiency calculated as a ratio of the energy recovered divided by the total energy for the heat is shown in Table 2.

Table 1. Energy balance of Heat A.

Input energy:	KWH/ton	%
Electrical	418.1	79.5
Chemical (Natural Gas)	56.4	10.7
Chemical (from C oxidation)	51.0	9.8
Total energy	525.5	100.00
Output energy		
To melt	353.00	67.17
To slag (13%)	53.81	10.24
Losses	118.71	22.59

Table 2. Operational and total energy efficiency of melting steel for Heat A.

Charge melting	Correction	Total for heat
79.1%	21.9%	67.2%

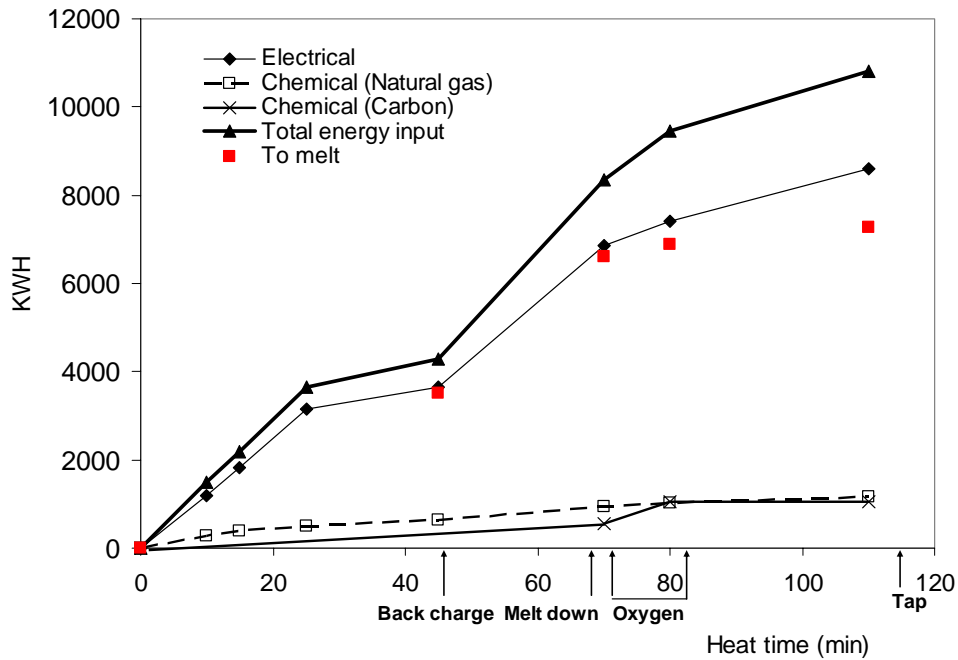


Figure 3. Sequence of energy input during Heat A.

The heat balances for two other observed heats are summarized in Tables 3 and Table 4 and the comparison of melting, power-on time, and energy consumption for all three heats is given in Table 5.

Table 3. Energy balance of Heat B

Input energy:	KWH/ton	%
Electrical	427.34	74.35
Chemical (Natural Gas)	99.10	17.24
Chemical (from C oxidation)	48.3	8.40
Total energy	574.75	100.00
Output energy		
To melt	357.00	62.11
To slag (13%)	53.81	9.36
Losses	163.94	28.52

Table 4. Energy balance of Heat C.

Input energy:	KWH/ton	%
Electrical	447.79	81.16
Chemical (Natural Gas)	51.09	9.26
Chemical (from C oxidation)	52.86	9.58
Total energy	551.74	100.00
Output energy		
To melt	352.00	63.80
To slag (13%)	53.81	9.75
Losses	145.93	26.45

Table 5. Comparison of heats

Heat	Heat time (min)	Power-on time (min)	Electrical energy (KWH/t)	Chemical (Natural gas) energy (KWH/t)	Total heat losses (%)	Delay
A	110	80	418.1	56.4	22.6	No delay
B	191	71	427.3	99.1	28.5	1 hour (crane)
C	125	77	447.8	51.1	26.4	10 min (burner)

These results show the potential benefits of supplemental chemical energy on productivity, electrical energy consumption and energy efficiency. Delays to the EAF for scheduling or equipment breakdowns have negative effects on the savings as illustrated by these heats:

- a one hour delay (Heat B versus Heat A) increased the electrical energy consumption by 10 KWH/ton, nearly doubled the natural gas consumption, increased the heat losses by 30% and decreased productivity by over 40%
- just a 10 minute delay (Heat C versus Heat A) increased the electrical energy by 30 KWH/ton, decreased the energy efficiency of steel melting by 20% and decreased productivity by 10%.

3. Comparison Before and After Major Technological Improvements

The energy and productivity were compared for approximately 600 heats produced before and after the Co-Jet installation. In addition, production with a basic slag/refractory practice is compared to the previous practice using an acid slag/refractory practice (with and without SiC additions).

3.1 Electrical energy consumption. Figure 4 and Table 6 compare the electrical energy consumption on a per ton basis (using total weight of ferrous scrap and ferroalloys) for production before and after the Co-Jet installation. The Co-Jet practice decreased the average electrical consumption by 49 KWH/t (10%). In addition, there were heats without delays with electrical energy consumption of over 100 KWH/t (20%) lower than the average before the Co-Jet, illustrating the potential decrease with efficient scheduling.

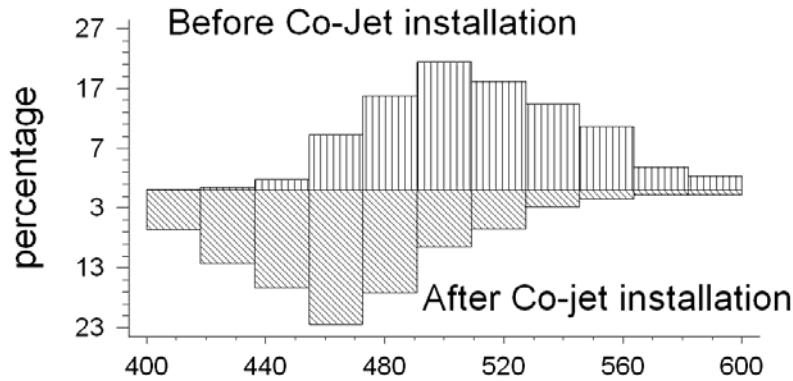


Figure 4. Histogram of electrical energy consumption (in KWH/ton) in a basic EAF.

Table 6. Statistics for electrical energy consumption in a basic EAF.

	Before Co-Jet	After Co-Jet
Number of heats evaluated	627	561
Mean (KWH/t)	513.9	464.8
Standard deviation (KWH/t)	37.7	47.0

The large value of the standard deviation indicates the effect of delays on the energy consumption. Heats with no delays were consistently low in energy consumption (between 400 and 420 KWH/t).

3.2 Furnace productivity.

Melt-down time was defined as the time in a heat from when the power was first turned on until the scrap was completely melted (flat bath). Results comparing the melt-down time before and after the Co-Jet installation are summarized in Figure 5 and Table 7. With the Co-jet, the melt-down time decreased by approximately 15% (14 minutes) from the previous practice. However, there is potential for a 30% decrease in the melting time based on the typical times measured during heats observed during the trials.

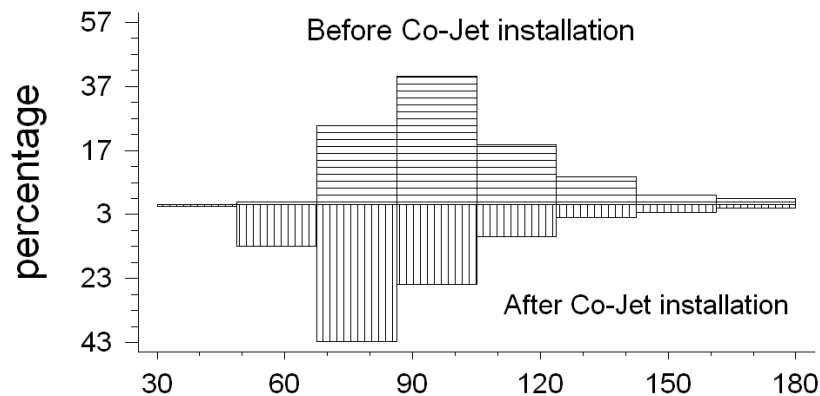
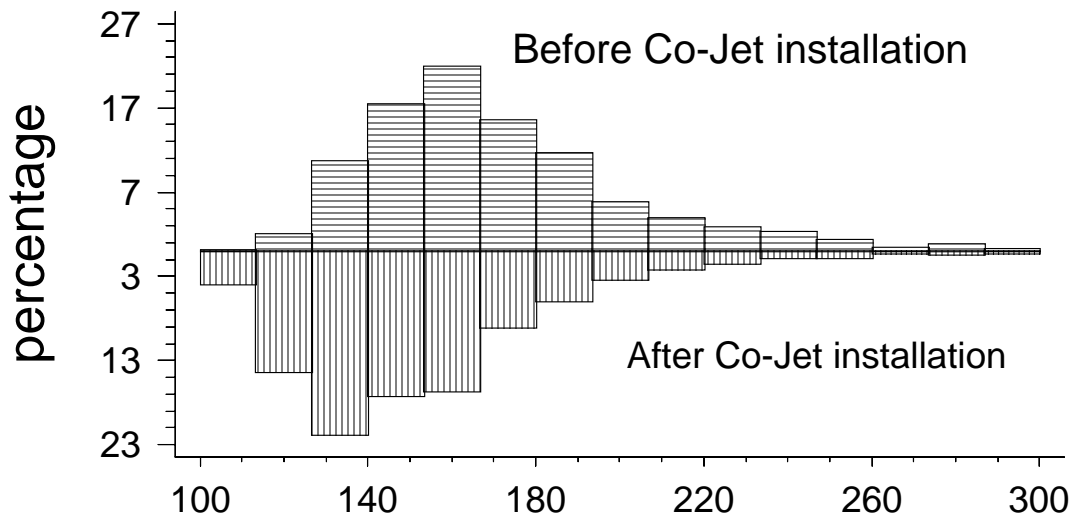


Figure 5. Histogram of melt down time (in minutes) for the basic practice EAF.

Table 7. Statistics for melt-down time in the basic practice EAF

	Before Co-Jet	After Co-Jet
Number of heats evaluated	627	561
Mean melt-down time (minutes)	104	90
Standard deviation (minutes)	29	30

Heat time, defined as the time from charging to tap, is compared before and after the Co-Jet installation in Figure 6 and Table 8. The average total heat time decreased by 22 minutes (15%) using the Co-Jet practice. There is potential for significant additional heat time savings based on one of the trial observed heats in which the total heat time was 110 minutes, nearly 40% less than the average time before the Co-Jet installation.

**Figure 6.** Histogram of total heat time (in minutes) for a basic practice EAF.**Table 8.** Statistics for total heat time (in minutes) for a basic practice EAF.

	Before Co-Jet	After Co-Jet
Count	627	561
Average	176	154
Standard deviation	51	38
In one observed heat		110

3.3 Comparison of acid and basic melting practices. The energy consumption and heat time comparison for different EAF practices are summarized in Table 9. The data was collected from different time periods in the same EAF starting with acid refractories (with and without SiC) and progressing to basic refractories (before and after Co-Jet installation). In the acid practice, SiC additions provided a noticeable productivity and energy improvement. The installation of a basic lining improved steel quality but increased the energy consumption mainly for slag formation. The Co-Jet and oxyfuel burner installation provided a substantial electrical energy savings with an even greater potential savings in the future as the operators become more comfortable with the technology and begin streamlining the operation to allow for the full production potential.

Table 9. Electrical consumption and productivity with different EAF melting practices.

	Acid lining no SiC	Acid lining with SiC	Basic lining	Basic lining with Co-Jet	
				Average	Best observed
Mean KWH/ton	484	464	514	464	418
Mean Heat time (min)	197	178	176	154	110

4. Trial of Industrial Ladle Using Lightweight Low Thermal Conductivity Lining

Several trials using a laboratory scale ladle have been done in the past at the Missouri S&T research laboratories to reduce heat losses in ladle during steelmaking. One trial involved an alumina based porous refractory having a 900 to 950 kg/m³ density and porosity in excess of 75%. The coefficient of thermal conductivity (k) of porous alumina varied from 0.7 W/m²K to 0.9 W/m²K. The porous alumina working lining was tested as a pre-fabricated ladle insert of 1" (2.54 cm) thickness with a liquid steel holding capacity of 45 kg (100 lb). The ladle insert was fired at a high temperature (1600°C) before being installed into a steel shell with 2.5" dry silica insulation lining. Preheating and melting procedures, along with rate of heat transfer calculation across the refractory, are described in detail in a previous article³. The results of the previous research showed that the porous alumina reduced the energy lost to and through the lining allowing for longer metal holding times and significantly lower heat losses in comparison to the commonly used, 70 % alumina castable lining (referred to as "common lining").

The goal of this part of the research was to run an industrial trial using a lightweight low thermal conductivity alumina lining to determine the benefits/challenges of this material in a production foundry. For the industrial trial, a partnering foundry provided a shank ladle of 750 lbs (liquid steel capacity) and the ladle was prepared in the Missouri S&T laboratories before being transported back to the foundry for use. The dimensions of the steel shell were 18" internal diameter and 22" height. For the first trial, porous alumina was prepared similar to previous laboratory tests³ but rather than casting as an insert, the materials was cast directly into the steel shell similar to the foundries normal practice. The ladle was dried out and heated by placing *MoSi* heaters inside the ladle. During the ladle heating, a large amount of shrinkage occurred at the inner surface because of the material properties and the directional heating and thermal gradients inside lining wall. Large cracks developed in the inside of the lining after cool down. In addition, the mechanical properties of the material were insufficient for use in an industrial application. Although the porous alumina lining developed in previous work³ could be used in the future as pre-formed, pre-fired ladle inserts, there were not furnaces large enough in Missouri S&T to allow for this work. Therefore, the research changed course to develop refractory materials that could be cast into a ladle in the plant similar to current industrial castable practices.

In the second trial, a commercially available, low thermal conductivity and relatively low density alumina based castable lining (referred to as "commercial lining") was utilized. The commercial lining is cement bonded and has very effective insulating properties due to its micro-porous aggregate and micro-porosity density. The thermal conductivity of the commercial lining (approximately 0.9 W/m²K) is less than the common lining (around 2.4 W/m²K). This difference enhances the efficiency of using an additional outside insulating lining made from a very low thermal conductivity, light weight material (referred to as insulating lining). The insulating lining minimizes energy losses during molten metal transfers due to its properties of low thermal conductivity and low density. In this case, the mixture of these materials is denoted as "sandwich lining". The properties of the sandwich lining in comparison to the common lining are given in Table 10.

Table 10. Properties of lining materials.

Properties	Sandwich		Common castable
	Insulating lining	Commercial lightweight castable	
Density, kg/m ³	235	1600	2300
Thermal conductivity, W/m ^o K	0.17	0.5-0.9	2.1-2.4
Max. Service Temp., °C	1100	1650	N/A
Composition	47 % <i>SiO</i> ₂ , 45 % <i>CaO</i>	85-87 % <i>Al</i> ₂ <i>O</i> ₃ , 13-14 % <i>CaO</i>	69 % <i>Al</i> ₂ <i>O</i> ₃ , 26 % <i>SiO</i> ₂

The effective properties of the sandwich type lining which consisted of layers made from commercial and insulating linings with a thickness fraction x_i were estimated under following rules:

- Effective density with the rule of mixtures:

$$\rho = \sum_i \rho_i x_i \quad (1)$$

- Effective coefficient of thermal conductivity (k) from equivalent heat flux:

$$k = \frac{1}{\sum_i \frac{x_i}{k_i}} \quad (2)$$

An effective density of 1.36 g/cm³ and an effective thermal conductivity of 0.37 W/m^oK were calculated for the sandwich lining using equation 1 and 2, respectively based on 2” thickness of commercial lining and 0.5” thickness of insulation lining. The results are also displayed in Figure 10, which shows that the combination of the commercial and insulating linings provides a lower thermal conductivity and density when compared to the commonly used castable lining with 70 %-90% alumina.

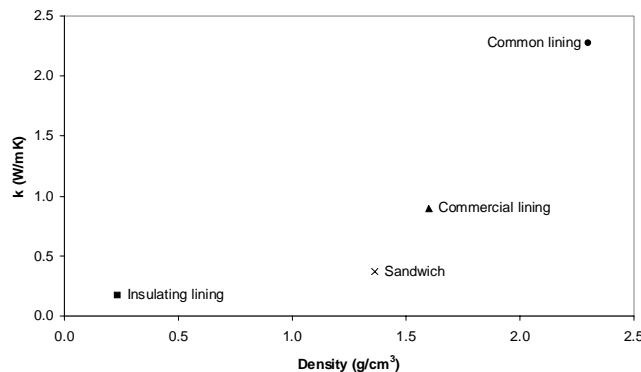


Figure 10. Thermal conductivity and density of lining materials.

The same industrial shank ladle that was used for the first porous alumina trial was also implemented in the second trial. The second trial involved placing the insulating lining between the steel shell and castable lining. The insulating refractory was supplied in the form of 36” x 12” x 4” thick boards and were cut ½” thick to assemble the sides of the actual ladle and 1” thick to accommodate the bottom. Mortar was used to attach the insulating slices to the shell. Preliminary tests showed that the commercial lining undergoes a fast set time at the moment of pouring, which can be solved by adding a set-retarder. Therefore, a set-retarder was added to the castable material during mixing. The ladle was set on a portable

stinger vibrator to help the flowability of material. Unfortunately, the central core moved during setting on the vibrating station resulting in a non-uniform thickness ($\pm 0.5''$) when the central core was removed (Figure 11).



Figure 11. a) Insulation lining inside the steel shell b) ladle with cast commercial lining.

The refractory surface was gradually heated to a final soak temperature of 2460°F (1350°C) over five hours. Thermal images were captured during the process using an Infrared SnapShot camera. Figure 12 displays both the optical and infrared (IR) images of the pre-heated ladle. The IR displays the highest steel shell temperature as 513°F (267°C) and the lowest temperature of 346°F (174°C) towards the bottom of the ladle. These differences were generated by the difference in heat flux through the walls and the bottom based on the different thicknesses. Overall, the shell temperature was significantly lower in temperature when compared to the same size ladle made from high density alumina lining ($400\text{-}500^{\circ}\text{C}$) indicating the improved insulation.



Figure 12. (a) Ladle during initial soaking and (b) steel shell temperatures during the soaking process.

The ladle was slow cooled to 200°F (97°C) over eight hours. Upon examination of the ladle, there were some visible hairline cracks in the lining including one diagonal crack along the bottom of the castable along with a few small cracks along the sides of the shell. It is likely that they were produced during the core removal and the contraction of the refractory during early curing. The ladle was coated with a refractory mortar before use and sent to the participating foundry. At the foundry, the ladle was preheated using a vertical gas preheater to an inside temperature of approximately 1879°F (1026°C) as measured with the IR camera. The shell temperature of the pre-heated ladle (Figure 13) was significantly less when

compared to a previously measured ladle made from common alumina castable and pre-heated in the same way (Table 11) indicating significantly lower energy losses with the new sandwich refractory.

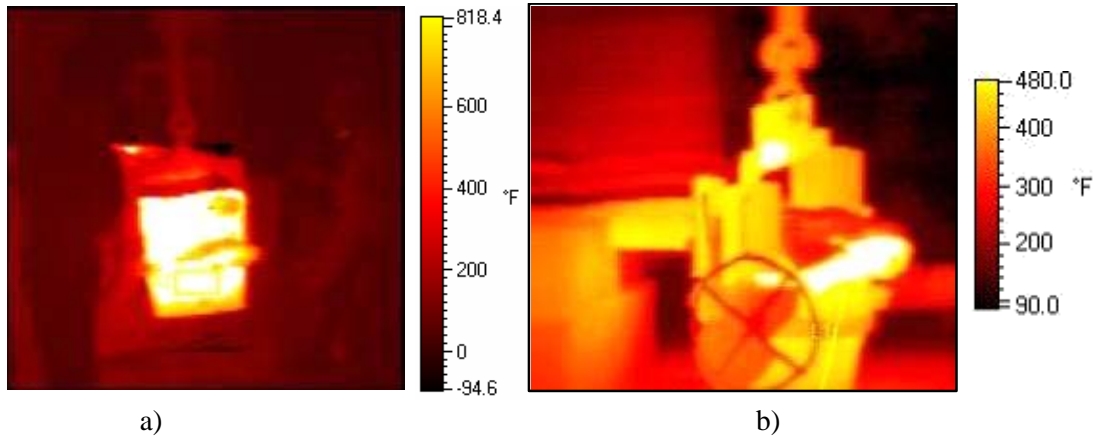


Figure 13. IR images of preheated ladles with (a) common alumina castable and (b) the sandwich lining

Table 11. Average shell temperature of common alumina castable compared to the sandwich lining.

Common castable	Sandwich lining
820 °F	328 °F

Each heat was tapped from one to four times (depending on furnace capacity and charge weight) into the ladle for pouring. The molten steel temperature was collected from six of the ladles poured using the sandwich refractory and averaged and compared to the average temperatures from multiple heats poured with the same ladle using common alumina castable (Figure 14). The sandwich type lining averaged a total temperature loss of 95°F from the last furnace temperature to the ladle temperature after 5 minutes of hold time. This is significantly less than the average temperature loss of 155°F after 5 minutes of hold time for common alumina castable ladles. The energy loss through the sidewalls is 65% greater with a common alumina castable lining than with the sandwich lining.

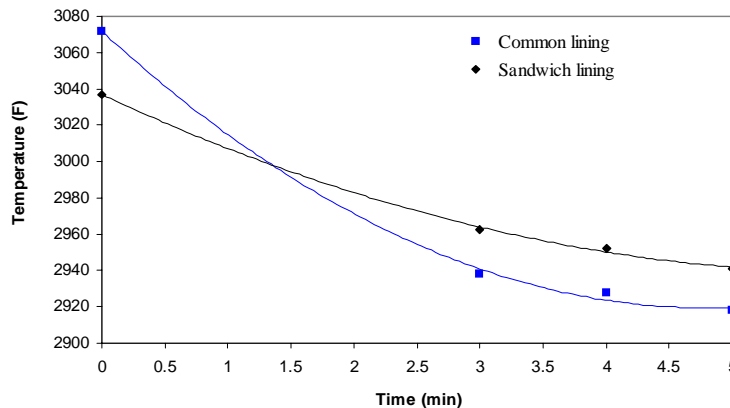


Figure 14. Average temperature of molten steel from the last temperature at tap to pouring.

FLUENT modeling was done based on the laboratory property measurements and industrial trial measurements. The mathematical model compares the required tap temperature for steel when tapped into a ladle preheated to 1650°F (900°C) for two hours and constructed from common alumina castable or the sandwich lining. Two types of boundary conditions are considered, open top allowing radiation from the melt and partially isolated (1/4" thick slag). In all cases, the steel was poured at the same temperature

(2900°F) after 10 minutes of hold time in the ladle. Figure 15 compares the model results with experimental data. The model data demonstrates that the sandwich provides significantly lower energy losses compared to the regular castable lining used in industrial ladles and allows for much lower tap temperatures (50° to 70°F lower) to produce the same pour temperature.

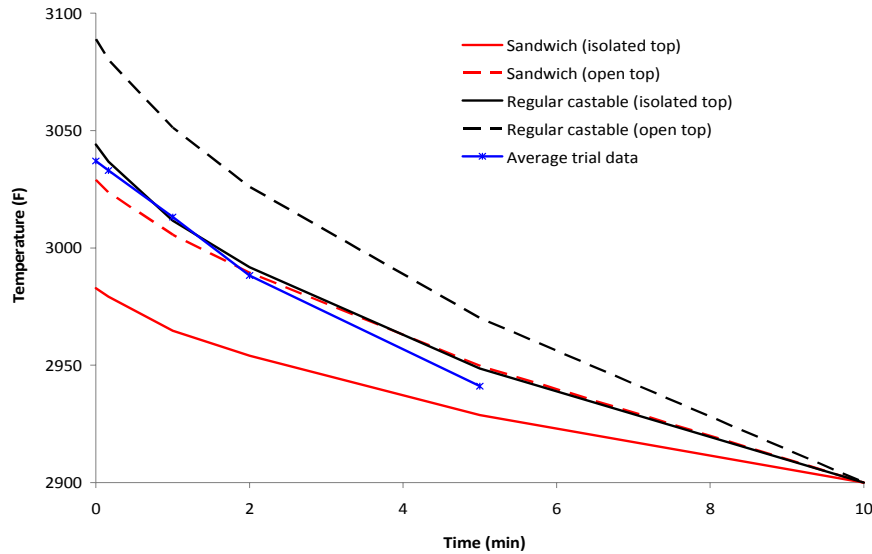


Figure 15. Common alumina castable (black) and sandwich lining (red) compared under different boundary conditions (open top – dashed lines and isolated top – solid lines)

During the sequential tapping and pouring of the molten steel into the ladle, a crack was noticed on the bottom of the refractory after four taps. The crack was in the same location as the original crack noticed before the first heat. During the 13th pour, the ladle bottom got red hot and metal leaked through the bottom. The failure area of the bottom was near the point of tap stream impingement and may be due to the extreme force of moving liquid steel eroding the refractory surface. Normally, liquid impact erosion takes place when liquid impacts the solid surface at high velocities creating circumferential cracks on the solid surface. Subsequent impacts expand cracks and pre-existing cracks accelerate damage on solid surface. Larger pieces of the surface are detached because of the intersection of cracks within material⁴. The pre-existing crack coupled with the new material with lower mechanical properties most likely accelerated the erosion in the bottom of the ladle. Figure 16 shows the bottom of the ladle at the end of the campaign.

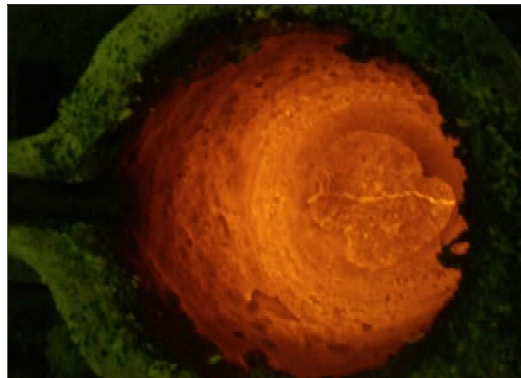


Figure 16. Ladle after pouring displaying erosion and crack on the bottom.

Future trials will include a dense refractory impact pad to prevent erosion through the new materials along with elimination of the insulating board from the ladle bottom.

5. Summary and Conclusions

1. The new melting practice, including the installation of the oxy-fuel burner and Co-Jet along with other improvements (carbon probe, transformer replacement) have resulted in statistically significant savings in energy use and EAF productivity (decreasing heat time).
2. When compared to the acid practice (acid slags and lining), the basic melting process in the EAF (basic slags and linings) provides lower levels of impurities (sulfur and phosphorous). However, the basic slag forming additions of high calcium lime increases the energy consumption for raw material melting. The oxy-fuel burner and Co-Jet along with other improvements have decreased the electrical energy consumption and increased overall energy efficiency of melting steel in EAF with the basic lining.
3. Comparison of the observed heats with average statistical data show that there is considerable opportunities for energy and productivity improvement through scheduling, melting practice optimization, and reducing production delays.
4. In the industrial ladle test trial, the commercially available, low density alumina refractory along with calcium silicate insulating lining nearly cut the molten metal temperature losses in half during melt handling. The suggested combination of lining materials provided a much better ladle insulation due to the fact that the shell temperature did not increase significantly between the tap and the end of the four heats. The material has excellent thermal characteristics but still needs to be proven for long campaigns. The mechanical properties of low density materials are compromised possibly resulting in a material that is more susceptible to erosion from the hydrodynamic force exerted by the stream at tap. Future trials will utilize a bottom tap impact pad to prevent the bottom erosion extending the life of the ladle.

6. Acknowledgements

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