THE TRUTHS AND MYTHS OF FREEZE LINING TECHNOLOGY FOR SUBMERGED ARC FURNACES

P.L. Duncanson and J.D. Toth

UCAR Carbon Company Inc., Columbia, Tennessee, USA.
E-mail: Peter.Duncanson@GrafTech.com and Jeff.Toth@GrafTech.com
Website: http://www.graftech.com/acm

ABSTRACT

Since 1995, when "freeze lining" refractory systems were introduced to the ferroalloy industry, they have gained in popularity, due to the freeze lining's reputation for reliability, safety, and the contribution it makes to profitability.

As with many popular and effective technologies, however, the freeze lining has spawned low-cost pretenders that claim the "freeze lining" name. On the surface they appear to contain some of the components of the technology, such as thermally conductive materials, but they fail to incorporate all of the principles that define a true Freeze Lining.

The term "freeze lining" refers to the refractory system's ability to maintain a temperature profile that is low enough to freeze a layer of process material on its hot face, which insulates the refractory and prevents direct contact with molten metal and slag. In doing so, the common wear mechanisms found in the submerged arc furnace - chemical attack, erosion, and thermal stress - can be prevented. These wear mechanisms are all related to high temperature; thus, they are prevented by maintaining low temperatures.

Certain refractory properties and design concepts are absolutely necessary for the lining system to function as a true Freeze Lining. The paper explains these requirements and why they are important - the Truth of freeze linings - and further explains why systems that ignore one or more of these requirements cannot claim to be freeze linings, thereby exposing the Myths.

1. INTRODUCTION

The freeze lining concept for submerged arc furnaces began to gain acceptance in 1995, and its use has been growing steadily since. In a relatively short time the system has proven to be more reliable, safer, and more economical than conventional linings comprised of either large carbon block or carbon paste and ceramic.

Not all freeze linings are created equal, however, and in many cases the term is incorrectly applied. Many people believe simply using thermally conductive refractory materials constitutes a freeze lining; while thermal conductivity is a required property, it is equally important to configure the materials correctly and to distinguish between theoretical properties and practical properties.

1.1 Refractory Wear Mechanisms

Three wear mechanisms are prominent in submerged arc furnaces: alkali attack, thermal stress and erosion (or dissolution). Each of these is directly related to high temperatures. Alkali attack only occurs at elevated temperature (between 800°C and 1100°C); thermal stress is a direct function of temperature and thermal expansion; erosion occurs if the refractory is too hot to freeze a protective layer.

It is a logical conclusion that wear can be prevented if temperatures are kept low. This is the fundamental concept behind the freeze lining.

1.2 The Lining as a System

It is critical to understand that the lining is much more than refractory materials. The lining is really a system that includes not just refractories, but also the shell, the cooling medium, and the process itself. The system is also dynamic; the makeup will change according to the system's thermal characteristics.

Only by fully understanding the requirements and adopting this "systemic" approach will a true Freeze Lining be achieved.

2. DEFINING A FREEZE LINING

2.1 What is a "Freeze Lining"?

The term "freeze lining" is derived from the lining's ability to freeze process materials and form a protective accretion ("skull") on the hot face of the refractory. To accomplish this, the hot face temperature must be sufficiently below the solidus of one or more of the materials being produced by the process. If the frozen accretion is relatively stable, it will become the working lining of the furnace, protecting the refractory and providing an insulating layer to keep temperatures low.

If there are any barriers to efficient heat transfer, however, either as a result of material properties or changes in the lining structure, the hot face temperature can be too high to freeze a stable protective layer. A true Freeze Lining must be able to transfer heat efficiently to the cooling system, and continue to do so reliably for the entire expected lifetime, so that refractory temperatures are kept low and wear is prevented.

Therefore, the authors put forth the following definition of a *Freeze Lining*:

"A Freeze Lining is a system incorporating refractories, the shell and a cooling system, with consideration given to the process. Every component of the system is designed to transfer heat efficiently, which will keep refractory temperatures low and enable the formation of a protective layer on the hot face of the refractory. In addition, the system is configured to prevent heat transfer barriers from forming later. In this way the common temperature-dependent wear mechanisms are prevented and a long lifetime is assured."

2.2 What is not a freeze lining?

In many ways it is easier to determine when a lining does not meet the criteria of a true Freeze Lining. Simply put, if a lining contains any components that do not support optimum heat transfer, it cannot be called a freeze lining. Any barriers in the system will force refractory temperatures higher, which only reduces the ability to freeze the skull and encourages the previously noted wear mechanisms.

Heat transfer barriers fall into two categories: those included by design, and those that are accidental. Designed barriers are relatively easy to understand; generally they are part of a more traditional lining concept in which the primary purpose of the refractory is to protect the shell. The most common examples of designed barriers are ceramic refractory and the lack of an active cooling system for the wall.

Accidental barriers are somewhat more difficult to recognize, because their inclusion in the lining is rooted in a lack of understanding of what makes a true Freeze Lining. Many times they occur because the designer assumes they transfer heat efficiently, when in fact they do not.

Below are some common examples:

- Carbon ramming paste data sheets often claim high thermal conductivity. In reality ramming paste is a poor conductor; its conductivity depends on high density and high baking temperature, neither of which is achieved in practice. Rather than curing at high temperatures, ramming paste tends to dry out over time at low temperatures, allowing an air gap to form, which is a further barrier.
- Large carbon block linings generally do not include enough allowance for lateral expansion and vertical expansion. When they heat to operating temperature, the compressive load caused by expansion leads to excessive stress and, ultimately, cracking. Cracks are tremendous barriers to heat transfer. In addition, long carbon blocks must transfer heat a great distance, increasing thermal resistance and therefore temperature.

- Cooling systems may be inadequately designed for the total refractory system. If there is insufficient capacity for heat removal, perhaps because the delivery method is deficient or the medium is incapable of high heat loads, temperatures will rise significantly and the lining will fail.

All of these elements have been used as components in lining systems that are billed as “freeze linings”, but it can be seen that they do not really meet the definition of the true Freeze Lining.

3. HEAT TRANSFER CONCEPTS

3.1 Introduction to Thermal Resistance

A fundamental knowledge of conductive heat transfer is helpful when trying to apply freeze lining principles. The rate of heat transfer per unit of surface area in a thermal system is known as heat flux, denoted by *q”*, and calculated as shown in Equation (1). SI units are shown.

$$q''\left[\frac{W}{m^2}\right] = \frac{k\left[\frac{W}{mK}\right]\Delta T[K]}{l[m]} \tag{1}$$

where: k = thermal conductivity
ΔT = temperature difference across the thermal system, or between two points
l = distance of heat transfer

It’s often easier to understand heat flux and one-dimensional heat transfer by drawing an analogy between the thermal system and a simple electrical circuit, as shown in Figure 1.

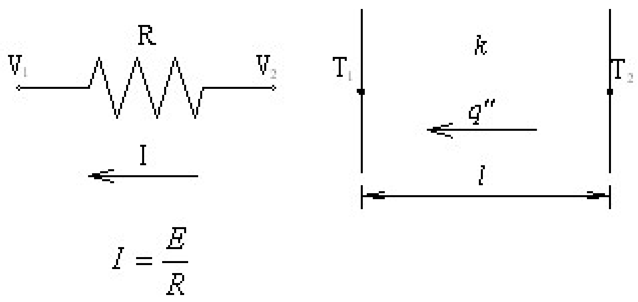

Figure 1. Electrical / Thermal Analogy.

In Ohm's Law, I is the current (or rate of energy transfer), E is the voltage drop (V_2 - V_1, the difference in energy level), and R is the resistance. In the equivalent thermal system, *q”* is the rate of energy transfer (heat flux), while ΔT (or T_2 -T_1) is the difference in energy level.

Comparing Ohm’s Law and the heat flux formula, we derive an expression for thermal resistance R as shown in Equation (2).

$$\frac{1}{R} \equiv \frac{k}{l} \quad \text{or} \quad R \equiv \frac{l}{k} \tag{2}$$

Therefore it can be seen that thermal resistance is a function of the length l and conductivity k, and the effect of each on resistance is apparent.

The other heat transfer mechanism present is convection – heat transfer between a moving fluid and a solid body. In the case of a refractory system, convection is present between the process liquid and the wall, and between the refractory or shell and cooling system.

Resistance due to convection must also be considered in the heat flux equation; it is simply the inverse of the convection coefficient h, as shown in Equation (3).

$$R \equiv \frac{1}{h} \tag{3}$$

As with an electrical circuit, each component is added as a series of resistors, using the process temperature and cooling temperature as the boundary conditions, and calculating the heat flux, as in Equations (4) and (5).

$$R_T = R_{cooling} + R_1 + R_2 + ... + R_n + R_{process} \tag{4}$$

$$q" = \frac{T_{process} - T_{cooling}}{R_{Total}} \tag{5}$$

Heat flux is the same in each component of the lining. Therefore the heat flux can be used to calculate temperature drop in each component, beginning with either boundary and working through the entire lining.

3.2 The Dynamic Thermal System

A submerged arc furnace lining is a dynamic thermal system that drives toward an equilibrium heat flux that is determined largely by the boundary conditions (convection heating and convection cooling). The system is dynamic because the components can change according to temperature conditions. For example, if the total resistance is high, hot face temperature will be high, which can cause refractory loss until it reaches a temperature at which it will no longer wear. At this point the lining has reached its equilibrium resistance and heat flux.

Conversely, if the resistance is very low, hot face temperature will also be low, possibly below the freezing point of the process. In this case process material begins to freeze on the hot face, adding thermal resistance and reducing heat flux until the hot face reaches the liquidus. Again the lining has reached a thermal equilibrium, this time by adding process material. *This is the basic principal of the true Freeze Lining.* A consequent principal says that it is better to reach equilibrium by adding process material than to destroy the lining.

The system can also react to process changes. If productivity is increased, the hot face temperature will increase as well, which will force a change in lining thickness. A conventional lining will lose additional refractory, while a freeze lining will only lose some of the frozen layer.

The importance of thermal resistance and the differences between conventional linings and a true Freeze Lining will be discussed later.

4. CONFIGURING A TRUE FREEZE LINING

4.1 Components

According to the previously stated definition of a Freeze Lining, the lining must be able to transfer heat efficiently, and be configured to prevent a reduction in heat transfer efficiency over its expected lifetime. When configuring the lining, several factors are key to meeting these requirements. The benefits of each element, and the consequences of neglecting it, are noted below.

Thin lining – As thermal resistance is directly related to heat transfer distance (see Equation 2 above), the thin lining provides the lowest resistance.

A thick lining creates higher resistance, which drives hot face temperature higher. Not only is the refractory more prone to wear at high temperature, it also expands more and creates more internal stress.

Small pieces – Small pieces have small expansion and therefore create little or no stress when they expand, especially when they have sufficient expansion allowance. Small pieces can also be fit tightly to the cooling system without ramming paste.

Large pieces expand proportionally more, making each piece more likely to crack and introduce an air gap through which gases, vapors and liquids can penetrate. Perhaps more importantly, cracks interrupt heat transfer, further increasing temperature. Large pieces also require ramming paste to fill between refractory and shell, introducing another unnecessary barrier to heat transfer.

Expansion allowance – Even when expansion is minimized by using small pieces, it must be accommodated. Without allowance for expansion, stress will be created as the refractory rises to operating temperature, possibly to the point of failure. Some type of expansion allowance must be provided in all directions.

When expansion is not properly accommodated, excess expansion is converted to compressive load, ultimately leading to cracking. Again, cracks are a heat transfer barrier and a pathway for attack from gases, vapors and liquids.

Tight fit to cooling – Intimate contact between refractory and cooling through a thin carbonaceous cement joint provides the lowest resistance

Thermal conductivity of ramming paste depends on baking temperature and ramming density. High conductivity is never achieved in field installations, however, because the void to be filled is very large and the paste is in direct contact with the cooling. The ram will instead form a low-conductivity barrier to heat transfer, and may even form an air gap if it dries and shrinks before properly baking.

Thermally conductive refractory materials – Thermal resistance is inversely related to thermal conductivity. Therefore to decrease resistance, materials with high thermal conductivity such as carbon, semigraphite and graphite should be used. (For the purposes of this discussion, the term “carbonaceous” will refer to materials in which carbon is the majority component, i.e., carbon, semigraphite and graphite. “Carbon-containing” materials, such as carbon-magnesite refractory with a 20% carbon content, are considered insulating materials.)

Insulating materials such as ceramic refractories have very low conductivity relative to carbonaceous materials, and thus have a higher resistance and higher temperatures. They also tend to expand at a much higher rate, which compounds the problems associated with insulating materials.

Robust cooling system – An active cooling system is absolutely essential to extract the amount of heat required to maintain low temperatures and freeze a protective skull. It must be engineered so as to ensure even distribution, sufficient capacity for the expected heat load, and reliability as conditions change over the lifetime. As with every other component, a proper cooling system has the lowest possible thermal resistance.

Ambient or forced air systems, external serpentine systems, and localized sprays simply do not have sufficient capacity – they all have very low convection coefficients and consequently high resistance.

It can be seen how these factors interact to create and maintain low thermal resistance, resulting in low temperatures. *They are all critical elements of a true Freeze Lining,* and failing to include them all causes the system to fail. Indeed, a common myth of freeze linings is that one can be constructed simply by using conductive refractories, using small pieces, or adding a cooling system.

4.2 Details of Configuration

Figure 2 depicts the typical configuration of the true Freeze Lining.

The standard wall thickness varies from 300 mm to 527 mm (9” to 18”), composed of a graphite tile 70 mm thick and Hot-Pressed™ carbon brick[1] for the remaining thickness. The carbon brick has a maximum width of 229 mm (9”), allowing it to fit tightly to the shell with a thin joint of carbonaceous cement.

As far as the lining is concerned, submerged arc furnaces generate heat in a somewhat concentrated area – in front of the electrodes – while the area between electrodes has a relatively low heat load. On the other hand, the cooling system covers the entire external surface area. The graphite tile layer against the shell helps redistribute heat from the high-load zones to the low-load zones and better balance the cooling system.

The cooling system is typically a continuous water film on the exterior of the shell. (Other types of cooling are available, but they have not gained widespread acceptance in submerged arc furnaces; thus we will refer only to the water film.) There are different methods for distributing water evenly over the shell, some more effective than others; nevertheless even distribution is as important as quantity to the performance of the system. The system must be engineered to provide the proper quantity and distribution, but simply put, there should be a continuous water film on every part of the shell, with no dry or steaming areas. Any attachments to the shell that could deflect water flow must be also dealt with so that dry spots do not develop downstream.

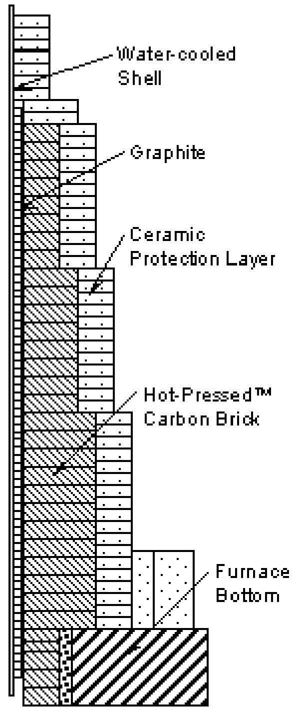

Figure 2. Freeze Lining Configuration.

A carbonaceous lining must be protected from oxidation when the furnace is first started. During this short time period the refractory begins to heat up, the skull has not yet formed, and there is an oxidizing atmosphere present. For this reason a ceramic protection layer is necessary. This layer is considered sacrificial – it is fully expected the ceramic will be gone shortly after the furnace reaches full productivity. Portions of the protection layer may also stay in place as part of the permanent skull.

5. COMPARISON OF RESULTS

One-dimensional thermal modeling can be performed to compare the expected results of different lining configurations. (Although in reality heat is continually transferred in three dimensions, for the purpose of comparison one dimension is relatively accurate for a large portion of the furnace.) The differences between the true Freeze Lining and other systems become obvious.

Table 1 compares three indicators of long-term performance: hot face refractory temperature, skull thickness, and hot face expansion. Five different systems are analyzed.

The results show that the True Freeze Lining (Case 1) has the lowest hot face temperature and the thickest frozen layer. In addition, because the expansion is low, it will not crack and efficient heat transfer is maintained.

By contrast, the large block hearth wall (Case 2) has a higher hot face temperature and much higher expansion. (The higher total expansion is a product of the higher temperature, a higher coefficient of thermal expansion, and larger piece size.) Although it is able to freeze a small skull initially, the expansion causes a high compressive stress and the block is subject to cracking.

Once the block has cracked (Case 3), it is impossible to freeze a skull, temperatures rise, and the block expands more. (It is worth noting that a ram annulus can shrink and form an air gap with the same effect.) At this point the block lining is well on the path to failure.

[1] Hot-Pressed™ is a trademark of UCAR Carbon Company Inc.

The conventional ceramic/paste lining (Case 4) starts at a high temperature due to the use of insulating materials. The carbon paste is subjected to chemical attack and a protective layer cannot freeze. This configuration is mainly used when an active cooling system is not present; its main purpose is to protect the shell.

Case 5 has the same configuration as Case 1, but demonstrates the effect of poor or no cooling. When the lining relies on ambient air conditions for cooling, it cannot survive, thus proving the cooling system is as important as refractory properties and configuration.

Therefore the True Freeze Lining is the only configuration capable of surviving typical furnace conditions.

Table 1. Comparison of Key Indicators of Long-term Lining Performance.
(See Appendix 1 for input parameters)

Case	Description	Refractory Hot Face	Skull Thickness	Hot Face Expansion	Result
1	True Freeze Lining 70mm graphite + 457mm Hot-Pressed™ carbon brick	589°C	81mm	0.45 mm	Low temperature, low expansion, good skull formation, no chemical attack
2	Large carbon block 500mm long block + 75mm ramming paste	995°C	38mm	2.42 mm	Subject to chemical attack, high hot face expansion, subject to stress
Case	Description	Refractory Hot Face	Skull Thickness	Hot Face Expansion	Result
3	Large block w/ crack 500mm long block + 75mm paste + 0.5mm crack	1418°C	0	4.17 mm	Subject to chemical attack, very high hot face expansion, no skull
4	230mm ceramic + 350mm carbon paste	1514°C	0	N/A	High hot face temperature, subject to chemical attack
5	Freeze Lining without cooling – 70mm graphite + 457mm Hot-Pressed™ carbon brick, ambient air cooling	1453°C	0	1.14 mm	High temperature, high expansion, no skull

6. BENEFITS OF THE FREEZE LINING

Even the best technology is worthless if it provides no value to the user. There must be some benefit to justify adopting a technology, whether it is measurable in terms of cost savings, or less tangible, such as a safety or environmental benefit. Fortunately the Freeze Lining has both tangible and intangible advantages.

6.1 Intangible Benefits of the True Freeze Lining

By definition, intangible benefits cannot be measured directly, but they nonetheless carry a significant value, and may even override other issues. The True Freeze Lining brings two such benefits to the furnace operator:

- Safety – Because the system is designed to prevent wear and maintain its integrity over the lifetime of the furnace, it is much safer and much less prone to breakouts. Risk is reduced for both personnel and equipment.
- Environmental – Traditional paste linings give off a tremendous amount of fume as they are cured prior to startup, which must either be collected or released to the atmosphere. The Freeze Lining produces a minimum level of emissions, and it requires no special curing or drying procedure.

6.2 Tangible Benefits of the True Freeze Lining

After considering the intangible benefits noted above, the choice of lining technology is largely one of economics. The owner/operator must make the distinction between "economical" and "low cost", however – too often the terms are confused. The initial investment is certainly important, but it is only one part of the total cost over the lifetime of the furnace. Installation time, installation labor, heatup time, and intermediate repairs must also be considered – each has an impact either in terms of direct cost or the value of lost production. Finally, there is value associated with a longer life: the total costs are distributed over more total production, and there is a financial benefit if the next reline is delayed.

We have already seen how the refractory materials and configuration that make up the Freeze Lining prevent wear. The ultimate goal, then, is to operate the furnace longer between major relines, with fewer or no intermediate repairs. The True Freeze Lining carries an added technical advantage: it typically takes less time to install the lining and start the furnace than when conventional lining technology is used.

These costs can be modeled individually and in aggregate to compare the relative value of lining systems. UCAR Carbon Company has developed a real-time spreadsheet-based model that directly compares two systems.[2] The model allows the user to enter local financial and production parameters, and expected values for each area that has a cost effect. The total costs are divided by total production during the lifetime to find a net cost per ton of product.

Several examples will be given to demonstrate the potential value of the True Freeze Lining. (All values are USD [$] unless noted.) Input parameters are summarized in Appendix 2. In every example the cost is the sum of the individual item plus the capital cost, divided by the lifetime production. The costs of other factors are set to zero.

6.2.1 Installation Time

Because bricks are easy to handle and install, time savings can be realized, which translates into labor savings and additional production. The cost in this case is labor cost and lost production during lining installation. See Table 2.

Table 2. Installation Time Comparison.

	Paste Lining	Freeze Lining
Installation Days	10	5
Cost per ton	$1.72	$1.40
Savings	$0.32/ton	

6.2.2 Faster Heatup

The need to cure a paste lining prior to operation adds many days to the construction schedule, while the Freeze Lining requires no special procedure to dry or cure. In this case cost savings are entirely from recovered production. In fact, one Freeze Lining user recovered the entire cost of the lining with savings from heatup time. See Table 3.

Table 3. Heatup Time Comparison.

	Paste Lining	Freeze Lining
Dryout/Curing Days	20	3
Cost per ton	$3.03	$1.08
Savings	$1.95/ton	

6.2.3 Intermediate Repairs

Conventional linings typically must be repaired at least once per year on a planned stop. There is a material cost associated with this, as well as further lost production. The Freeze Lining is designed to eliminate intermediate repairs, although an intermediate taphole repair may be required. Recognizing this, the Freeze Lining is also designed to simplify taphole repairs and minimize the outage time. See Table 4.

---

[2] A copy of the UCAR model is available by contacting the authors.

Table 4. Intermediate Repairs Comparison.

	Paste Lining	Freeze Lining
Repairs required	4	1
Days per repair	5	1
Cost per ton	$2.91	$0.17
Savings	$2.74/ton	

6.2.4 Longer Lifetime

Longer lifetime is the most significant factor in the economics of linings. The True Freeze Lining is generally accepted as superior technology, but the extra capital cost typically must be justified by a longer life. In reality, all other factors being equal, the lifetime of the Freeze Lining must only be 5% longer or less. Two cases are presented here: with the Freeze Lining operating only one more year beyond the paste lining, and a more realistic case with the Freeze Lining operating three more years than the paste lining.

Table 5. Lifetime Comparison.

	Paste Lining	Freeze Lining
Lifetime (years)	5	6
Cost per ton	$5.42	$4.48
Savings	$0.94/ton	
Lifetime (years)	5	8
Cost per ton	$5.42	$2.85
Savings	**$2.57/ton**	

Two factors contribute to the savings: total costs are distributed over far greater total production, and the cost of the next reline expressed in terms of present value is reduced.

6.2.5 Total Savings

Table 6 tabulates the total savings when all the examples given above are taken together. (Note that since the factors are interrelated, the individual savings do not equal the total.)

Table 6. Summary of Costs per Ton.

	Paste Lining	Freeze Lining	Savings
Installation time	$1.72	$1.40	$0.32
Heatup time	3.03	1.08	1.95
Intermediate repairs	2.91	0.17	2.74
Longer lifetime	5.42	2.85	2.57
Total	**$12.59**	**$3.67**	**$8.91**

The savings possible with the Freeze Lining are obviously significant, even when the extra cost to purchase the Freeze Lining is included. In addition, there may be other savings realized; with the more robust Freeze Lining, productivity may increase, or the insulating skull may reduce heat loss and power consumption.

These are influenced heavily by local factors, however, and are not modeled here. The complete model is shown is Figure 3.

UCAR

Ferroalloy Furnace Refractory Economic Model

Production Rate (T/Month)	**10,000**
Product Value (Per T)	**500**
Daily Labor Rate (Per Manday)	**500**
Incremental Profit Margin	**50%**
Cost to reline	**5,000,000**
Cost of Money	**10%**

	Paste Lining	UCAR Chill-Kote®	Benefit (Cost)
Lining Refractory Cost	**150,000**	**300,000**	(150,000)
Cooling System Installation		**100,000**	(100,000)
Installation Time (Days)	**10**	**5**	5
Labor Force (persons)	**10**	**10**	0
Installation Mandays	100	50	50
Labor Cost	50,000	25,000	25,000
Heatup Time (Days)	**20**	**3**	
Lost Production During Installation and Heatup (T)	10,000	2,667	7,333
Sales Value of Lost Production	5,000,000	1,333,333	3,666,667
Lost Profit at 50% incremental margin	2,500,000	666,667	1,833,333
Repairs During Lifetime	**4**	**1**	
Repair Duration (Days)	**5**	**1**	
Cost of Repair	**20,000**	**20,000**	0
Lost Production During Repairs (T)	6,667	333	6,333
Sales Value of Lost Production	3,333,333	166,667	3,166,667
Lost Profit at 50% incremental margin	1,666,667	83,333	1,583,333
Total Cost of Interim Repairs	1,746,667	103,333	1,643,333
Expected Lifetime (Years)	**5**	**8**	3
Present Value of Next Reline	3,104,607	2,332,537	772,070
Total Production Between Relines (T)	600,000	960,000	360,000
Total Cost	7,551,273	3,527,537	4,023,736
Lining Cost per Product Tonne	12.59	3.67	8.91

Figure 3. Economic Model Spreadsheet.

7. CONCLUSIONS

Freeze lining technology has become the preferred lining system for submerged arc furnaces, having proven in recent years to have performance that is superior to more traditional lining technologies. The operator must be cautious, however, as some systems that claim to be freeze linings do not include all the necessary elements of a True Freeze Lining.

To truly be considered a Freeze Lining, the lining must first be considered as a system that is designed to freeze process materials on the hot face of the refractory. Furthermore, the system must be configured in such a way that efficient heat transfer is maintained over the entire lifetime, and degradation is prevented. The system must have no barriers to heat transfer built in, and must prevent them from forming during operation. Certain elements of design and construction are required to achieve such a system; any lining that fails to include *all* elements cannot be call a True Freeze Lining.

Finally, the operator should accurately assess the economics of his lining choice. It is commonly believed that the Freeze Lining is more expensive than a conventional lining; *this is probably the greatest myth of all*. When all the costs of a lining are considered, the True Freeze Lining will be more economical and have greater value to the operator.

APPENDIX 1: HEAT TRANSFER CALCULATION PARAMETERS

External water cooling
- Convection coefficient = 3950 W/m^2
- Temperature = 30°C

Process
- Convection coefficient = 75 W/m^2
- Temperature = 1600°C
- Solidus = 1350°C

Thermal Conductivity

Steel shell ....52 W/mK
Ramming paste ....5 W/mK
Graphite ....140 W/mK
Hot-Pressed™ carbon brick..................16 W/mK
Micropore carbon block ....14 W/mK
Ceramic brick ....1.5 W/mK
Frozen skull ....2 W/mK
Air...0.01 W/mK

Coefficient of Thermal Expansion

Hot-Pressed™ carbon brick.............3.5×10^{-6} mm/mm°C
Micropore carbon block ....5.0×10^{-6} mm/mm°C

APPENDIX 2: ECONOMIC MODEL INPUT PARAMETERS

Production rate.. 10000 tons/month
Sales value $500/ton
Profit on incremental production... 50%
Complete cost to reline ....$5 million
Labor cost $500/manday
Discount rate... 10% annual
Paste lining capital cost $150000
Freeze lining capital cost (including cooling system) $400000
Standard lifetime .... 5 years