# A techno-economic balance for zonal

The selection of refractory lining design and installation of targeted high-wear areas of torpedo ladle lining using innovative techniques have doubled the life of torpedo ladles to 2,500 cycles equating to the transport of 775kt hot metal per ladle before relining. This is the first step in the direction of endless lining in torpedo ladles, argues **RB Gupta***

**Abstract**
A fleet of 12 refractory-lined, steel torpedo ladles are used by the Rourkela Steel Plant to transport molten metal from Blast Furnace No 5 to steel melt shop No 2 (SMS-II). These torpedo ladles have a 350t capacity and can maintain the metal in a molten state ready for charging the BOF converters for up to 22 hrs. The refractory linings in the torpedo ladles have to be replaced periodically. Previously, the lining life was 1100 – 1200 cycles after carrying 300 to 350kt of iron. This required critical transport capacity to be removed from the process flow during relining.

To improve life, a zonal lining development group was formed which introduced an innovative 'window' repair programme. Here, zoning of areas of excessive refractory wear was undertaken and repairs to these regions executed either by using higher grade refractories or, in some cases, by increasing refractory thickness. New repair technologies were incorporated and the cumulative effect of all these factors has seen torpedo lining life extend to carrying 600kt of hot metal and life is still growing.

Innovative repair methods include coating a new lining with a compound developed in-house which prevents the lining from oxidation during pre-heating. Inspections are conducted to monitor the shell temperature, by visual inspection of the lining; and by tracking the tonnes carried since the previous lining repair. Thermo-graphic readings are recorded each week and allow partial window repairs in specific areas to extend the life of the torpedo lining in a balanced manner.

| Refractory Materials | Slag zone | Impact pad | Barrel | Cone | End disc |
|---|---|---|---|---|---|
| Safety 1, Insulation | 50mm | 50mm | 50mm | 50mm | 50mm |
| Safety 2, 42% Alumina | 90mm | 90mm | 90mm | 90mm | 90mm |
| Safety 3, 50% castable | 20mm | 20mm | 20mm | 20mm | 20mm |
| **Wear-out lining** | | | | | |
| Alumina-silicon Carbide-Carbon | 270mm | 410mm<br>375mm | 340mm<br>305mm<br>320mm<br>283mm<br>245mm | 340mm | 340mm |
| Mouth Y Anchors (LCC-90 with steel fire) | 325mm<br>350mm | AISI - 310<br>AISI - 310 | | | |

Table 1 Current refractory practice of torpedo ladles at Rourkela Steel Plant

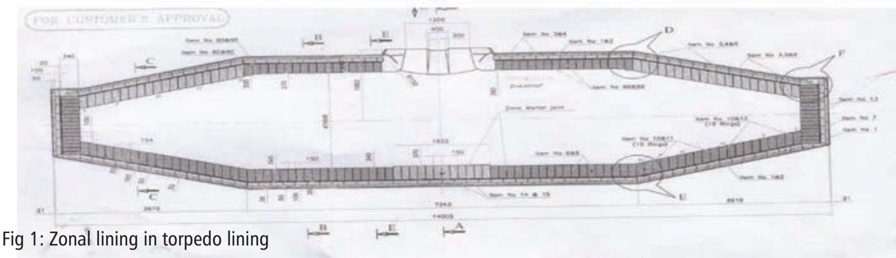

Fig 1: Zonal lining in torpedo lining

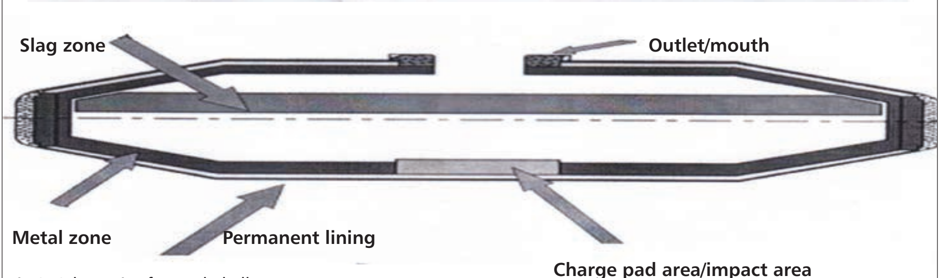


Fig 2: Schematic of torpedo ladle

These practices have almost doubled the lining life to over 2,122 cycles to date and in future the life is expected to reach over 2,500 cycles or 775kt of hot metal transported.

In India, most integrated steel plants have either been modernised or are in the process of modernisation to increase capacity and productivity while reducing costs. The capacity of the various units such as blast furnaces, steel plant (BOFs), mills and so on, has increased considerably. The previous open top ladles to transport hot metal from the blast furnaces to the steel shops have been replaced by large capacity torpedo ladles. Torpedo ladles are not just

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# lining of Torpedo ladles at Rourkela

a means of transporting hot metal, they also acts as reaction vessels, for example for desulphurisation. This has placed an additional severe strain on the refractory lining, calling for customised refractory engineering solutions, operating practices and new managerial tools.

At Rourkela Steel Plant, Blast Furnace No 5 has an annual capacity of 2.8Mt. A fleet of 12 torpedo ladles, each with a capacity of 350t, transport the molten metal to the steel shop. To improve the life of the refractory lining of these ladles a state-of-the art lining design was developed using two types of zonal lining targeting refractory quality and lining thickness. Both methods are presently in use. The current refractory practice is summarised in **Table 1**.

Each torpedo ladle is lined with Alumina-Silicon Carbide-Carbon refractories. Zonal lining, according to thickness in various parts of torpedo ladle, is shown in **Fig 1**. Each vessel averages 3.3 cycles/day in 7.5 hr/cycles. The cycle begins at the blast furnace where the liquid metal is poured into the torpedo ladle. The hot metal resides in the ladle for approximately 4.3 hours for transportation and pouring. On reaching Steel Melting Shop No 2, the vessel is emptied into a transfer ladle for BOF charging. The empty torpedo car returns to the blast furnace cast house for the next charge. During transfer in the loaded condition, the temperature of the steel shell is recorded at various points using laser guns to estimate the amount of refractory wear at these points.

The main objective of the present work was to enhance refractory lining life from 276kt to more than 650kt of hot metal transported without losing sight of safety, quality, cost and the minimum availability of 10 torpedo cars out of 12.

| Sl. No. | Description | Unit | Value |
|---|---|---|---|
| 1 | $Al_2O_3$ min. | % | 70 |
| 2 | $Fe_2O_3$ max. | % | 0.9 |
| 3 | Carbon min. | % | 10 |
| 4 | SiC | % | 6 to 7 |
| 5 | Bulk Density, min. | gm/cc | 2.70 |
| 6 | Apparent Porosity, max. | % | 6 |
| 7 | Cold crushing strength, min. | kg/cm2 | 550 |
| 8 | Permanent linear change after reheating at 15,000C for 2 hrs., max | % | 0 to 0.6 |
| 9 | Refractoriness, min. | 0C | 1835 |
| 10 | Refractoriness under load at 2 kg.cm$^2$, min, ta | 0C | 1700 |
| 11 | Thermal expansion at 1000$^0$C, max. | % | 0.7 |
| 12 | Type of bonding | Resin | |
| 13 | Dimensional tolerance : + 1.5% or + 2.0mm whichever is greater | | |

Areas of application: Working layer; impact pad, area adjacent to impact pad, slag zone and end wall
(a) High Alumina-Silicon Carbide-Carbon bricks

| Sl. No. | Description | Unit | Value |
|---|---|---|---|
| 1 | $Al_2O_3$ min | % | 84 |
| 2 | $Fe_2O_3$ max | % | 2.0 |
| 3 | Bulk Density, min | gm/cc | 2.75 |
| 4 | Apparent Porosity, max | % | 21 |
| 5 | Cold crushing strength, min | Kg/cm2 | 500 |
| 6 | Permanent linear change after reheating at 1500$^0$C for 2 hr, max | % | + 0.3 |
| 7 | Refractoriness, min | 0C | 1835 |
| 8 | Refractoriness under load at 2 kg.cm$^2$, min, t/annum | 0C | 1540 |
| 9 | Spalling resistance, min (Air Quenching method) | Cycles | 30 |
| 10 | Reversible Thermal expansion at 15000C, max. | % | 1.1 |
| 11 | Dimensional tolerance : + 1.5% or + 2.0mm whichever is greater | | |

Area of application: Working layer of torpedo ladle – non slag zone area and free board.
(b) High Alumina (84% $Al_2O_3$) bricks

Table 2 Specifications of wear-out lining of torpedo ladles as used at RSP

## Stresses in key zones

Key areas in the torpedo ladle when used to transport hot metal are the impact area, metal zone, slag zone, roof and mouth area. The stresses experienced in these regions are:

- Impact Area: This is located on the base of the ladle and is subjected to extreme mechanical stress. The iron stream impacts directly onto the refractory during the filling operation. The impact force depends mainly on the height from which the metal stream falls and on the amount of iron tapped. Erosion during filling also depends on the capacity and geometrical design of the torpedo ladle. The impact area is also subjected to thermal stresses caused by the high temperature of molten metal and by thermal cycling. Additionally, chemical stresses prevail in the impact area due to the influence of metal and slag composition.
- Metal Zone: This area remains in contact with the molten iron both during any metallurgical pre-treatment and during transport and subsequent emptying at the steel shop. This area is subjected to stress caused by the weight of the molten iron and these are particularly prominent during filling and emptying the torpedo. This area is also subjected to chemical stress due to the influence of the chemistry of the hot metal and in-ladle metallurgical treatments.
- Slag Zone: The slag zone remains above the metal line and contains a reactive and aggressive slag. This area is subjected to chemical stress due to the corrosion by the slag. The slag line condition is extremely severe during any pre-treatment processes and during emptying of the vessel due to fluctuation of slag basicity and flux injection.
- Roof: This is also called ‘free

| Operational Parameter (Controlling item) | Specific Value Target | Average 2015-16 |
|---|---|---|
| Hot metal total output from BF-V | + 2.8Mt / year | |
| • No. of torpedo ladles | 12 | |
| • Capacity of torpedo ladle | 350t -420t(Worn lining) | |
| • Operation cycle per day | 3.33 | |
| • No. of torpedo in circulation at any point of time | >10 | |
| • Refractory maintenance (repair) | 1 | |
| • Refractory + Mechanical | 1 | |
| Torpedo Ladle dimensions | Height – 46650mm, Width – 3758mm | |
| Hot metal transport / run | 315 – 365t | |
| Tilting angle | Normal + 1200 / max. 3600 | |
| **Hot Metal Quality** | | |
| Temperature (0C) | 1472 – 1499 / 1515 + 15.3 | |
| Si (%) | 0.40 – 0.69 | |
| S (%) | 0.28 – 0.31 | |
| FeO | 0.43 – 0.51 | |
| Basicity | 0.93 – 0.98 | |

Table 3 Torpedo ladles operational conditions at Rourkela Steel Plant

board'. The roof is subjected to severe stresses with regard to thermal and thermo-mechanical conditions.

- Mouth Area: This area is subjected to mechanical stress in the form of abrasion due to the flow of the entire quantity of molten metal. This area is also subjected to thermal stress due to temperature cycling during and after emptying of the molten iron.

**Wear mechanism & material selection**

For the first time within SAIL, a complete lining design along with refractory supply, application and supervision was introduced. Accordingly, at the project stage, torpedo ladles were relined with key zonal wear areas given increased thickness using Alumina-Silicon Carbide-Carbon refractory as the wear out lining in all the zones, and a 90% Alumina ultralow cement castable at the locking portion and in the mouth area. The details are given in **Table 2**. The main reason Al2O3-SiC-C bricks were chosen is their superiority in terms of corrosion resistance and thermal spalling resistance. The first ladle was removed from service after handling 276kt of hot metal. This was the first of several ladles using the revised lining method and was taken out of service after 1,122 cycles. Thus it showed no increase in life over the conventionally lined ladles.

As a first step toward attaining an extended life a study was conducted to identify wear mechanisms and introduce innovative repair techniques to extend torpedo ladle life and thus minimise refractory cost, and also increase the availability of the 10 torpedo ladles throughout the year without losing any hot metal. **Table 3** summarises torpedo ladle operations at the Rourkela Steel Plant.

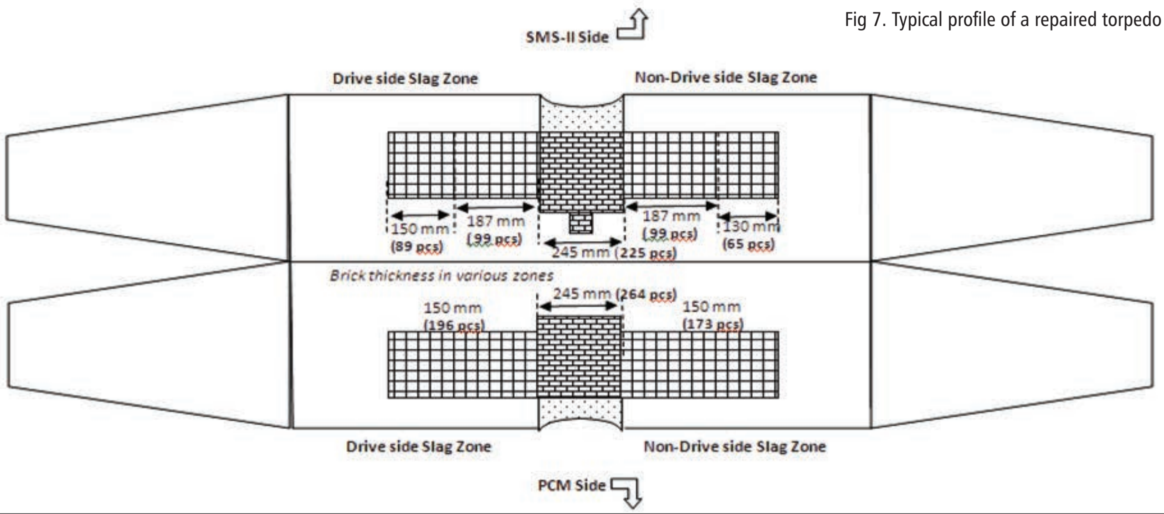



Fig 7. Typical profile of a repaired torpedo ladle

| Before windows & metal heel concept implemented | | | | | After window repair & metal heel concept implemented | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ladle No. | 1st Rep. | 2nd Rep. | 3rd Rep. | Final | Ladle No. | 1st Rep. | 2nd Rep. | 3rd Rep. | 4th Rep. | Life on Impact Pad (Final life also) |
| 5 | 327 | 693 | 948 | 1122 | 4 | 572 | 777 | 1256 | 1731 | 1995 |
| 9 | 548 | 702 | 950 | 1311 | 7 | 576 | 853 | 1379 | 1704 | 2034 |
| All repairs in slag zone & upper free board area and in the locking portion. | | | | | 1 | 431 | 939 | 1456 | 1800 | 1957 |
| | | | | | 3 | 659 | 1157 | 1491 | 1649 | 1889 |
| | | | | | 6 | 262 | 680 | 1200 | 1488 | 2122 |
| | | | | | 8 | 317 | 683 | 902 | 1399 | 1720 |
| | | | | | In all above ladles bottom impact was never charged or repaired even after campaign life. Remaining thickness > 80 – 95mm even after highest life of 2122 cycles (657820tHM) | | | | | |
| Avg life ⟶ 1216.5 cycles | | | | | Avg life ⟶ 1952.83 cycles | | | | | |

Table 6: Torpedo ladle refractory life before and after window repair along with metal heel practice

| Cycles | 350-450 | 450-600 | 950-1000 | 1325-1650 | 1650-1750 | 1750-2200 | 2200-2600 |
|---|---|---|---|---|---|---|---|
| New lining | LR | 1st GR | 2nd GR Mid Life | 3rd GR | LR | End of campaign | Future Life |

LR = Localised repair – GR = General repair

Fig. A: RSP Torpedo Ladle service life plan

## Monitoring wear profile

For geometric and thermal reasons, visual inspection of the refractory lining wear profile is poor and difficult and is restricted to the area close to the mouth at the central region. For visual inspection, the barrel portion only is visible. A lack of proper inspection may seriously jeopardise operating safety. If hot metal leaks from a torpedo ladle, catastrophic consequences may ensue to the blast furnace or steel shop facilities.

Improved visual lining inspection procedures were instigated when the torpedo ladle was cold during maintenance, and employed thermal imaging during operating for hot inspection. In addition to ensuring operational safety as a primary function, monitoring the wear profile closely is a techno-refractory-management tool, which enables continuous optimisation of lining design with a view to enhancing service life while reducing maintenance cost.

## Metal heel practice

The erosion rate of the impact area is the highest among all of the torpedo refractory. To prevent metal break-out from this area in most steel plants the torpedo ladles are cooled to room temperature and inspected after a fixed quantity of molten metal has been transported (450 – 500 cycles). The impact zone is repaired or relined as necessitated by the result. In RSP's case, the repair of this area is eliminated completely by adopting the 'hot heel' practice. The hot metal from the torpedo is not completely emptied at the steel shop, leaving about 10-15t of hot metal in the bottom at all times. This is drained out completely only when the ladle is put down for mid-life repairs. This hot heel acts as a cushion to the falling stream of molten metal during filling, and consequently the bricks of the impact area never face the impact of the falling stream except when newly relined or repaired. This metal heel practice not only reduces wear in the impact zone, but also lowers thermal fluctuations before filling and after emptying the ladle and so eliminates or reduces due to spalling.

At RSP, the erosion of the impact pad now matches that of the ultimate lining life of 2034 cycles (more than 600kt of hot metal handled).

Wear of the remaining zones of the torpedo ladle refractory takes place due to corrosion of the working lining. This is caused by infiltration of FeO from the slag reacting with refractory components $Al_2O_3$ and $SiO_2$ to form low melting phases of hercynate (mp 1550°C), fayalite (mp 1210°C) and cordierite (mp 1320°C). Also, CaO in the slag reacts with the alumina-silicate refractory to form low melting compounds such as anorthite (mp 1550°C). Formation of these low melting phases deteriorates the refractory lining. In totality, at RSP, refractory wear in the torpedo ladle is due to this chemical and mechanical erosion, and not because of thermal spalling. The main areas of erosion are the locking portion ie just below the spout (1m x 1m area), part of the slag zone, and the lower free board zone. To take care of this, a novel window repair concept was introduced and so far has been applied successfully to 14 torpedo ladle repairs. Gunning of hot alumina-silicon carbide-carbon bricks is not performed as it increases the spalling tendency of the gunned area.

The metal heel practice along with the window repair concept has increased the refractory life of RSP's torpedo ladles by 60% as shown in **Table 4**.

## Service life plan and repair schedule

Torpedo ladles are repaired when the minimum remaining lining thickness near the most worn out area is down to 80mm in a step-like fashion. Here, bricks of up to 150 – 180mm thick can be laid. A typical ladle service life plan is shown in **Table 5**. A typical profile of a repaired torpedo ladle is shown in **Fig 2**. Normal repair was carried out in the free board, slag zone and in the locking portion. The impact pad did not require any repair even after 2034 cycles. For repairing these areas, special brick shapes were designed and procured. In the absence of shorter brick lengths, longer bricks were cut to size.

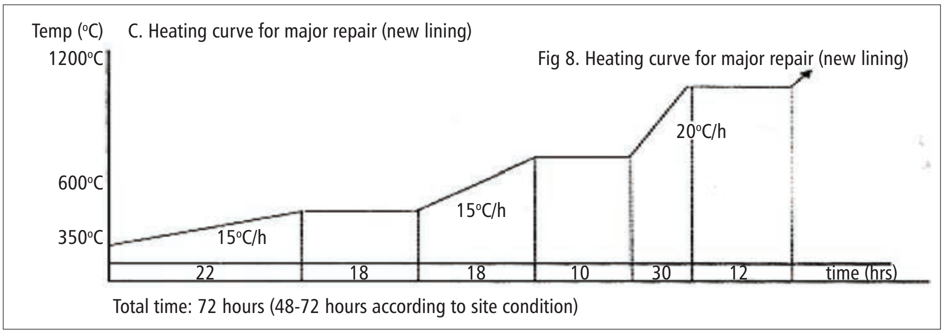
Sometimes localised repairs are carried out in the steel side pouring spout area in the locking area replacing approximately 1m2 of bricks using monolithic casting with the aim of running the torpedo for 30 – 35days (90 – 105 cycles) until the next general repair is due. The Torpedo ladle service life plan at RSP is shown in **Table**

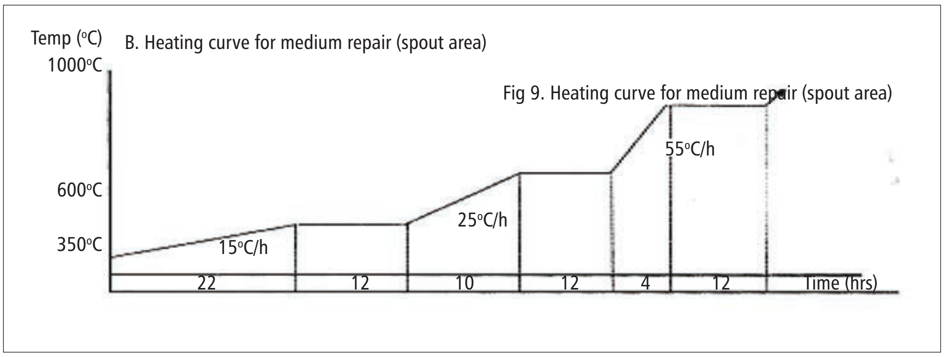
| Type of repair | Duration (day – shift) | Man hours | Material used (t) | Life on such repair | Main reason of early out |
|---|---|---|---|---|---|
| Localised repair (LR) | 8 hrs. | 48 | 1.0 | 100 – 125 | Main/TLC is taken out for Mechanical greasing of boggy & gear |
| General repair (GR) | 3 day cooling<br>3 day working<br>3 days heating | 384 | 4t bricks,<br>10t castables | 350 – 400 | Mechanical work on boggy & gears also takes place |
| Mid-repair | 3 day cooling<br>3 day working<br>3 days heating | 400 | 6t bricks,<br>10t castables | 350 – 400 | |

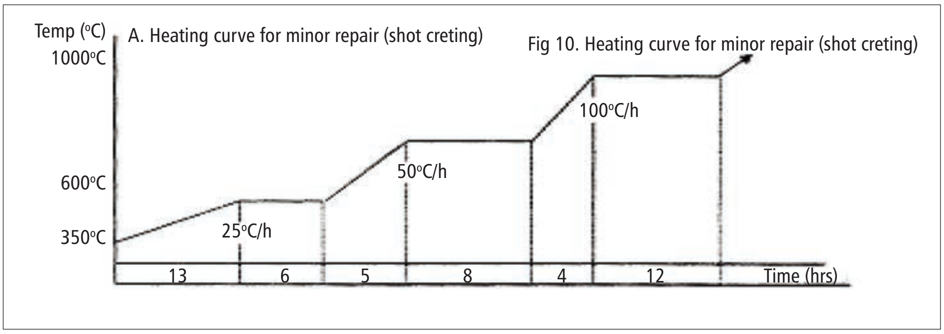
Table 7: RSP Torpedo repair schedule

| Before | | | | After | | | |
|---|---|---|---|---|---|---|---|
| | consumption & cost | | | | consumption & cost | | |
| Avg. life (Cycle) | kg/tHM | Rs./tHM | Rs./Cycle | Avg. life (Cycle) | kg/tHM | Rs./tHM | Rs./Cycle |
| 1100 | 0.41 | 21.99 | 7037.8 | 1916.33 | 0.215 | 11.49 | 4957.39 |

Table 8: Techno-economics of RSP TLC – Refractory lining before & after introduction of window repair & metal heel practice




**5**, with three outages for general repairs plus two local repairs. **Table 6** shows the repair schedule. All mechanical repairs like greasing of the gear box and boggy greasing also done along with refractory repair.

**Techno-economics**

After the introduction of the window repair concept and hot metal heel practice the cost of hot metal handling through the torpedo ladles has fallen nearly 30% as shown in **Table 7**. This has not only reduced cost and refractory consumption, but also enhanced availability.

**New Technologies**

***Modification in heating cycle following repair / new lining:*** This was carried out with the aim of homogeneity in the heat-up of replaced refractory to achieve a constant and uniform removal of water (free and combined) and binding compounds. Uniform temperature distribution with a regular heating rate lessens thermal stresses upon the refractory lining thereby mitigating the number of cracks. Also, uniform heat penetration fosters more favourable conditions for chemical reactions in the lining. This strengthens material properties while reducing thermal shock when hot metal is freshly poured into the repaired torpedo ladle. The modified heating cycles have been shown in **Figs 3-5**.

Sometimes the oxidation of the refractory lining due to a high oxygen potential arises from an excessive amount of combustion air during pre-heating. The carbon refractory material oxidises and this creates fresh pores on the lining surface which are then infiltrated by hot metal and slag. To circumvent this problem a ceramic 'agalmtolife' based coating was developed and applied over the lining prior to pre-heating.

***Online inspection and thermography:*** After 450 cycles all torpedo ladles are emptied and inspected but on a daily basis the spout area, barrel portion, conical adjacent to the barrel and shell temperature


are measured when the torpedo is in the filled condition. The temperature of the shell is measured at the metal zone, bottom, slag zone, conical and free board. At RSP, if the temperature of the torpedo shell exceeds 255°C anywhere there is danger and the ladle is taken out of service within three to four cycles, emptied and placed under a cooler for inspection and repair. Taking the shell temperature on a daily basis and analysing the result provides an assessment of the torpedo refractory lining wear profile. This has proved an excellent supporting tool to assess wear of the lining in a different area and helps in deciding any corrective action necessary.

***Development of new material:*** At present alumina-silicon carbide-carbon bricks are most commonly used for lining torpedo ladles, applying zoning by variation in thickness or in combination with 84% high alumina bricks in non-vulnerable areas. To develop alternative materials and lining designs for the various zones in the torpedo ladles a massive programme was undertaken by refractory shop engineers along with Manishree Refractories Pvt Ltd who supply the torpedo ladle refractories. Thermal spalling resistance is the most common requirement of torpedo ladle refractories. Besides this, zonal requirements for the slag line, corrosion resistance for the metal impact area, abrasion resistance for the free board (ceiling), and oxidation resistance are required. To improve each of these properties research was confined to alumina-silicon carbide-carbon Refractories. These bricks use alumina as the main aggregate to which graphite is added to provide resistance to spalling and slag penetration and the SiC protects the graphite from oxidizing and provides matrix reinforcement.

Two types of alumina were investigated:

- Brown fused alumina
- Bauxite based alumina


## Development of improved refractory

The raw materials used were bauxite, brown fused alumina, silicon carbide, flake graphite, silicon, boron carbide and resin as binder. Test samples were prepared from these materials under ambient temperature, mixing for 30 minutes, and made into test blocks 25mm x 25mm x 125mm and 50mm x 50mm by pressing in a hydraulic press at a pressure of 200MPA. They were coked at 200°C for 24 hrs. The effect of silicon, B4C, Carbon and SiC on the slag corrosion resistance were studied and then commercial production of these bricks was taken up and used for relining torpedo ladles. The effect of these elements is shown in **Figs 6-9**. Following trials it was found that brown fused alumina based materials with a carbon content 10-12%, SiC 7-8%, Si 3 -3.5%, and B4C 0.6% gave an optimum result for the slag line and impact zone. Bauxite based materials were best for other sections with carbon 9 - 10%, SiC – 9-10%, Si - 2%, B4C 0.4% and resin as binder.

## Conclusion

Following the increase in refractory lining after introduction of alumina-silicon carbide-carbon bricks containing 0.4 – 0.6% B4C and the implementation of window repair technology for specific wear zones plus hot heel practice to protect the impact zone, the life of torpedo ladles increased from 1,134 cycles to 2,122 cycles. This made it possible to ensure the availability of 10 to 11 torpedo ladles out of 12 and achieve the daily transport of 8,500t of blast furnace metal to the steel shop.

New refractory materials were developed with 0.4 – 0.6% B4C to improve oxidation resistance at a range of temperatures and a graphite and SiC increase improved slag erosion resistance. ■

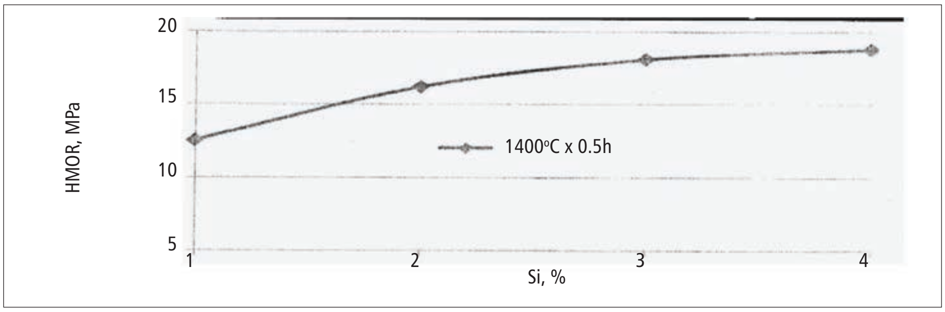



Fig 11. Relation between silicon addition and HMOR

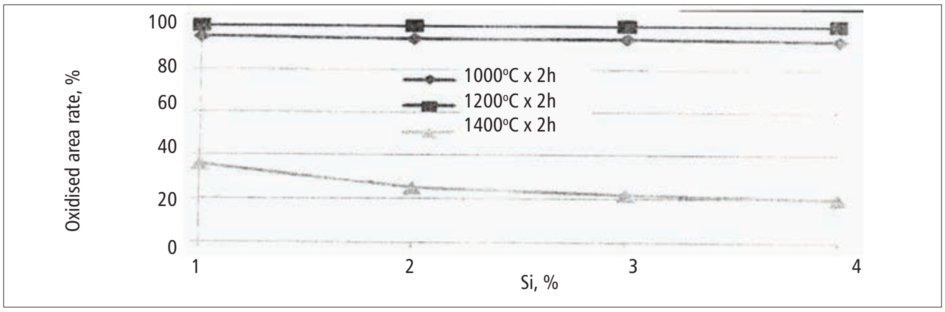



Fig 12. Relation between Si addition and oxidised area rate

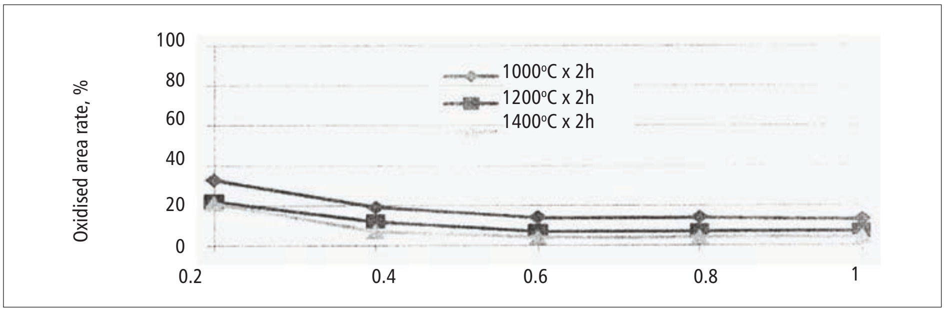



Fig 13. Relation between B4C and oxidised area rate

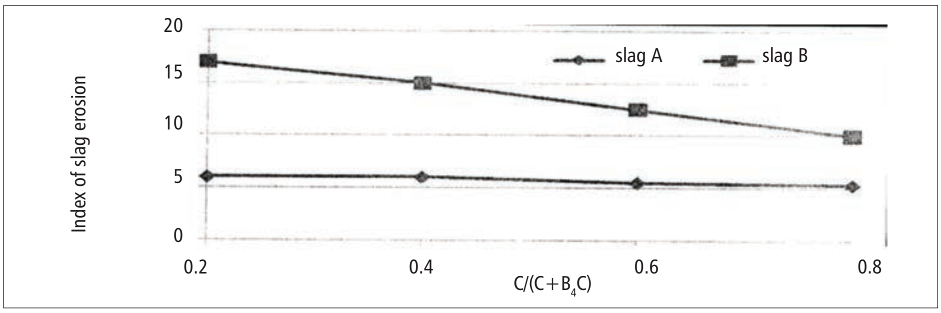



Fig 14. Relation between $C/(C+B_4C)$ and index of slag corrosion

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