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Improving Melting Efficiency Through the Application of New Refractory Materials

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Improving Melting Efficiency through the Application of New Refractory Materials

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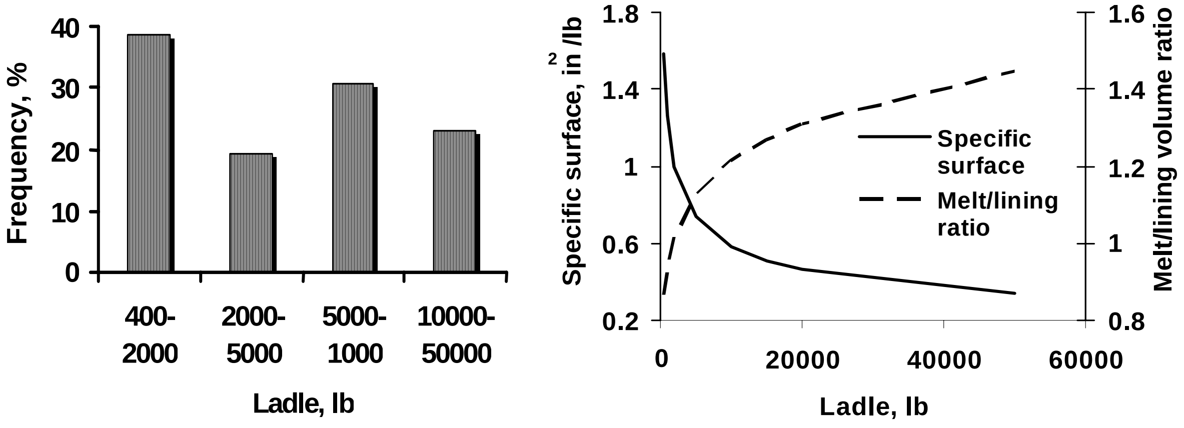
ABSTRACT

Ladle design and ladle practices have a significant effect on a foundry operation and product quality. Large steel temperature losses or instabilities in the pouring temperature are frequently compensated by tapping at higher temperatures dramatically increasing furnace and ladle lining wear, oxidation of the steel, alloying element losses, and energy consumption in steel melting. Ladle lining materials need to satisfy a complex array of often conflicting requirements. For example, ceramic materials for linings must possess a high strength at liquid steel temperatures to prevent erosion and crack formation. However, linings need to also have a low thermal conductivity which typically increases as the strength improves. Temperature problems became more severe with decreasing ladle size. This paper summarizes test work of new lining materials in a 100 lb liquid metal capacity ladle in the UMR foundry designed with a temperature measurement system installed in the lining. Several different working linings materials were tested under similar conditions. Results from these foundry experiments were compared with thermal conductivity measurements in the laboratory and computation fluid dynamic modeling results. From this work, UMR's newly developed porous alumina linings were shown to have properties that could result in significantly lowering energy requirements in steel foundries.

1. INTRODUCTION AND BACKGROUND

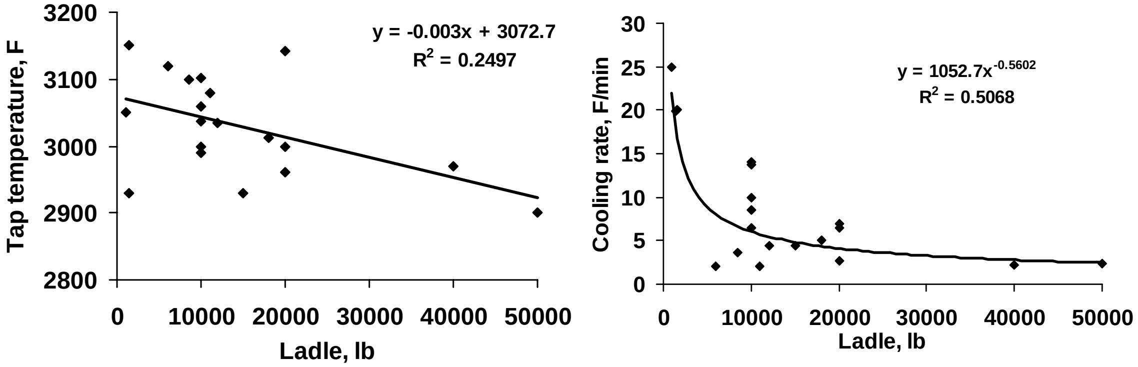
Effective ladle design is important for steel casting production. In foundry operations, the temperature of the liquid steel in the ladle is typically 150°F to 300°F above the steel's melting point to compensate for the heat losses in small ladles and the associated high cooling rates from the large surface area to volume ratios. High superheat is also necessary to provide sufficient steel fluidity to properly fill the mold cavity. In spite of the relatively short time that the steel is in contact with the ladle lining, the huge thermal gradients in the lining drive the high values of heat transfer through the refractory surface. Steel foundry ladles vary in capacity from 400 to 50,000 lbs as summarized in Figure 1A[1-2]. As the ladle capacity decreases, the lining surface area per lb of liquid metal increases (see Figure 1B). This is important because heat transfer is directly proportional to the surface area. For example, small ladles (<1000 lbs) have 5 times the surface area per ton as large ladles (>20,000 lbs) and therefore would experience 5 times the rate of temperature loss under similar ladle conditions (tap temperature, preheat, refractory types and thicknesses, etc.).

Heat transfer between the liquid metal and the ladle lining as well as the associated heat losses in foundry linings were analyzed using data generated at 20 steel foundries and from industrial measurements completed at seven foundries[1-2]. Temperature measurements were made using thermocouples and infrared cameras. Figure 2A shows a general trend of increasing tap temperatures with decreasing ladle capacity. Higher tap temperatures help compensate for the much higher rate of steel temperature loss in smaller ladles (Figure 2B). The cooling rate of the liquid steel through the ladle lining decreases exponentially based on increasing ladle size.



A) B)

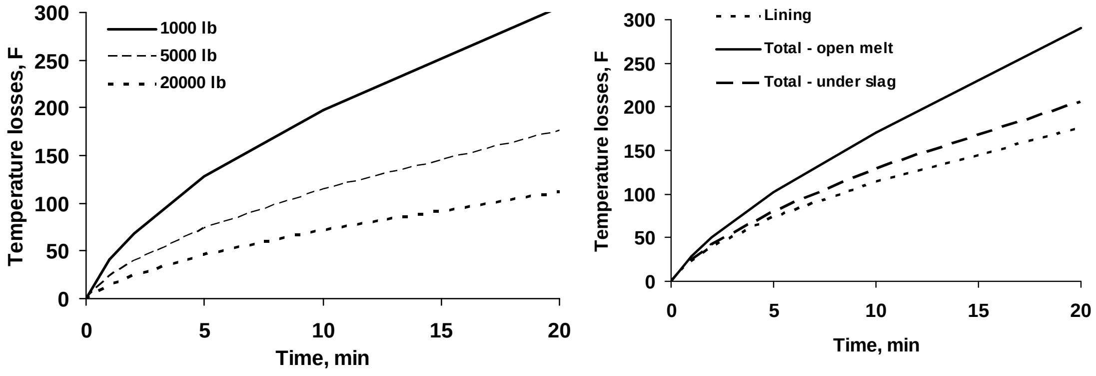
Figure 1. Distribution of A) steel foundry ladle size and B) lining surface/melt weight ratio [1-2]



A) B)

Figure 2. Effect of ladle capacity on A) tap temperature and B) rate of temperature loss[1-2]

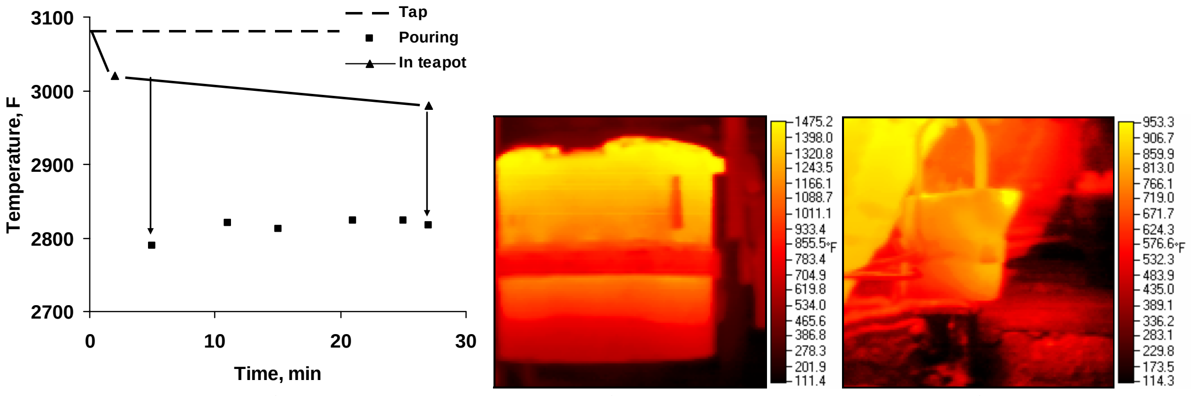
The temperature losses in the industrial ladles were also modeled using FLUENT, a commercial computational fluid dynamic software package. It was found that the results predicted by the FLUENT ladle model were very similar to the results observed in industrial foundries. The ladle size was shown to have a major influence on the rate of liquid steel temperature drop because foundry ladles are typically not at steady state (heat is not fully soaked into the lining) resulting in larger heat losses to compensate for heat accumulation in the lining (see Figure 3A). Figure 3B compares the different mechanisms of heat loss (lining accumulation versus radiation) while holding liquid steel in the ladle. Radiation losses could be minimized by using radiation protection devices (lid, special melt cover, etc.). Reduction in lining accumulation losses requires either lower thermal conductivity materials or much more effective ladle preheating.



A) B)

Figure 3. A) Influence of ladle capacity on temperature losses during holding and B) comparison of temperature loss by lining accumulation and radiation from the top surface of a 5000 lb ladle[2]

Some foundries tap the furnace into a large transport ladle which is used to pour shank type small capacity ladles. This more than doubles the melt lining exposure significantly increasing the magnitude of temperature losses. For example, one medium carbon and low alloy steel foundry melting in a 5 ton EAF, taps steel at 3100°F into an 11,000 lb. alumina lined teapot ladle preheated to 1955°F. The steel is re-ladled into a 1000 lb. shank ladle with a lining consisting of low thermal conductivity magnesia boards surrounded by dry sand to pour medium and small size castings. An example of the temperature losses during tap, while holding in the teapot ladle and in the re-ladled steel are given in Figure 4A. During the 30 minute pouring time, the total temperature loss was 280°F to 300°F. Infrared images of the teapot and shank ladles with liquid steel are given in Figures 4B and 4C.



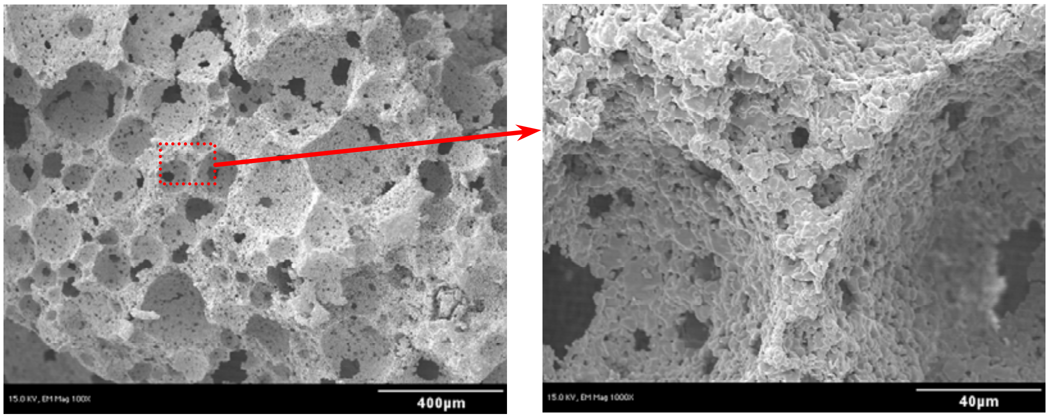
A) B) C)

Figure 4. A) Temperature of liquid steel in the 11,000 lb teapot ladle and 1,000 lb pouring ladle
B) surface of preheated alumina-lined 11,000 lb teapot ladle (before tap)
C) surface of empty 1000 lb shank ladle (lined with low density magnesia lining)

The large temperature losses associated with the use of foundry ladles led to UMR's research in developing new lining materials designed especially for steel handling in foundries. This paper outlines the development of these new lining materials.

2. NEW HIGH POROSITY CERAMICS FOR STEEL FOUNDRY LADLE LININGS

A basic alumina castable was reduced in density by adding alumina hollow spheres and calcium aluminate cement binder. In contrast to conventional alumina aggregates with density range from 3.5 to 3.7 g/cm^3, hollow alumina aggregates have a density range from 0.5 to 0.8 g/cm^3 and provide pores from 500 to 1500µm in size. It is this aggregate substitution that imparts the first level of porosity to this insulating castable. In order to render the castable foamable, additional matrix powders are required. In this case, ultrafine hydrateable alumina, calcined alumina, and calcium aluminate cement are added to lower the particle size distribution modulus and to provide the requisite fines as well as additional binder for the system. After charging the base-castable and additional fines into a paddle type mixer, it is tempered with enough water to allow the system to be characterized as an excellent vibratable or boarderline self-flow castable. At this moment, three surface active agents are introduced and the paddle blade is switched to a whisk attachment in order to facilitate air incorporation and the foaming process. Also added at this time is an engineered fugitive of organic microspheres with an average particle size of 20µm. This very low mass organic material volatilizes upon the initial heating of the castable leaving fine spherical porosity. The specific volume of the castable is increased dramatically during the mixing/foaming process. The prepared insulating castable material was then pre-cast into a plastic mold. Since the binder for this system is hydratable, the castable is treated similar to other castable materials in terms of maintaining a warm and humid environment for setting and curing.



A) B)

Figure 5. Scanning electron microscopy images of a foamed insulating castable fracture surface

To date, a bulk density of less than 1 g/cm^3 and porosity levels in excess of 75 vol. % has been achieved. Figure 5 is a scanning electron microscope image of a typical fracture surface of the foamed castable. The largest pores in the system are due to hollow alumina sphere aggregate (not shown in Figure 5). The second level of porosity (Figure 5A) is due to air incorporated during the foaming process. These pores range in size from 50 to 500μm and account for the vast majority of the porosity in the system. The third level of porosity (Figure 5B) results from the engineered organic fugitive material and has an average pore size of about 20μm.

3. EXPERIMENTAL PROCEDURE

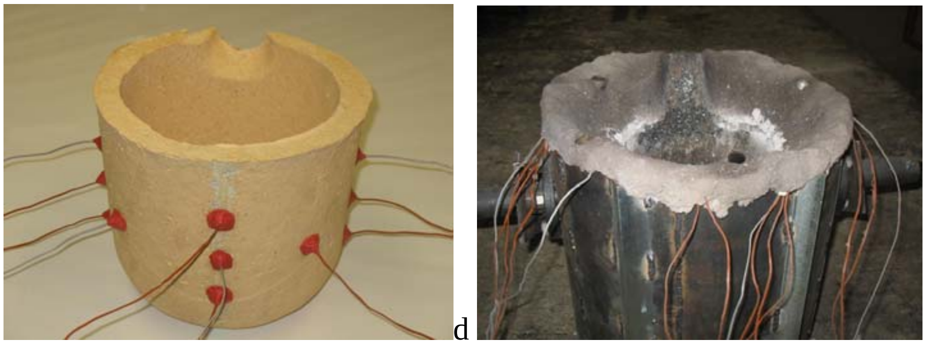
3.1 Lining materials and ladle test. Three types of lining materials were studied (see Table 1), a regular alumina based castable, a low density magnesia ladle insert, and a newly developed low density porous alumina castable. All materials were tested as a prefabricated insert with 1” thickness for a ladle of approximately 100 lbs capacity. The low density magnesia insert was used in the supplied condition while the inserts from two castable ceramics were poured into special plastic molds which were replicated from one of the commercial magnesia inserts. This resulted in all tested inserts being the same shape (Figure 6). The castable inserts were fired to 1400°C. Nine thermocouples were installed at different wall positions (inside, outside and in the middle) at three levels (upper, central and lower sidewall). In addition, three thermocouples were installed in the bottom (see Figure 7A). The insert with thermocouples was installed into a steel shell with approximately 1” dry sand layer surrounding the insert (Figure 7B). A National Instrument Data Acquisition System was used for data collection. Cast iron was melted to increase the possible holding time in the ladle without having solidifyed metal. The metal was superheated to 1650°C in induction furnace and tapped into the ladle. The ladle was held until the temperature reached a minimal temperature of 1330°C.

Table 1 Three types of lining materials studied

Ceramics	Density, kg/m^3
Alumina castable	2300
Low density magnesia crucible	1400
Porous alumina castable	900-950

A) B) C)

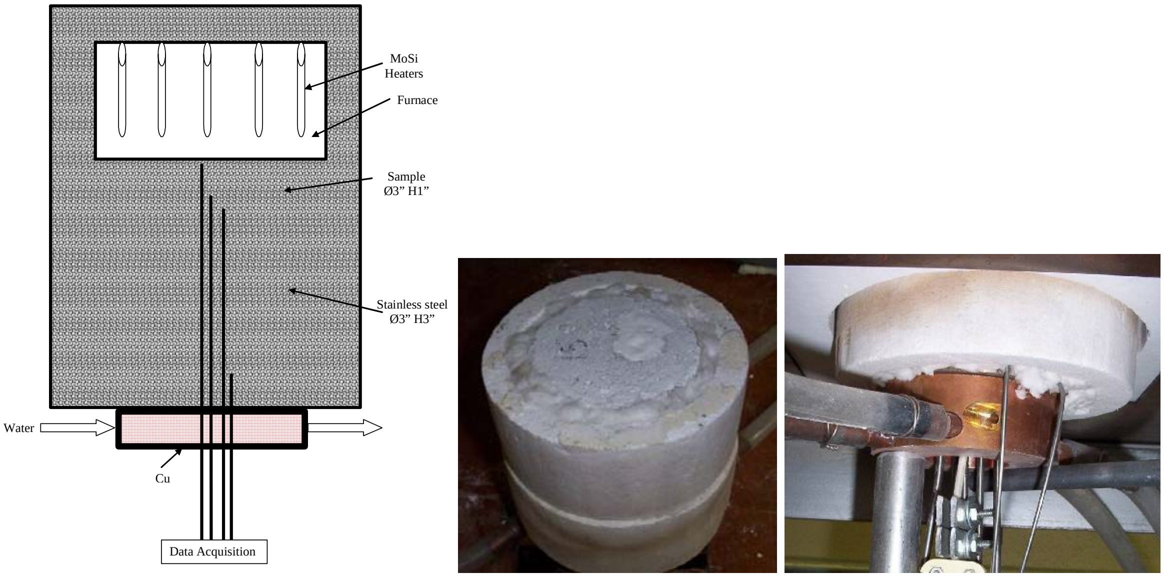
Figure 6. Lining inserts: A) regular alumina castable, B) low density magnesia one-piece insert and C) Porous alumina castable



A) B)

Figure 7. A) Insert with installed thermocouples and B) ladle with insert and thermocouples

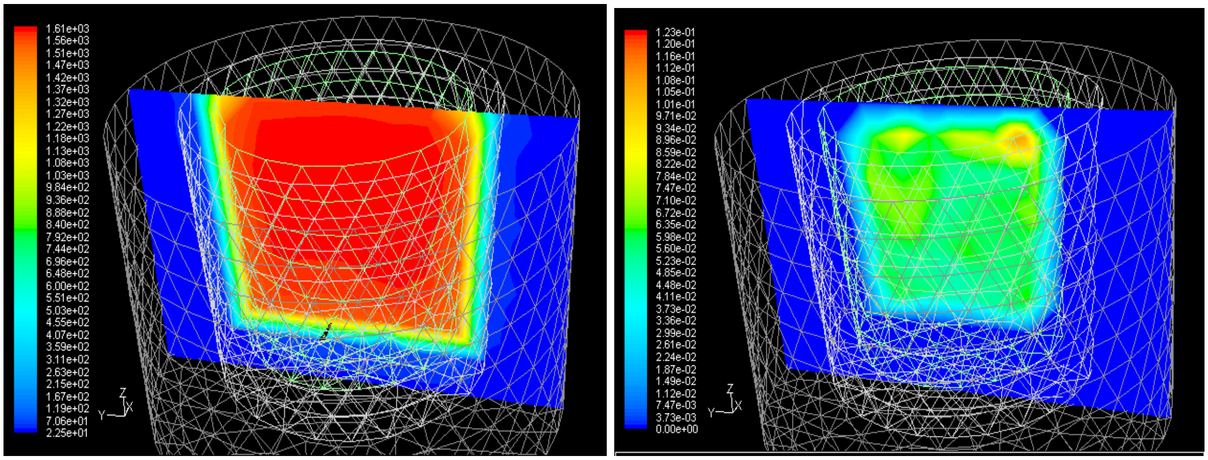
3.2 Thermal conductivity test. The coefficient of thermal conductivity was measured separately in the unidirectional steady state condition by placing a 3” diameter by 1” height sample of the refractory to be measured in the device illustrated in Figure 8. The top surface of the sample was exposed to high temperatures in a furnace with molybdenum disilicide heaters while the bottom surface contacted a stainless steel cylinder attached to a *Cu* water cooler. Thermal insulation surrounds the side surfaces of the sample and stainless steel. Thermocouples installed in the direction of heat flow allowed for a measurement of the thermal gradients inside the lining sample and the stainless steel reference which were used to for calculate the value of the coefficient of thermal conductivity.



A) B) C)

Figure 8. Unidirectional steady state thermal conductivity test: A) schematic of device, B) Sample mounted on stainless steel reference, and C) bottom copper water cooler.

3.3 Heat transfer modeling. Heat transfer was modeled using FLUENT commercial software. The model developed was for non steady state conditions taking into account the initial temperature of the melt, the three layers of the ladle lining (insert, sand layer, and steel shell) geometry, and the flow of the liquid metal in the ladle as a result of natural convection. The boundary conditions included coupling between the liquid metal and lining, radiation from the top surface with the possibility of changing slag layer thickness, and air convection outside the steel shell. Figure 9 is an example of the calculated temperature and metal flow in the ladle.

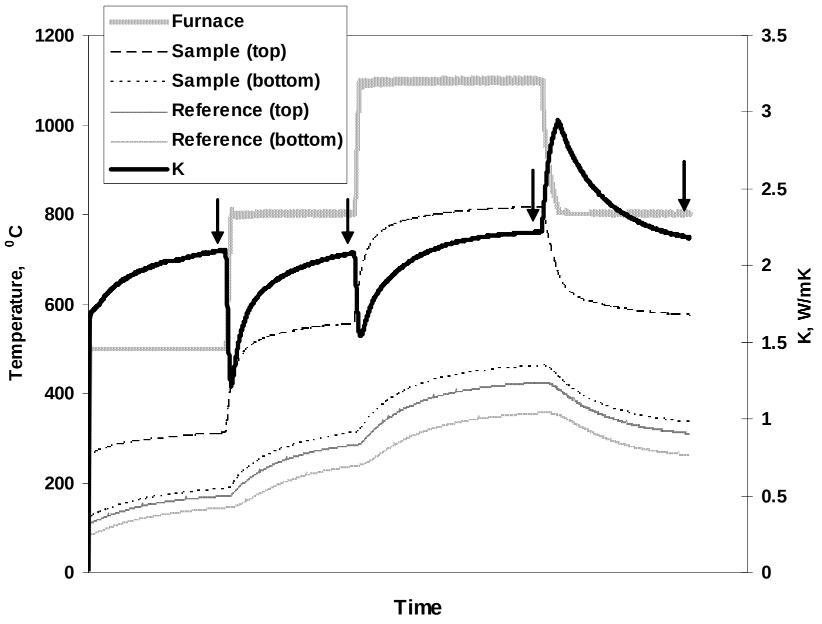


A) B)

Figure 9. A) Predicted temperature and B) metal velocity in the FLUENT model ladle.

4. EXPERIMENTAL RESULTS

4.1 Thermal conductivity measurement. Experimental data used to measure the thermal conductivity of the three types of linings are shown in Figures 10 through 12. The measurements were done at furnace temperatures of 500°C, 800°C, and 1100°C. The values of the coefficient of thermal conductivity were measured when the samples were close to steady-state conditions (shown by arrows in Figure 10A). The values of the coefficient of thermal conductivity for the two types of castable linings were stable (although significantly different) at the same temperature regardless of the number of temperature cycles. However, measurements of the low density magnesia board material showed unstable data as a result of the material eroding during the tests. The measurements were further complicated by the exothermic chemical reactions of binder decomposition. The comparison of thermal conductivity of different linings (Figure 13A) shows that the newly developed porous ceramic material has a thermal conductivity that is 2.2 to 2.8 times lower than regular alumina castable with much stabler properties than low density magnesia boards. Typically, low density materials are able to produce lower thermal conductivity but suffer from poor mechanical properties of the ceramics. The thermal conductivity of studied lining versus density is given in Figure 13B. The newly developed alumina porous castable lining has a low density but possesses much higher strength and thermal stability than the magnesia boards.



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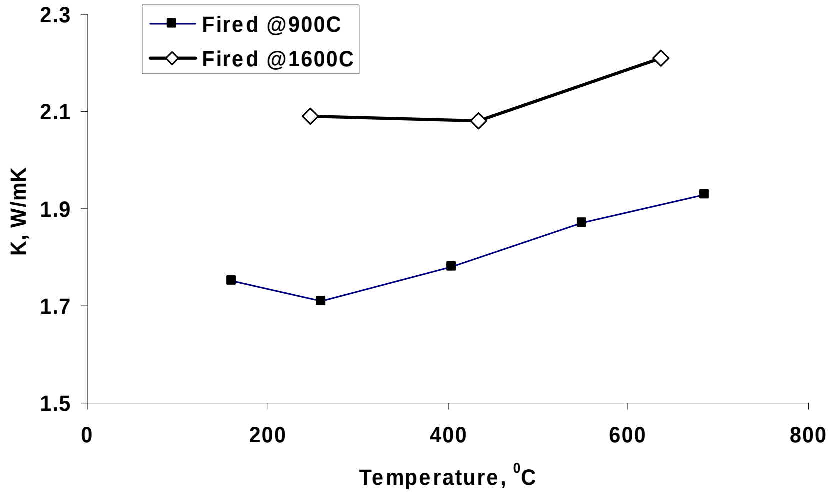
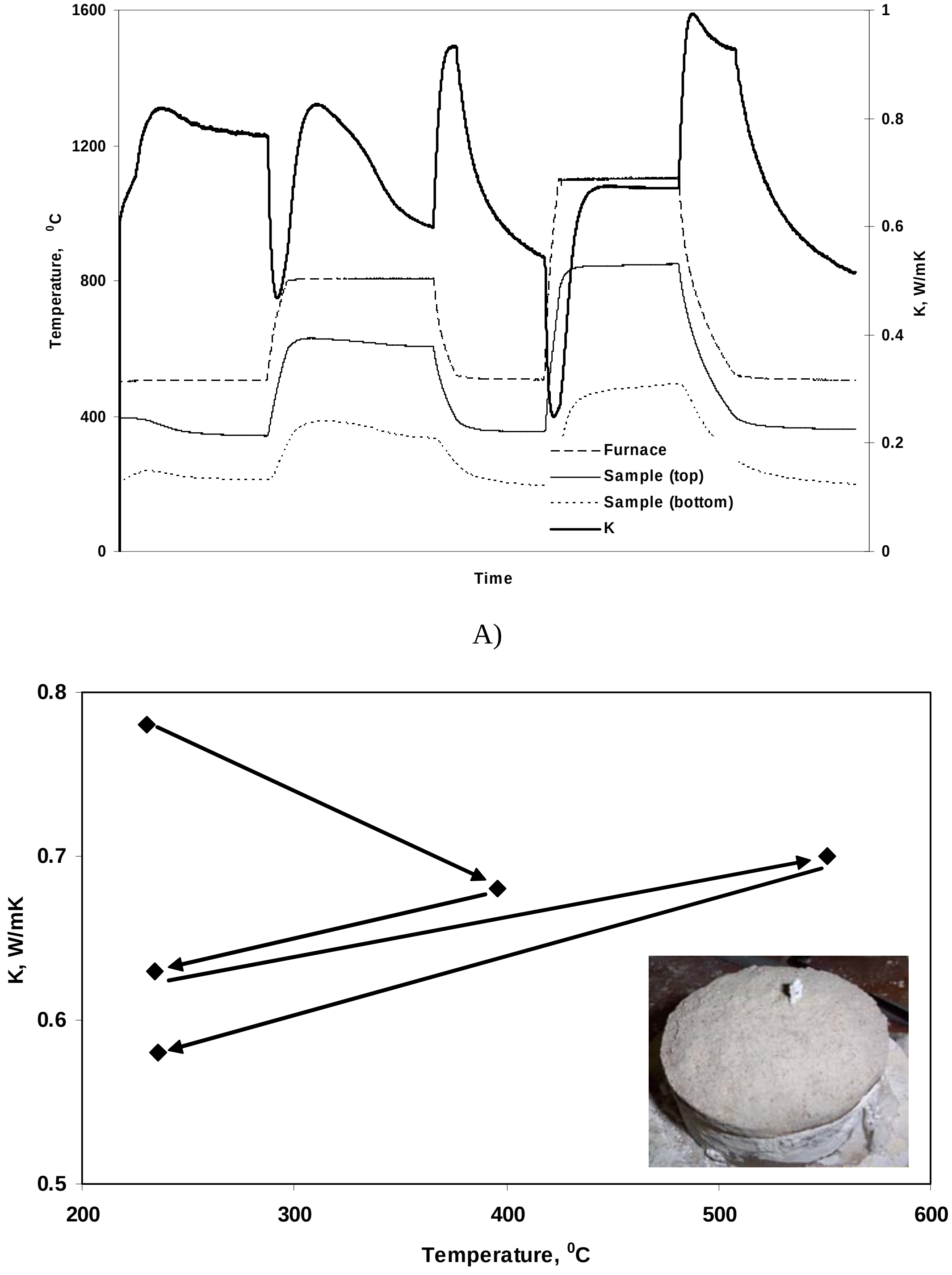


B)

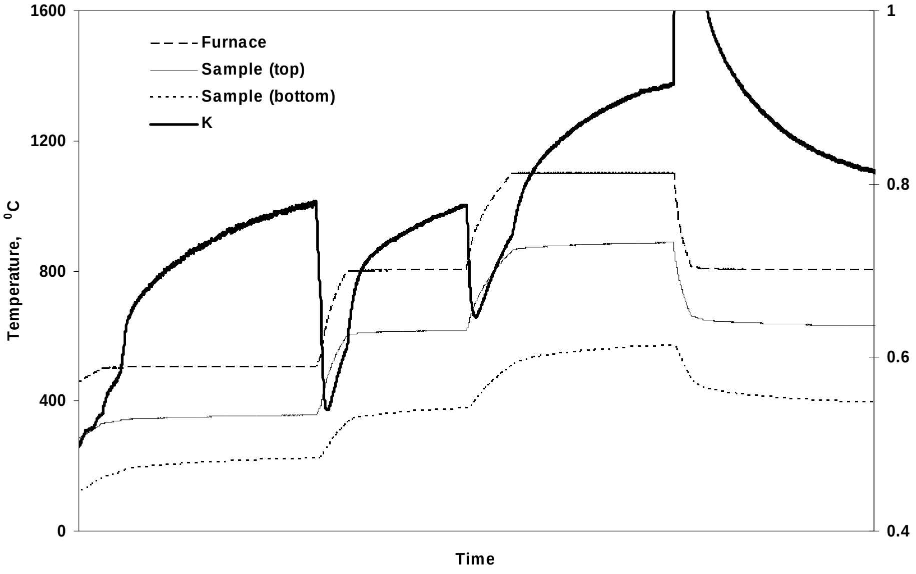
Figure 10. A) Thermal conductivity measurement data for alumina castable lining fired @1600 and B) comparison of coefficient of thermal conductivity of alumina castable lining fired @900°C and 1600°C



A)

B)

Figure 11. A) Thermal conductivity test data for the low density magnesia lining and B) the changing value of the coefficient of thermal conductivity during the test.



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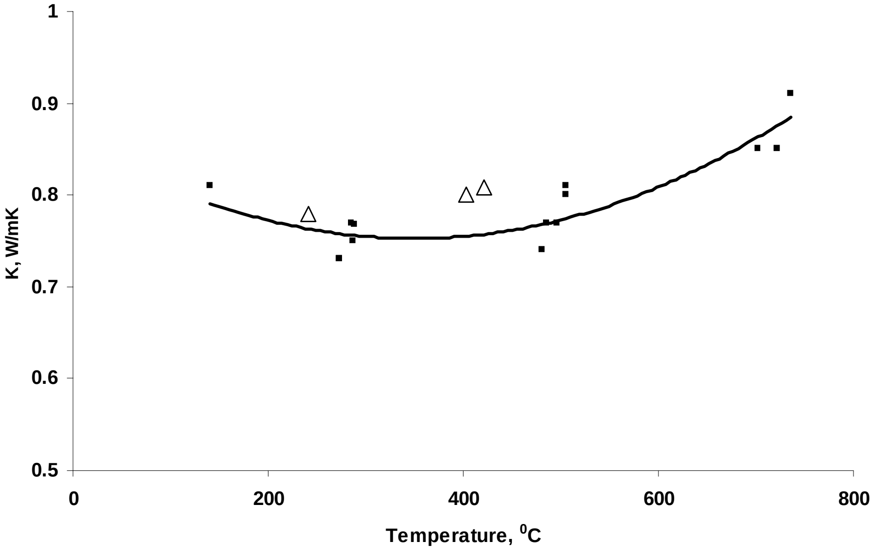
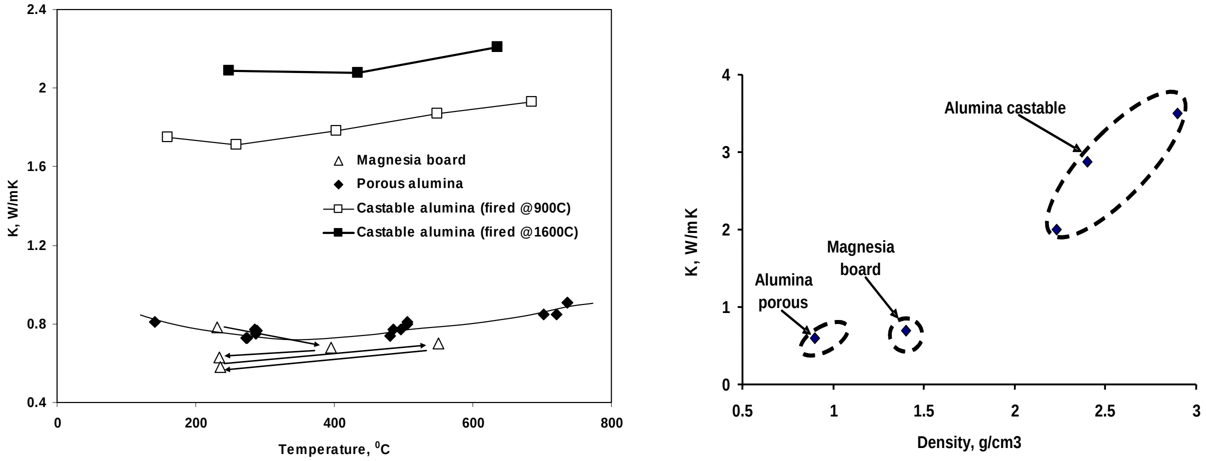


B)

Figure 12. A) Thermal conductivity test of castable porous alumina ceramic sample and B) thermal conductivity value versus temperature of two different porous alumina materials with different densities:

- 90% Al_2O_3 +8% CaO +2%SiO_2, density 0.8-0.85 g/cm^3 (black squares)
- 95% Al_2O_3 +4% CaO +1% other, density 0.95-1.0 g/cm^3 (open triangles).



A) B)

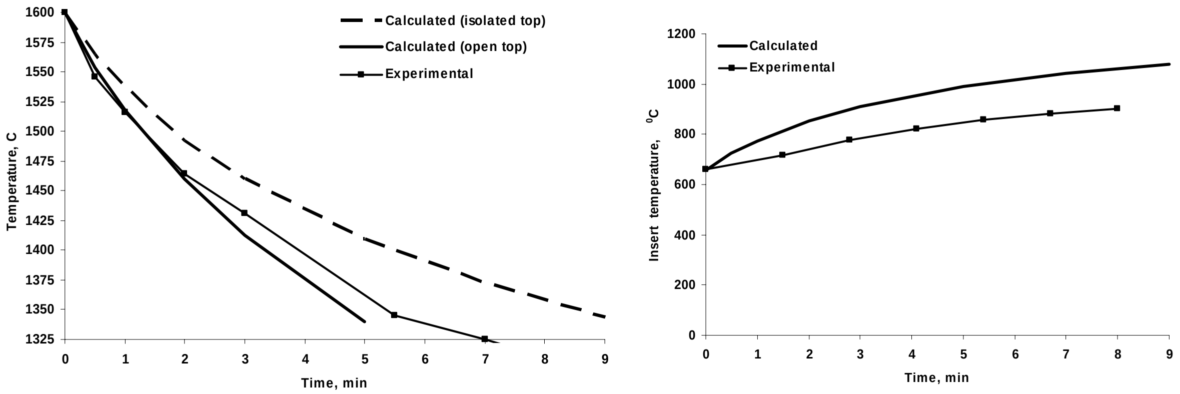
Figure 13. The effect of A) lining temperature and B) lining density on thermal conductivity of several different types of ladle linings.

4.3. Ladle lining tests.

Each of the three different types of ceramic ladle linings were inserted in the test ladle and surrounded by a 1” thickness of dry sand and tested under similar conditions to industrial foundries. The metal was tapped in each case at 1630°C into ladles at:

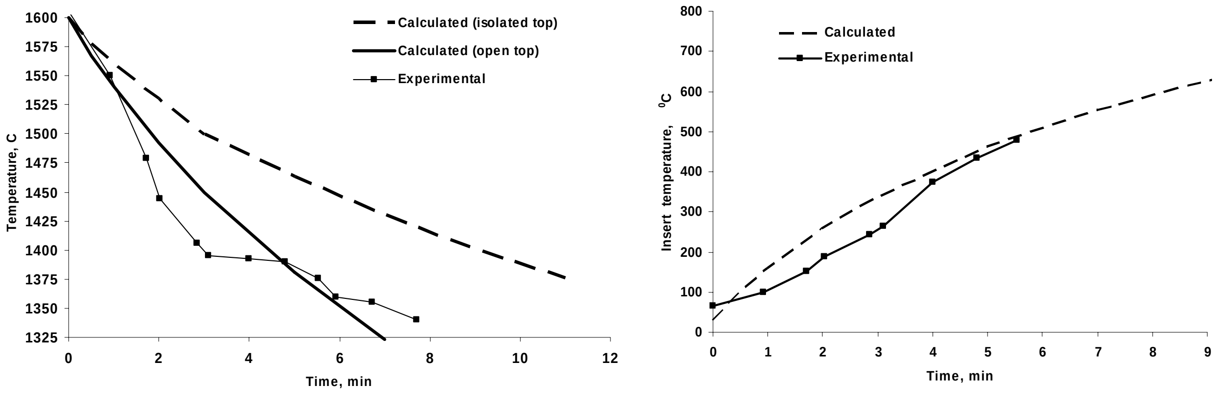
- Both castable alumina ladle linings (solid and porous) were preheated with a *SiC* electrical preheater to 700°C internal surface temperature for 2 hours;
- The ladle with the magnesia board insert was used at room temperature.

Calculations from the FLUENT model are compared to experimental results with varying lining types and conditions in Figures 14 through 16. The model calculations consider two extreme conditions, a fully isolated top of liquid surface (no radiation losses) and open melt surface where radiation and convection combine to reduce the liquid metal temperature during holding.



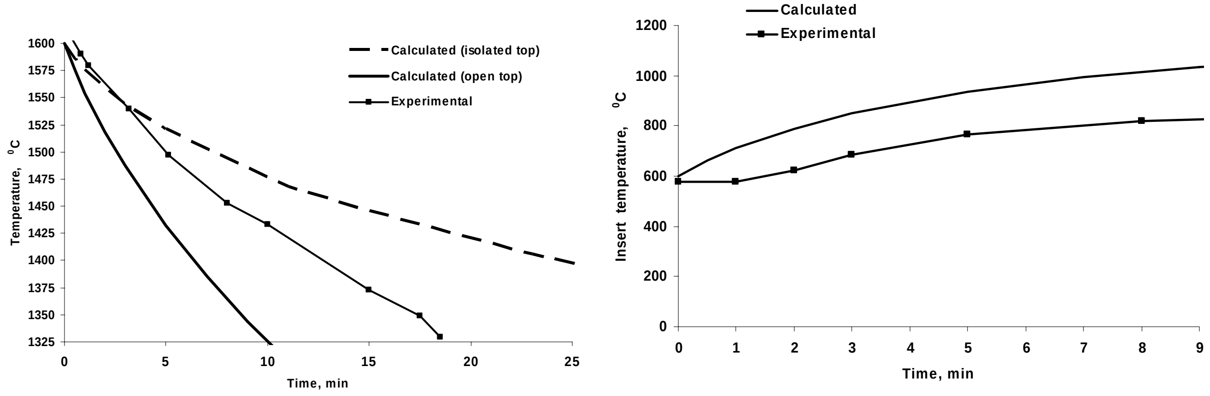
A) B)

Figure 14. Comparison of FLUENT model and experimental measurements for alumina castable: A) metal temperature and B) mid-section refractory temperature



A) B)

Figure 15. Comparison of FLUENT model and experimental measurements for magnesia board insert: A) metal temperature and B) mid-section refractory temperature



A) B)

Figure 16. Comparison of FLUENT model and experimental measurements for porous alumina castable: A) metal temperature and B) mid-section refractory temperature

4.4 Comparison of lining ceramics for steel ladle.

The differences in the physical properties of the linings had a significant influence on the liquid metal temperature losses while holding in the ladle. Figure 17 compares the effect that the three different lining types would have on the liquid metal temperature in the 100 lb ladle modeled using FLUENT. The results of the modeling are also compared with experimental results in Table 2.

Table 2. Ladle holding time for melt temperature to drop from 1600°C to 1350°C

Lining	Preheat, °C	Measured time experimental, min	Calculated time using FLUENT model, min	
			Open top	Isolated top
Alumina castable	700	7	5	10
Low density magnesia board	No preheat	9	7	13
Alumina porous castable	700	18	12	30

Figure 17 illustrates three fields representing the possible variations in time and temperature depended on the type of ladle materials and ladle procedure (with or without thermal isolation of top melt surface). This variation was used because of the wide variation in ladle practices encountered in the foundry industry. The alumina castable lining and the newly developed UMR porous castable lining were both used after preheating to 700°C because most foundries would preheat these types of ladles. However, the magnesia boards were used at room temperature initially because these materials were not designed for intensive preheat. Figure 17 illustrates that room temperature magnesia board ladles do have some advantages when compared to preheated alumina castable ladles. However, the newly developed porous alumina ceramics provide the possibility of cutting the temperature losses in one-half, effectively doubling the possible metal holding time in the ladle. The new porous lining is less sensitive to the preheat condition than normal castable linings.

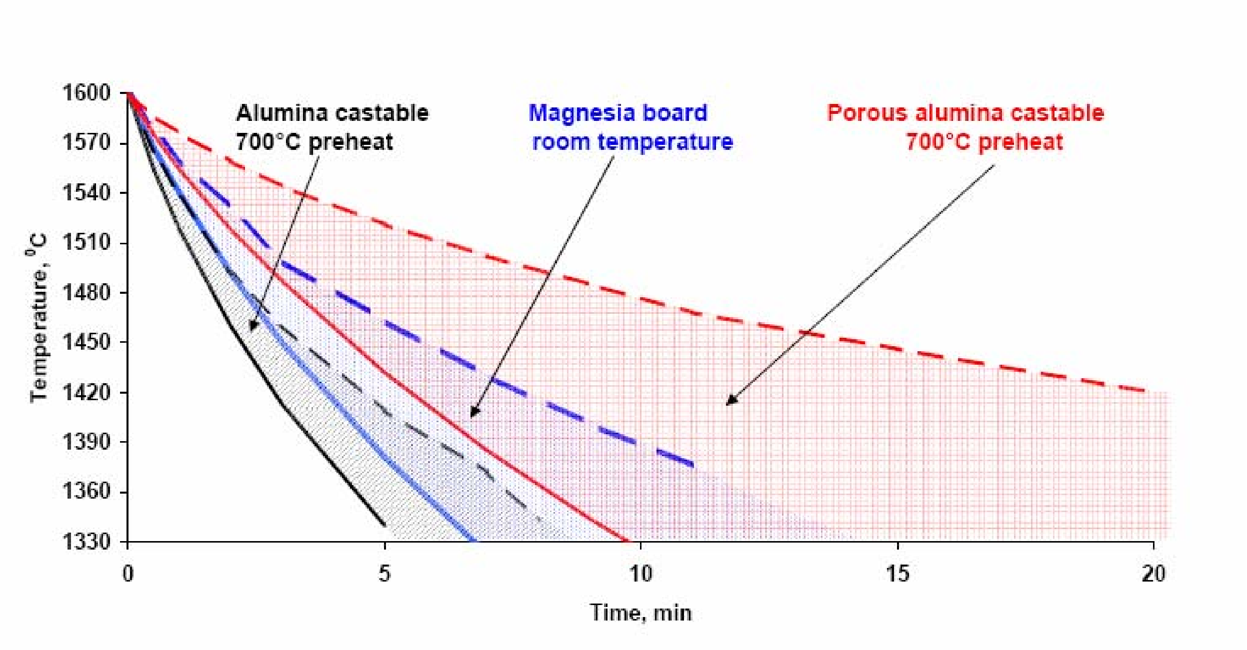


Figure 17. Comparison of melt temperature losses in the ladle with different linings (solid line – open liquid surface and dotted line – no radiation through liquid surface)

Experimental and FLUENT model data give us the possibility to model industrial ladles under different refractory lining and metal handling conditions. For example, Figure 18 illustrates the temperature profiles using the FLUENT model for 1000 lb ladles with an open melt surface covered by a thin layer of slag. In this case, three linings were compared to calculate the required tap temperature to pour after 12 minutes of handling time at a final pouring temperature of 2840°F. A tap temperature of 3275°F was required for a traditional castable alumina lining preheated to at least 1500°F to compensate for the heat losses in the ladle. Low density magnesia boards require a lower tap temperature (3200°F) with less variation in the pour temperature based on differing ladle conditions. The tap temperature could be reduced to 3080°F for similarly constructed castable porous refractory, a significant decrease in temperature due to the reduced energy losses using this new material.

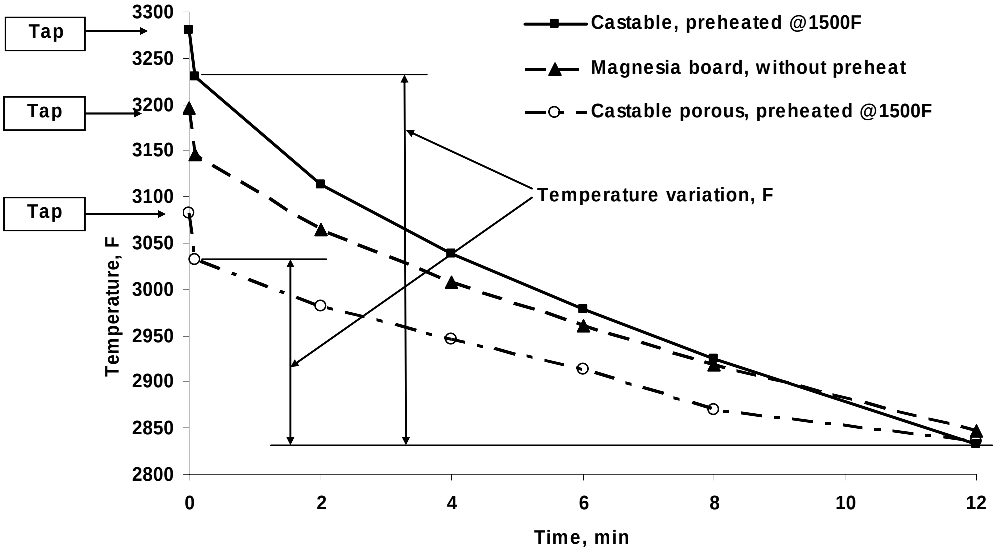


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Figure 18. Comparison of required tap temperatures for aim pour temperature of 2840F at 12 minutes after tap in 1000 lb ladles lined with different refractories (FLUENT model).

5. CONCLUSION

This article summarizes the effects of using different types of ladle lining on the heat and energy losses in melting operations. This paper showed the possibility of significant decreases in the tapping temperature (decreased energy usage) based on using low density porous refractory ceramics in place of traditional castable or low density magnesia linings.

6. ACKNOWLEDGEMENTS

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