A FINANCIAL MODEL FOR INVESTMENT IN HEARTH TECHNOLOGY[1]

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Abstract
As steelmaking companies and countries develop plans for expansion and improvement, investment in proven technologies to reduce operating cost or increase efficiency will be a major part of those plans. There are many such investments available today in the blast furnace area, including raw material charging, hot blast stoves, cast house design, coal injection, etc. If designed, installed, operated, and maintained correctly, these technologies have the opportunity to provide excellent returns on the investment. The blast furnace hearth has long been considered one of the most critical areas of the furnace. In recent years, new techniques for repairing and extending the useful life of the bosh, stack, furnace top, cast house, and other peripheral equipment have been developed that require at most only short stops. The hearth, however, remains as the one area that requires a costly extended stop for significant repair. Many blast furnace operators regard the hearth as the single factor that determines when the furnace must be stopped for full-scale reline or rebuild. Techniques have also been invented to extend the life of the hearth, but they typically have an impact on the operation. Titanium addition, grouting, and reduced productivity can have very large cost and profit effects. These costs are preventable, with the right investment in hearth technology. Unfortunately many operators still do not regard the hearth as an investment, but without a hearth that supports the operating goals of the company (higher productivity, lower operating cost, longer life), all other investments may be wasted and not achieve their desired return. UCAR Carbon Company Inc. has been a leader in the production of carbon and graphite products for more than 100 years. Since developing the freeze lining technology based on their unique Hot Pressed™ Brick process more than 40 years ago, UCAR has the only hearth system that is proven to support higher productivity and lower operating cost. The paper discusses how the hearth must be viewed as an investment, provides a model to calculate the returns, and demonstrates the extraordinary value of the UCAR freeze lining and its importance to the overall investment strategy.

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Introduction

UCAR Refractory Systems, being part of Graftech International Ltd, is the world leader in the carbon and graphite industry because we focus on maximizing our customers' bottom line and providing unparalleled support for their business. From the very beginning of the company in 1886 through today, we have worked in close partnership with our iron making customers by focusing on transforming their need into the best performing refractory solutions available. Technical and service leadership is the foundation for our business. UCAR/Graftech has over 11 manufacturing facilities on 4 continents and serves customers in 70 countries around the globe. In Parma, Ohio, the company owns and operates the largest R&D facility committed to carbon and graphite science in the world. (See Figure 1)

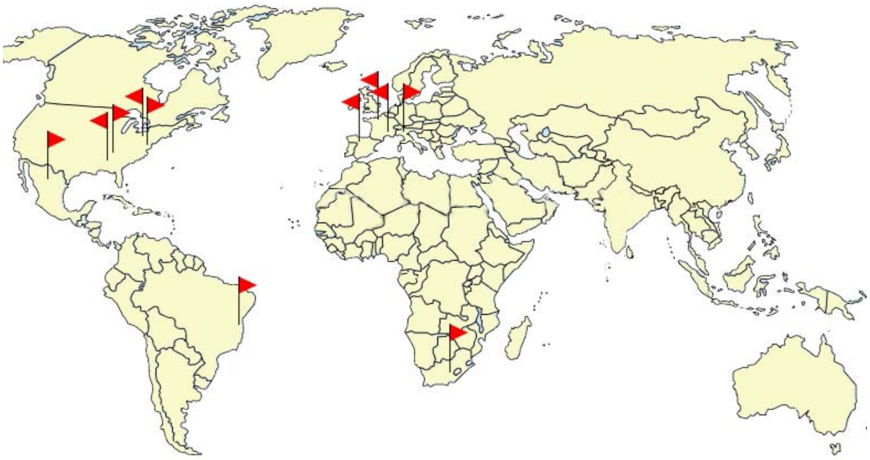

Figure 1 - Graftech manufacturing locations

Since the Hot-Pressed™ micropore carbon and semigraphite bricks forming the UCAR hearth lining were first introduced to blast furnace operators by UCAR, the popularity has increased steadily. This is due to the fact that this hearth lining has proven to be to be a major factor for reliability and safety. While block hearth wall linings are generally designed to wear at a certain rate each year, and the hearth wall dictates the end of the campaign, the UCAR hearth wall is designed to completely prevent wear. This is what differentiates UCAR from the conventional carbon refractory suppliers today.
Iron makers looking to meet aggressive growth targets can, with the help of the financial model described in this paper, conclude that a small savings obtained by purchasing a low cost conventional refractory hearth lining is more than lost over time. The model will facilitate for operators to predict the full value of their hearth refractory lining investment. And as always, the proof is in the results. This paper will include a real life example of a performance comparison between the UCAR hearth lining and typical conventional hearth linings at the famous Baosteel plant in China.

Fundamentals of the UCAR Concept

The UCAR hearth wall concept is based on the fact that all significant hearth wear mechanisms are related to high temperature. Alkali attack only occurs above 800°C; thermal stress is a result of extreme thermal expansion; and erosion occurs when iron contacts the carbon refractory directly for extended periods. Therefore if temperatures can be maintained at a low level, wear is prevented.

There are four key elements of the UCAR hearth wall system (Figure 2, UCAR Concept):

- The wall is thin compared to traditional block designs, typically less than one meter thick, which promotes more efficient heat transfer and lower temperatures at the hot face.
- Small Hot-Pressed™ bricks are used instead of large blocks. Small pieces have small expansion, and hot face rings can expand independently of cold face rings, reducing internal stress. It is NOT recommended to cut small pieces out of a large carbon block and refer to these as “bricks”; the properties of any baked carbon block is well known to vary from one end to the other, and from the center to the surface. Just as a chain is only as strong as its weakest link, all bricks in the hearth wall system must meet the highest standards. The Hot-Pressed™ bricks have superior thermo-mechanical properties, and have proven their superiority in many long furnace hearth campaigns worldwide.

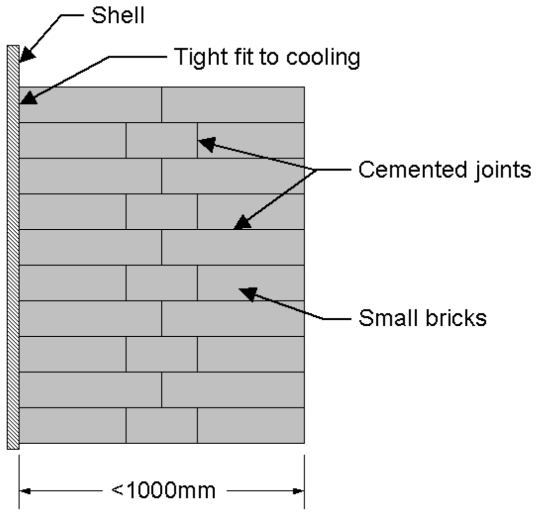

Figure 2 - UCAR Concept Elements

- There is no ramming between the brick rings and the cooling elements (shell or stave). Ramming paste has poor conductivity compared to baked carbon refractories, and it can become dry and granular or separate from the refractory, causing an interruption in heat transfer.
- Carbonaceous cement is used on all brick surfaces to fill the joints, bond bricks together, transfer heat, and most importantly, absorb expansion without creating stress.

When these principles are followed, the hot face temperature of the hearth wall is below the freezing temperature of slag and iron, and a protective skull is formed on the face of the wall. The skull insulates the brick, pushing temperatures even lower, and protects the brick from iron contact and erosion. Figure 3 shows the temperature profile in the block hearth wall; note that the hot face temperature is too high to freeze the protective layer.

Figure 4 shows the temperature profile through the UCAR hearth wall. Note that the refractory temperature is kept below 800(d)C in all locations.

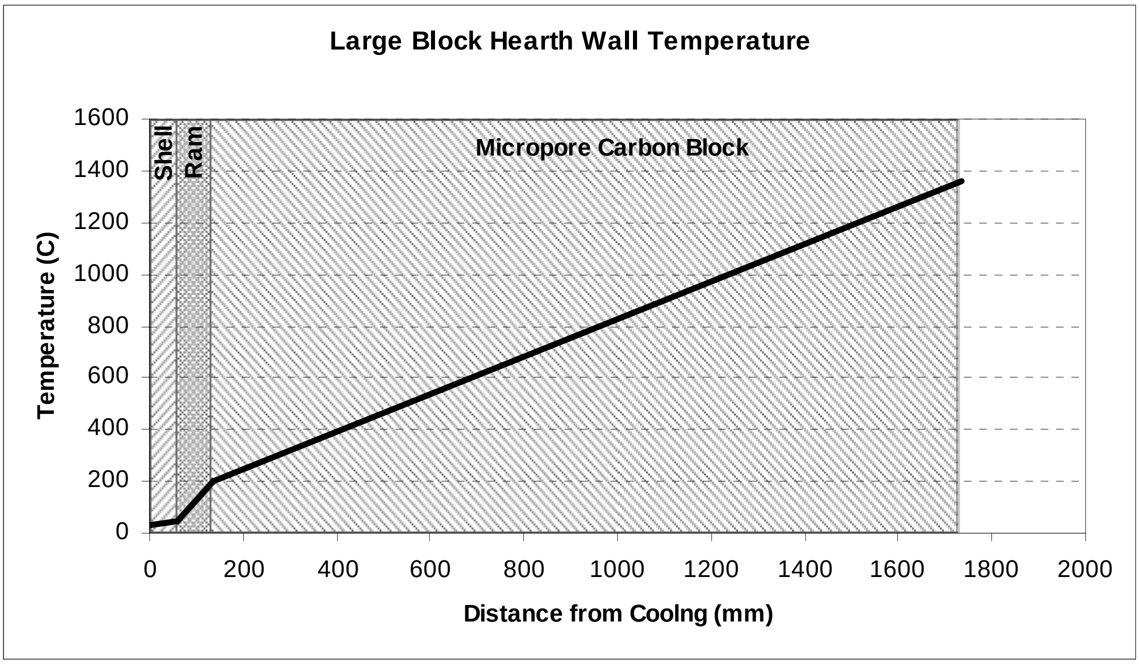

Figure 3 - Block Hearth Wall Temperature Profile

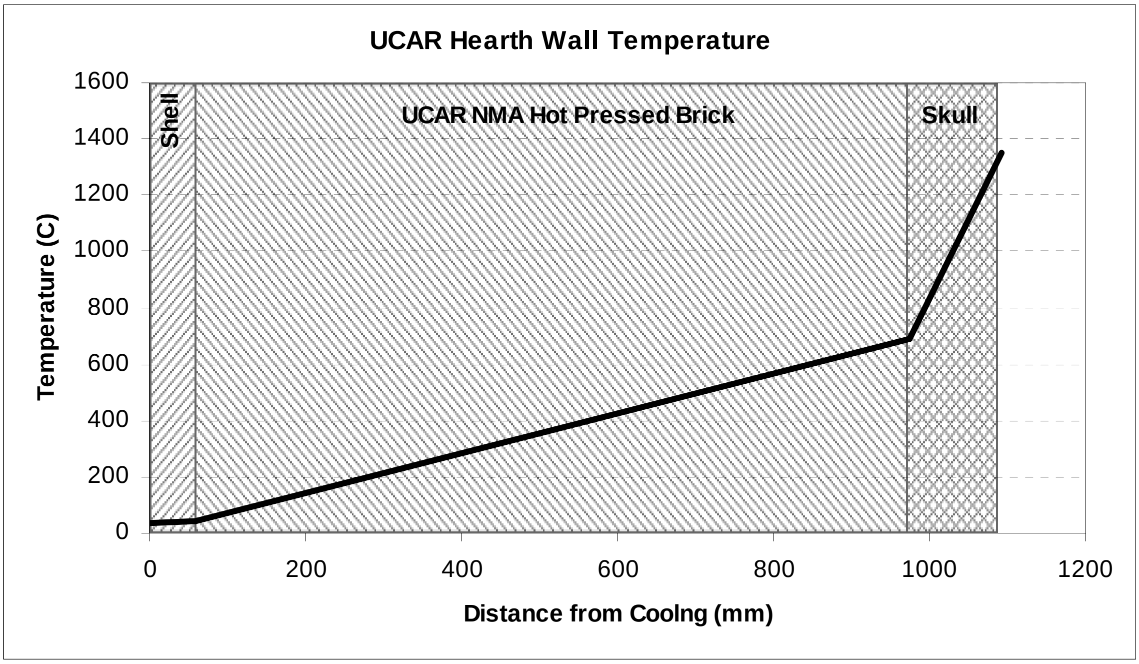

Figure 4 - UCAR Hot Pressed Brick Hearth Wall Temperature Profile

The UCAR hearth lining allows for increased productivity

Owners will commonly invest tens of millions of dollars for faster and more accurate raw material charging, higher hot blast temperature and greater blast volume, coal injection, greater working volume, a better casthouse, etc. It is relatively easy to calculate the benefit of each improvement, and therefore determine whether it provides adequate financial return to justify the investment. In the ironmaking world it is now widely accepted that most of these improvements are worthwhile investments.

For example, one way to increase productivity is to burn the coke faster at the tuyeres and so increase the smelting rate. This can be done in various ways. Increasing the blast volume blown to burn the coke quicker will work, but tends to increase the pressure drop across the furnace. This can result in instability to the process as well as putting strains on the charging system, eroding the designed 50% overcharge capability. Operators thus tend to resist going this path.

However, if extra oxygen for injection is available *with* extra flame temperature coolant, such as coal or steam, this increases the coke burning rate and increases the overcharge as well as the overcharge capacity (in the case of coal), as the coal replaces the extra coke needed.

So in simple terms, more oxygen in the blast furnace and more coal injection at constant flame temperature, results in additional tons from the set working volume of the furnace. Empirical and long term experimentation made at a leading iron maker in Europe shows that it is fully possible to, by the addition of O_2 together with additional coal injection, produce approximately 5% extra iron with unchanged pressure drop.

The production increases achieved can provide the following financial gains for a medium size furnace producing 7,500 tons/day. The additional 375 tons/day will accumulate to approximately 133,000 tons over one year at 97% availability.

A modest contribution to profit can be assumed to be $100/ton. Therefore the increased production results in an additional $13.3 million annual profit for the company. With a typical life of at least 20 years for a furnace with a modern hearth design, the total value of this productivity improvement is over $260 million, *with a net present value of over $113 million*.

However, this very attractive investment, and every other investment in productivity, is wasted if the furnace hearth is not capable of handling the additional tons. The hearth must have sufficient volume for increased iron flow, and must be designed to prevent wear over the lifetime so that higher productivity can be maintained.

When conditions demand increased production, the advantage of the thin and thermally conductive UCAR hearth lining has proven itself. A typical UCAR thin hearth and bottom pad lining offers a hearth volume that is approximately 20% larger than a conventional large carbon block hearth lining. As the conventional carbon block linings are designed to be consumed over the campaign of the furnace, safety has to be built into the system, resulting in very thick refractory hearth walls and therefore a much smaller hearth volume. Because of the larger hearth volume offered by the UCAR lining, it can easily accommodate the extra iron required in the furnace sump.

The UCAR hearth lining also avoids the need for other measures that are typically employed to achieve the planned lifetime of the furnace. With conventional large block hearth walls, practices such as titanium addition, grouting, and reduced productivity are common, but they come with a very large cost that is usually not considered when choosing the hearth design and refractory materials. The need to reduce production to extend hearth life, in particular, can eliminate any value from investments in higher productivity.

Economics of Investing in a Hearth Lining - The Complete Model

The furnace hearth is usually ignored when investing for productivity. Many owners make the mistake of assuming all available hearth refractory designs and products are equal, and basing the purchase decision only on price. Although the hearth itself will not increase productivity directly, as noted above the hearth is a critical part in supporting higher iron production. The wrong choice will prevent gains from being realized (making other improvements wasted), and can even add to operating cost.
Such losses can far outweigh any savings gained in the hearth refractory purchase price. For this reason, a comprehensive financial model is needed to accurately analyze the complete costs and benefits of choosing the technology to be applied to the furnace hearth. In this way the hearth is treated as an investment, and the value of modern hearth technology can be clearly demonstrated.
For the benefit of blast furnace operators, UCAR has developed such a model. Its components include:

- Installation time
- Grouting the hearth wall to improve heat transfer
- Using titanium to protect the hearth wall
- Reducing productivity to reduce heat load

The model shows each component as a direct comparison between the UCAR system and a conventional block system. When the cost of the block system is incurred in the future, i.e., the later part of the operating campaign, the cost is reduced to net present value.
For this paper, each component will be addressed individually, as if all other factors were equal, then all will be modeled together. All examples are based on a mid-sized blast furnace (approximately 3000 m³, producing nominally 7,500 tonnes per day). Conservative assumptions have been made for the paper, but the model is completely interactive, i.e., all inputs can be adjusted to match individual operations.
An example of the entire model can be seen in Appendix A.

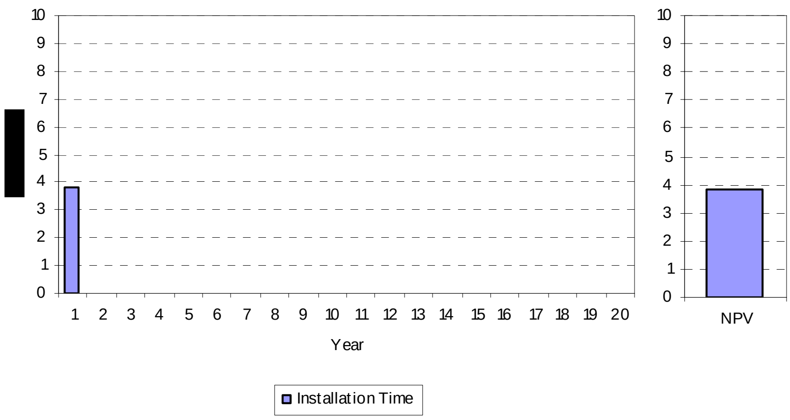

Figure 5 - Faster Installation

Installation Time

Because the UCAR hearth wall system is built from small bricks that can be easily handled and do not require hoists in the furnace to set in place, the wall can be built faster than a conventional block lining. The furnace itself usually determines the critical path of the overall rebuild construction project; therefore any time that can be saved during refractory installation can lead to the furnace starting sooner, and additional iron production.

The model estimates the UCAR brick hearth wall can be installed five days faster than a block wall, an immediate value of $3.8 million (see Figure 5). **This by itself is greater than the entire cost of the hearth wall.** In fact some UCAR customers have justified their purchase on this point alone - the cost of the hearth wall has been paid back as soon as the furnace starts.

But even in cases where the construction schedule is not an issue, the benefits of the UCAR lining are evident, as shown in the following analyses.

Hearth Wall Grouting

The block hearth wall concept depends on the ramming joint to transfer heat between the blocks and the cooling system. Over time the ram can become dry and granular or shrink and develop a gap. In either case, heat transfer is interrupted and refractory temperatures rise, leading to increased cracking, alkali attack, and erosion. A program of regular grouting is often initiated in an attempt to restore heat transfer across the ramming space.

Since the UCAR system does not depend on ramming for heat transfer, grouting is extremely rare and is not done on a programmed basis.

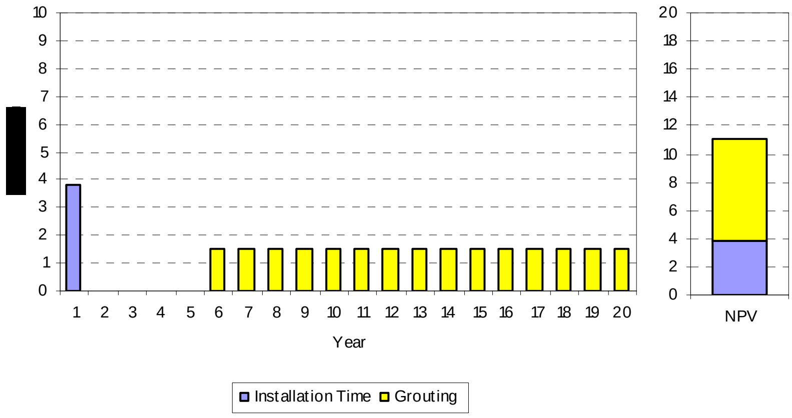

Figure 6 - Installation and Grouting

Grouting is often the first measure taken to protect the block hearth wall because evidence of an air gap is easily seen in most temperature monitoring systems. While some operators begin grouting their block hearth wall as soon as the furnace starts, it is realistic to predict that a grouting program would start after five years[*], and that the furnace is stopped two times per year for one day only for grouting (see Figure 6). Using these parameters, the NPV cost of grouting is $7.2 million, mainly in two days of lost production per year, a cost that is easily avoided by installing the UCAR system.

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[*] In many furnaces around the world, we have seen that “problems” start for the big block linings much earlier than in 10 years. In the last 12 months alone, the blast furnace community has been forced to witness how six (6) major blast furnaces in Europe, using big carbon block hearth linings, have had disaster breakouts requiring emergency repairs and causing tremendous production and financial losses. In three of these cases the hearth walls were less than 8 years old.

Titanium Addition

When erosion begins to consume the block hearth wall, one of the first operator responses is to add titanium-bearing ore (ilmenite) to the burden. In fact some operators begin adding ilmenite at the beginning of the campaign as a precautionary measure.

Not only does ilmenite ore cost more than standard ore, it also requires additional coke, a "double penalty".

This example again assumes ilmenite addition beginning after ten years at a rate of 1.5% of hot metal output. At an estimated cost of $1.28/ton hot metal, the annual cost is almost $3.4 million, and NPV is $8.0 million (Figure 7).

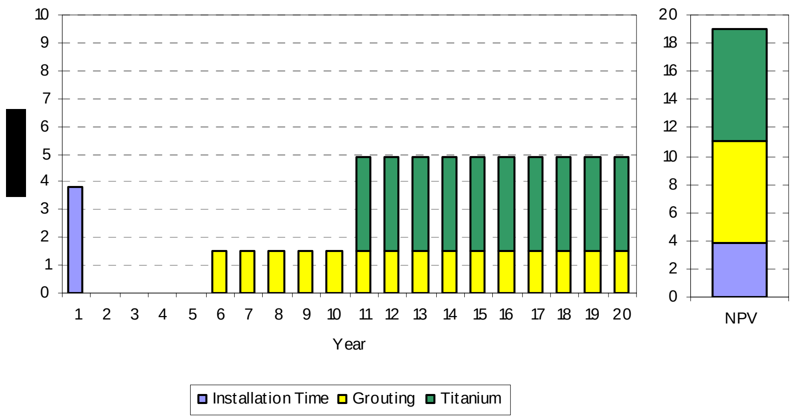

Figure 7 - Installation, Grouting, Titanium

As has been seen so far, the cost of a block hearth wall can be extremely high when the operator is forced to counteract hearth wall erosion with grouting or titanium addition. Next we will discuss the most costly reaction of all, reduced production.

Reduced Productivity

In an effort to reduce heat load on the hearth wall, operators reduce iron production rates by anywhere from 5% to 20%. The measure is generally effective; refractory temperatures drop within a few days, but the operator typically finds that any increase in production drives temperatures back up just as quickly. Therefore the campaign can only continue at reduced production levels.

This cost is extraordinarily high, however. If daily production is reduced only 10%, the annual production lost is 265,000 tons, which represents lost profits of $26.5 million to the company. Again assuming production is reduced after ten years, **NPV is a staggering $63 million** (Figure 8).

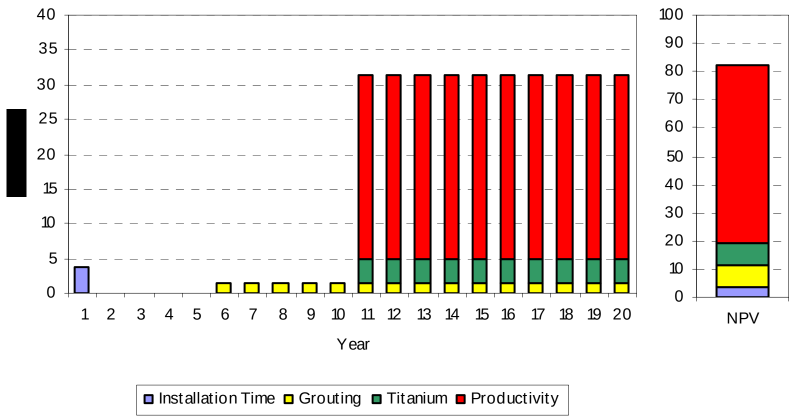

Figure 8 - Installation, Grouting, Titanium, Productivity

In many cases this is more than the entire cost of a reline.
Furnaces utilizing a UCAR brick hearth wall do not typically have to reduce productivity to protect the hearth wall. One of the highest productivity furnaces in the world has been operating more than 22 years since the last reline of the hearth wall. Whereas furnaces using large block hearth wall technology must reduce productivity in later years, this operator has been increasing production consistently since 1984, and they have no plans to stop the furnace for reline.

Combined Effects

It is unlikely that any of these actions will be taken alone. When the furnace starts to show signs of hearth difficulty, operators are likely to take all possible actions to reduce the risk, regardless of the cost.
The various factors are not strictly additive. For example, the effect of titanium use, which is calculated in cost per ton of hot metal, is slightly reduced when production is reduced. Since the reduced production is by far the greatest part of the total cost, and most cost is experienced in later years and thus subject to greater discounting, it is relatively accurate to simply add the four components[**].
The table below summarizes the present value of the cost components:

Component	NPV ($ million)
Installation time	3.8
Grouting	7.2
Titanium	8.0
Reduced production	62.9
Total	**81.8**

All these costs can be avoided with wise investment in the proper hearth technology. Only the UCAR hearth has proven that it can reach long life without requiring extra maintenance and operating cost and reduced productivity. In addition, as shown earlier, there is an opportunity for further productivity improvements that are only possible with the UCAR lining. **The combined Net Present Value over the 20-year lifetime is nearly $195 million.**
Although it may have a marginally higher cost than the hearth lining available from other suppliers, the above figures prove conclusively that the investment in a UCAR hearth lining is extremely worthwhile.

[**] A more accurate year-by-year analysis yields net present value of $80.6 million.

The Proof is in the Results:
The Experience of Different Carbon Refractory Lining Concepts at Baosteel

In 1990 Baosteel, the largest steel producer in the People's Republic of China, had three blast furnaces in operation. All the furnaces had identical cooling designs in the hearth and all had inner volumes of 4063 m^3. Before the 1990's Baosteel used conventional carbon blocks but found the severe wear of the carbon wall prohibitive to long campaign goals for the furnaces. Baosteel took the decision to explore the area of long blast furnace campaign life and part of this exploration involved using the three main carbon hearth refractory designs to establish which design was best suited to achieve their original goal of a 12 years continuous campaign life at a productivity rate of 2.283 t/(m^3.d). Let us take a closer look at the results at Baosteel;

<u>Furnace #1</u> On furnace #1, Baosteel installed micro pore and super-micro pore big blocks with a typical ceramic cup protection lining. They also installed a temperature monitoring system in the hearth pad and hearth wall. After only 3 years in to the campaign the temperatures in the hearth bottom jumped to a record high level of 770^{o}C and the hearth wall temperatures also started to go up. With these rapid temperature increases Baosteel concluded that after only 3 years the ceramic cup protection had gone. The temperatures in the hearth walls continued to increase over time and six years in to the campaign Baosteel calculated that less than half the micro pore carbon big block wall remained. Baosteel also calculated that with the high temperatures in the wall the Zn vapor in the furnace would be penetrating the micro pore carbon big blocks and creating a "brittle" zone. The hearth wall thickness of the 2nd campaign on furnace #1 was thicker than that of the 1st campaign, but it is proved by Baosteel's experience that the thicker lining doesn't guarantee the longer life

Because of the problems with the severe erosion of the micropore carbon big blocks Baosteel had to formulate a plan of preventative action for furnace #1. This included reducing the coal injection, closing tuyeres, adjusting the tapping sequence, charging ilmenite, and reducing production levels. In addition they had to grout regularly to overcome the air gaps between the micro pore carbon big blocks and the shell.(1)

<u>Furnace #2</u> Furnace #2 also installed micropore and super-micropore big blocks only, but with no ceramic cup protection. Again they installed a temperature monitoring system in the hearth pad and hearth wall. As with furnace #1 the temperatures increased over time and the micropore and super-micropore big blocks were eroded and the hearth wall thickness reduced over time. The temperatures and erosion of the micro pore carbon blocks were not as bad as on furnace #1 but this is probably due to the productivity being lower at only 2.1 t/(m^3.d) and coal injection also being lower at 165 kg/t.

Again because of the problems with the severe erosion of the micro pore carbon big blocks Baosteel had to formulate a plan of preventative action for furnace #2. This included reducing the coal injection, closing tuyeres, adjusting the tapping sequence, charging ilmenite, and reducing production levels. In addition they had to grout regularly to overcome the air gaps between the micro pore carbon big blocks and the shell.

Because of the constant abnormal rise in the temperatures on furnaces #1 and #2 Baosteel have produced an "Air Gap Index" to help monitor and control the hearth erosion problem. Baosteel have concluded that blast furnaces with hearth configurations of big micro pore carbon blocks have air gap problems caused by cracks in the micro pore carbon but furnaces with UCAR Hot-Pressed ™ carbon bricks do not have this problem. [2]

Figure 9 - Baosteel No. 3 Blast Furnace

Furnace #3. The #3 furnace at Baosteel was installed with the UCAR Hot-Pressed ™ carbon and semigraphite bricks, and started in 1994. A temperature monitoring system was also installed in the hearth pad and hearth wall. In September 2006 the campaign life reached 12 years and *during the whole campaign* the hearth temperatures have been low and stable. Baosteel have stated that the hearth temperature on furnace #3 has been the lowest of all three of their blast furnaces. The Baosteel monitoring system clearly shows that after 12 years there has been no erosion of the UCAR Hot-Pressed ™ carbon bricks in the hearth wall. This has been achieved with productivity levels over 2.4 t/(m^3.d) and coal injection rates at over 200kg/t.

The results of the Baosteel experience of the different carbon linings show that furnace #1 will only achieve a campaign life of 11 years and a productivity rate of 2.3 t/(m^3.d). Furnace #2 has achieved a campaign life of 16 years but with a lot of preventative action and a low productivity rate of 2.1 t/(m^3.d). The only furnace that has exceeded the furnace campaign life goals of Baosteel is furnace #3 using UCAR Hot-Pressed ™ bricks. Furnace #3 has achieved the campaign life of 12 years to date and will continue as no relining of the hearth carbon is planned. It has also been the highest productivity furnace in the whole of China with productivity levels over 2.4 t/(m^3.d).

Baosteel have now set new goals for their furnace campaign lives; continuous operation for 20 years with the average productivity 2.32t/(m^3.d). Baosteel have concluded that the only way they will achieve these new goals is by using the UCAR Hot-Pressed™ carbon brick hearth concept and by 2008 will have converted 100% of their furnaces to the UCAR system.[3]

Summary of the carbon refractory hearth linings in the Baosteel furnaces:

- In 2005 Baosteel built a new furnace #4 and installed UCAR Hot-Pressed^{TM} carbon and semigraphite bricks.

Figure 10 - Installation of the UCAR lining in Baosteel No. 4 Blast Furnace

- In 2006 Baosteel furnace #2 was rebuilt with UCAR Hot-Pressed^{TM} carbon and semigraphite bricks, replacing the micropore and super-micropore big carbon blocks.
- In 2008 Baosteel furnace #1 will be relined with UCAR Hot-Pressed^{TM} carbon and semigraphite bricks replacing the failed micro pore and super-micro pore big carbon blocks with ceramic cup.
- In 2006 furnace #3 achieved a campaign life of 12 years at high productivity levels using UCAR Hot-Pressed^{TM} carbon bricks. <u>There are no plans to reline this furnace.</u>

Conclusion

As the first stage of integrated steel production, the blast furnace is critical to the profitability of the company. If iron is not made in the blast furnace, finished steel is not shipped to customers. For a company to maximize profits, it must optimize blast furnace productivity.
There are many popular technology investments that have generally been proven to increase furnace productivity within the same given working volume, but such investments are only profitable if the productivity is actually realized over the entire campaign. Conventional large block hearth technology has, over and over again, been a limiting factor that has prevented many steel producers from achieving maximum

profits as they have been forced to take costly measures to keep the hearth wall from failing.

Their common mistake is failing to treat the hearth as an investment. It has been proven, both in financial calculations and in operation, that choosing an advanced technology for the furnace hearth will avoid these costly measures. Only the UCAR Hot-Pressed™ Brick hearth wall has demonstrated that it can support high productivity and long life without grouting or titanium. **It is an excellent investment that will pay for itself many times over during the life of the furnace.**

The authors wish to thank Mr. John Davidson, Lincolnshire Ironmasters, and Mr. Fred Rorick, Rorick Inc., for their contributions to this paper.

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4 Appendix A - Investment Model Example

UCAR

Blast Furnace Hearth Investment Model

Production Rate (T/Day)	**7,500**
Cost of Lost Production (Per T)	**100**
Daily Labor Rate (Per Manday)	**500**
Ilmenite Cost (Per T HM)	1.28
Cost of Money	**10.0%**
Ilmenite Charge (T TiO2 per T HM)	**1.5%**
Coke penalty (T coke per T TiO2)	**0.25**
Coke cost (per T coke)	**100**
Ilemite Cost (per T ilmenite)	**60**
Total Ilmenite cost (per T HM)	1.28

	Block System	UCAR System	Benefit (Cost)
Refractory Volume (T)	**600**	**500**	
Refractory Unit Price	**2,500**	**4,000**	
Lining Refractory Cost	1,500,000	2,000,000	(500,000)
Installation Time (Days)	**15**	**10**	5
Lost Production During Installation (T)	112,500	75,000	37,500
Value of Lost Production During Installation	11,250,000	7,500,000	3,750,000
Expected Lifetime (Years)	**20**	**20**	0
Years of Reduced Production	**10**	**0**	10
Productivity Reduction	**10%**	**0%**	
Annual Reduced Production	262,500	0	262,500
Annual Cost of Reduced Production	26,250,000	0	26,250,000
Present Value of Reduced Production Cost	62,186,161	0	62,186,161
Grouting Program (Years)	**10**	**0**	10
Grouting Stops per Year	**2**	**0**	2
Length of Each Stop (Days)	**1**	**0**	1
Cost of Grouting per Stop	**10,000**	**0**	10,000
Lost Production per Year for Grouting (T)	15,000		15,000
Total Annual Cost of Grouting	1,520,000		1,520,000
Present Value of Grouting Cost	3,600,875	0	3,600,875
Ilmenite Use (Years)	**10**	**0**	10
Annual Ilmenite Penalty	3,346,875	0	3,346,875
Present Value of Ilmenite Penalty	7,928,736	0	7,928,736
Total Production Between Relines (T)	49,875,000	52,500,000	2,625,000
Present Value of Total Cost	86,465,772	9,500,000	76,965,772
Total Cost per Produced Tonne	1.73	0.18	1.55