ABSTRACT
Thermal insulation in ladles is important in saving thermal energy and optimizing operational cost. Other benefits are to maintain the steel shell temperatures of liquid metal holding vessels under threshold temperatures and reduce steel shell deformation by minimizing thermal mechanical stress. ArcelorMittal Burns Harbor has evaluated insulation materials in the area of steel transfer ladles. The current paper will discuss the benefits of insulation materials during service. The wear mechanisms and failure behaviors will be also reviewed.

1. INTRODUCTION
The modern steel ladle has been evolved from liquid holding vessel to liquid metal processing unit since continuous casting was implemented in the 1980’s. Until the 1970’s, the ingot casting only required very short residence time of liquid metal in steel ladle. Continuous casting in the 1980’s has significantly changed the steel ladle process. Processing time increases significantly with other metallurgical operations.

The evolution of steelmaking processes drove refractory developments. Fireclay bricks were developed into high alumina brick, and later into graphite containing refractories. Graphite containing refractory bricks improved the steel ladle life significantly. However, graphite containing refractory with longer processing time increased the ladle steel shell temperatures further. Higher shell temperatures increase thermal mechanical stress in the steel shell which often leads to deformation. Long-term exposures above the critical temperature form cracks in steel shell. To countermeasure these problems, the steel shell temperatures need to be reduced. Several attempts have been made to implement the use of insulation materials between ladle steel shell and safety lining. The current paper will discuss the key factors of insulation materials, benefit, and failure behaviors.

2. THINGS TO CONSIDER
2.1. THERMAL CHARACTERISTICS
The important material properties of insulation materials are thermal behaviors at elevated temperatures. In order to have low thermal conductivity, most of insulation materials show higher porosities and lower mechanical strength comparing to conventional safety lining materials. Without understanding of high temperature properties of insulation materials, it would encounter premature failure in ladle applications. The steel ladle experiences severe thermal cycling. When the ladle full of liquid steel is lifted, the steel shell will be flexed. This steel flexing also creates the friction between steel shell and insulation materials. When liquid metal is in the holding vessels, the ferrostatic pressure will also be transmitted to the insulation materials. Understanding thermo-mechanical properties of insulation materials is essential to obtain the best return on investment. Only the results for rigid boards are therefore reported here.

Fig.1 Linear expansion of insulation materials without load at elevated temperatures
Fig. 1 shows the thermal behavior of insulation materials without load at elevated temperatures. Insulation materials slightly expand up to 900°C and start to shrink beyond 900°C. It appears that most insulation materials maintain stability without significant shrinkage until 900°C.

However, applying load significantly changes the thermal behaviors of insulation materials. Linear variation under load is shown in Fig. 2. All insulation materials show significant shrinkage behavior beyond 650-800°C, which is much lower than the linear change without load. These results indicate that each insulation material behaves differently under load at elevated temperatures.

Insulation A starts to shrink gradually from 600°C to 950°C and shrinks rapidly beyond 950°C. Insulation B maintains stability until 700°C. Insulation C shows slight shrinkage at 300°C and maintains integrity until 900°C. Insulation D shrinks very little at 200°C and maintains integrity up to 820°C. For example, if the interface between safety lining and insulation material often reaches ~800°C, insulation B and D should be avoided to prevent catastrophic shrinkage. Insulation C would be preferred because it maintains integrity until 900°C with 0.8% shrinkage.

The conditions in service are however quite different from the testing conditions. The tested samples are thermally fully soaked in the furnace. The hot face of the insulation layer can actually be subject to a higher temperature in service without jeopardizing the integrity of the insulation material.

The interface temperature between safety lining brick and insulation board needs to be evaluated prior to application. An important point is that thickness of insulation materials should be designed not to exceed critical shrinkage temperature in the worst case scenario of worn linings. An example of thermal profiles calculated in steady state conditions for the non-insulated and the insulated linings is shown in Fig. 3.

![Linear variation under load](image)

Fig. 2 Linear expansion of insulation materials under load at elevated temperatures

Selecting right insulation material and thickness is the key to successfully use insulation materials.

2.2. LADLE SHELL DESIGN & CONDITIONS

The ladle design and conditions impact the performance of insulation materials. Old ladle with deformed ladle shell made it difficult to install insulation materials properly, which often crack the insulation materials prematurely. The relatively new ladle is recommended to make the best use of insulation material. The ladle shapes are also important to be considered. For example, the ob-round shape ladle designs are often used to increase the steel ladle capacity without changing crane design. The ob-round ladle shape makes it more flexing in the junction of round and straight ladle shell. If excessive ladle shell flexing is observed, the ladle needs to be reinforced by stiffener prior to application.\(^{(1)}\)
2.3. LINING STABILITY
The performance of a ladle lining in terms of number of heats at tear-out is a function of several properties of the refractory materials including, but not limited to, their physical and thermo-mechanical properties \(^{(2)}\). The stability and integrity of the lining depend on the different refractory layers and on their interactions. The addition of a rigid insulation board as a new layer has to enhance the stability of the lining to be successful. Insulation C used in this study presents a well-balanced stiffness/elasticity ratio and a good compromise between the thermal conductivity and the thermo-mechanical properties required for such application. It exhibits a resilient behavior and maintains its elasticity under cyclic loads up to 7MPa \(^{(3)}\). Such characteristic allows the material to relax back when a lower loading is applied which definitely helps for a better stability of the safety lining till the end of its campaign.

A thermo-mechanical simulation run with a ladle configuration similar to this study shows that insulation C actually introduces an additional expansion allowance \(^{(4)}\). The lower shell temperature also reduces the risks of shell deformation from the early stage of the preheating period till the end of the lining campaign. The working lining benefits from the use of the insulation board with lower circumferential compressive stresses and lower plastic strain at the hot face during service. The insulated lining is tighter in service and more compliant with lower tensile failure at the hot face. A more uniform closure of the brick joints and lower risk of joint opening in the different layers during multiple thermal cycles are expected through the whole lining thickness \(^{(5)}\).

3. RESULTS AND DISCUSSION
3.1. INITIAL IMPLEMENTATION
The primary reason to use an insulation material in the steel ladle was the shell temperature range. A temperature higher than the maximum service temperature of the shell steel grade is considered as a major safety issue because of the potential formation of hot spots and of the high risk of ladle breakout. High shell temperature is also a source of extra maintenance to control the shell integrity. The life of the working lining brick in the non-insulated lining was limited to avoid excessive temperatures in worn conditions. The ladle capacity was then limited by the minimum thickness required to reduce the heat loss and the minimum freeboard height required by the process.

For this study, 12.7mm thick insulation C was added between the shell and the safety lining. This addition was compensated by a thinner safety lining brick, from 76 to 63mm. Shell temperatures were measured with a thermal camera at different locations of insulated and non-insulated ladles at the casting station, as shown in Fig.4. The residence time to this process stage is always longer than 90min.

![Fig.4 Example of thermal images used to evaluate shell temperatures. Left side: non-insulated ladle. Right side: insulated ladle.](image)

The addition of insulation C significantly decreased the shell temperature from 324°C±24°C \((n=16)\) to 276°C±12°C \((n=14)\) \((t\text{-test}, \ p=3.10^{-7}<0.05\), as shown in Fig.5.

![Fig.5 Example of shell temperature values for insulated and non-insulated ladles.](image)

The average reduction of the shell temperature is 48°C with a standard deviation...
cut in half. A lower dispersion of the shell temperatures is an indication of a more stable and more predictable process.

The maximum shell temperatures measured on non-insulated and insulated ladles were 367°C and 293°C respectively. The reduction in shell temperature allowed for improvements on refractory practices and productivity increase. The reduction of the overall refractory lining thickness was the first logical step to increase the capacity and/or freeboard height.

3.2. REDUCTION OF LINING THICKNESS

Further to the confirmation of the stability of the thinner safety lining, the thickness of working lining brick for the barrel area was reduced from 152mm to 127mm as shown in Fig.6. The total thickness for the barrel area was decreased from 241mm to 216mm. The total lining thickness for the slagzone area was unchanged.

The thickness reduction led to a 29°C increase in shell temperature with 305°C ±13.6°C (n=49) (t-test, p=1.10^-9<0.05) (cf. Fig.7). The shell temperature was still well below the maximum service temperature of the shell steel grade. The temperature at the hot face of the rigid board was below its maximum service temperature. The shell temperature of a non-insulated ladle with a reduced lining thickness was significantly higher, with temperatures ranging between 381°C and 394°C, above the recommended service temperature of the shell material.

3.3. BENEFITS FOR THE PRODUCTIVITY AND THE METALLURGICAL TREATMENT

The most evident benefit of adding the insulation material was the ladle capacity increase. The overall reduction of 13% of the lining thickness represents a capacity increase and an equivalent productivity increase over 3%. This directly implies a lower cost per cast ton for the ladle refractories in addition to the lower cost for the thinner safety lining brick, the brick life and gunning maintenance being the same as before. Thanks to the confirmed
heat loss reduction, further benefits are related to process improvements, energy savings and environmental impact.

The heat loss calculation shows a theoretical reduction of the conduction through the wall of 13% between the initial and final configurations of the refractory lining. An energy balance model of the ladle vessel was performed to confirm the reduction of the temperature drop rate of the molten steel during the whole metallurgical process cycle. The model is based on the specific operation conditions for the different stations of the process and the transfers between the stations (cf. Fig.8).

![Fig.8 Overview of the process cycle used for the energy balance model.](image)

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From the energy model and in-plant measurements, the temperature savings for the molten steel in the ladle from tap to end of casting are over 7°C. Different opportunities are then available to optimize the process. For example, these temperature savings can be distributed to save energy and heating time at the converter or treatment station, to reduce the tap temperature or to have more flexibility for the hot metal to scrap ratio at the converter. The temperature savings can also be converted into a larger Carbon to Aluminum ratio used as primary de-oxidants at the BOF to reduce the raw material costs, since the temperature loss during tapping is larger with carbon (6).

The benefits of a full distribution of the temperature savings to the Ladle Treatment Station are related to the economic savings, the flexibility of the process and the final quality of the cast products. A 7°C lower exit temperature represents a potential reduction of 25% for the Aluminum weight added as exothermic de-oxidant. The actual reduction has to take into account the Aluminum content required for the metallurgical process. Fig.9 shows the Al-O equilibrium for 1600°C and 1593°C. The lower treatment temperature can either be used to reduce the dissolved Oxygen content in the steel for a constant soluble Al content (horizontal arrow), or to reach a lower soluble Al content for a constant dissolved Oxygen content (vertical arrow). In the current operation conditions, it represents respectively a 9% reduction of the dissolved Oxygen content or a 13% reduction of the soluble Al content at the end of treatment. This flexibility can be applied to more complex systems with additional elements used as de-oxidants.

![Fig.9 Variation of the O dissolved in steel vs. soluble Al from a 7°C reduction of the molten steel temperature.](image)

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In terms of steel cleanliness, any reduction of the soluble Al content represents an opportunity to dramatically reduce the Alumina clogging at the caster and the non-metallic inclusion counts. For the environmental impact, a lower Al addition will also reduce the CO₂ gas generated at the ladle treatment station.

Finally, a lower reheating requirement means a potential shorter time of treatment at the ladle station. Assuming a 10°C/min for the reheating rate, the 7°C temperature savings are equivalent to an extra 1.5% of productivity increase.

4. CONCLUSIONS

The rigid board selected as the insulation material for steel ladle significantly contributed to the performance of the refractory lining and safer operations with dramatically lower shell
temperatures. The board definitely improved the thermal resistance of the lining resulting in a more stable and predictable process thanks to steady thermo-mechanical and physical properties over its full life. However steel ladle application requires preliminary precautions such as the control of the thermo-mechanical behavior at service temperature.

The benefits of the heat loss reduction were firstly applied to the significant increase of the ladle capacity and productivity. The remaining temperature savings allowed for process improvements and operations flexibility.

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