DIRECT CHARGED MELTERS

by

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In direct-fired aluminum melters, the primary source of heat is generally from a burner firing a gas or liquid fuel. Only a fraction of the energy transferred to the metal comes directly from the flame. The principle modes of heat transfer are:

A) radiation from the refractory (roof and sidewalls)
B) radiation from the gas blanket above the metal
C) direct radiation from the flame to the metal
D) convective heat transfer from the hot gases flowing across the metal surface

Although radiation from the refractory is generally acknowledged as the major source in all melters, it may be minor in some parts of the melting cycle.

Depending on the style of melter, efficient operation requires taking advantage of all the modes of heat transfer and designing to optimize those most effective during different parts of the melt cycle. The combustion system design must also address scrap configuration and preparation, thermal properties of aluminum and environmental concerns.

Figure 1 shows the thermal conductivity of aluminum and some of its alloys.

In the solid state, aluminum is an excellent conductor of thermal energy. For this reason, direct charged furnaces can be fired with very high gross inputs at the start of the cycle (provided scrap is heavy section). The metal conducts so well that it is able to absorb the heat rapidly, resulting in low flue gas temperature and high efficiency.
In the liquid state, the conductivity of aluminum drops to about half of that of solid aluminum. This means that at a given furnace temperature, the ability to transfer heat to a liquid bath decreases tremendously. This characteristic of liquid aluminum can be detrimental to the melt rate and efficiency of a direct charge melter except a true dry hearth melter designed with a raised hearth.

As the metal melts, a pool of liquid forms and eventually submerges the solid metal on the bottom of the charge. Once the solid are submerged, heat transfer is limited to the conductivity of the metal they are immersed in. When this loss in conductivity is coupled with the decrease in heat transfer surface area and the lower delta T between the source and receiver, the melt rate efficiency of a furnace can be seriously reduced. (Heat transfer surface area is reduced because the flat bath area generally does not equal the surface area exposed on a large pile of solid scrap.) (The delta T is reduced from more than 1000°F difference between flame or refractory and the metal to less than 200°F found between molten and solid aluminum. See Figure 10.

Figure 2 shows the heat required to melt and bring to tapping temperature a pound of aluminum. Ninety-three percent of the heat required is absorbed while the aluminum is in the solid state. This means that the majority of the energy required to melt aluminum is absorbed while the aluminum’s conductivity is the highest. Therefore, a direct charged melter’s efficiency
and melt rate is dependent on how much heat can be absorbed by the metal prior to submerging unmelted sections below the liquid surface.

Efficient direct charge melters involve a combination of the designs used to fire dry hearth and well charged melters. Dry hearth melters are intentionally designed to minimize submerging of the unmelted metal. The cold charge is placed on a hearth, and as it melts, the liquid runs off the hearth into a holding chamber. This is the exact condition found in standard direct charge melter after the first charge is made. (If the furnace requires more than one charge, portions of each subsequent charge will be submerged below the liquid surface.)

Radiation Heat Transfer

Figure 3 shows a typically charged furnace. The charged material is piled in to fill the furnace interior. The area between the roof and material is reduced considerably while in many instances the scrap is piled very close to the burner ports.

The primary mode of heat transfer to the charge is by radiation. Reradiation from the roof and sidewalls is the major source (Figure 4); radiation from the products of combustion (POC) is usually the second most intense source.

At the start of the melt cycle, the furnace door will be open for a period of time while charging. During this time, the furnace refractory will have cooled, decreasing the heat transfer from the walls and roof to the charge until the refractory has been brought back to the maximum operating temperature.

Gas Blanket Radiation

The second component of the radiation heat transfer is gas radiation from the POC. This includes direct radiation from the flame to the charge and the energy radiated from the blanket gases (POC) above the charge. Gas radiation occurs only from the triatomic molecules directly involved in the chemical process of combustion. These would include CO$_2$ and H$_2$O when burning natural gas. When burning natural gas with air as the oxygen source, approximately 26% of the POC are triatomic molecules. The remaining 74% is N$_2$ and inerts which do not radiate. When the furnace door is opened, the inrush of air further dilutes the CO$_2$ and H$_2$O. The amount of energy transferred from the gas blanket varies with the temperature of the gases and the thickness of the blanket.
Figure 5 shows the difference in the two sources of gas radiation. Where the flame envelope is high in temperature, it has a narrow beam and as we will see, the size of the flame envelope is questionable. The furnace gas blanket is lower in temperature but fills a greater volume and has a greater beam width.

Figure 6 shows the variation in heat transfer capability of a gas blanket as the beam width varies. Although the curve continues to rise after 6 feet, the gain is minimal and for economical furnace construction 60 inches is generally considered the optimum.

Figure 7

In reality, when the door closes after charging the furnace configuration looks more like Figure 7.
Because of the scrap pile location, there is little room for developing a large radiant flame. Radiation from the flame to the charge is minimal because of the lack of coverage and due to beam width. (Most radiant flames are generated by burners that slow the mixing of the air and gas. When this type of flame impinges on a cold scrap pile, quenching can occur. This will result in CO, VOC (Volatile Organic Compound), and soot formation, which can be an environmental problem.)

The hot gas (POC) beam width is reduced due to the lack of open furnace volume between the charge and the roof. As shown on Figure 6, the reduced beam width will reduce the heat transfer significantly. At first this loss of gas radiation along with the reduced radiation from the refractory would indicate that efficient melting in this furnace would be difficult. However, it may be possible to use the poor radiation configuration as an advantage.

As previously discussed, the objective when trying to melt a large pile of scrap is to pour as much heat into the aluminum as possible before the top metal melts and forms a pool of molten metal which submerges the solids to the bottom. Because of the reduction in radiation to the top of the pile, there is time to add heat to the material on bottom. The metal on the interior and bottom of the pile will see little if any radiation at the start of the cycle. Any heat gained will come via conduction from the surface metal and convective heat transfer from the POC that circulate around and through the charge. The looser the pile, the more circulation. Conduction from piece to piece will be minimal and unreliable while heat transfer from convection is based on the volume, temperature and velocity of the gas stream.

When the door closes after charging, the piles of scrap will have the maximum porosity and exposed surface area. More exposed surface area increases the potential for heat transfer. At this time, the hot POC must be forced into the pile so that the hot gases scrub as much of the exposed internal surface area as possible.

High velocity style burners are designed to be angled down firing into the pile. Hitting the pile with a very high velocity stream of hot gases results in hot gases being pushed into all the cracks and crevices. In addition, the venturi action of the burner pulls hot gases from the crown down into the POC stream increasing the volume of gases being forced into the pile. The volume of gases impacting or circulating through the load can be increased 5-7 times above the actual burner POC volume in a properly designed system.

The venturi action has an additional benefit in that it pulls the gases from the crown of the furnace and circulates this mass into the pile replacing it with cooler gases, Figure 8A. The result is the roof operates at a lower temperature during the early part of the melt cycle. This is important because if the roof reaches the temperature control set point or limit, the burners will begin to turndown. The load may still have significant exposed surface area and be able to absorb substantial amounts of energy. However, because of roof temperature limitations, the burner firepower will be reduced at the critical time for optimizing heat transfer and efficiency.
The metal exposed at the top of the charge is the easiest to melt. If the area above the metal becomes a stratified layer of hot gases due to poor burner configuration or velocity, the surface metal will melt rapidly and run down the pile until it resolidifies on the cold charge below it. This causes the surface of the pile to slag over reducing the surface area exposed for heat transfer. Less heat transferred to the pile and the furnace temperature continues to rise and the burner input reduces further.

The melting and resolidification cannot be eliminated entirely but should be minimized as much as possible. Each time the metal changes state from solid to liquid to solid, the potential for oxidation exists.

Ideally the gas flow pattern would be as shown in Figure 8B. The gas passes through a loose pile transferring as much heat as possible to the charge. This would result in very low flue gas temperatures and thus good efficiency.

Because the scrap density varies so greatly, the actual flow pattern looks more like Figure 9. The density of the scrap pile limits penetration allowing the burner to affect only part of the pile. For this reason multiple burner heads surrounding the pile are preferred on large furnaces. The more points of hot POC penetration, the more efficient the heat transfers. Raising the interior of the pile to as high a temperature as possible reduces the amount of energy required to complete the melting of the solids submerged in the molten aluminum.
Figure 10 shows a furnace after the majority of the charge has melted, submerging some of the solid scrap. These same conditions can occur when a second charge is added to a furnace partially filled with molten metal.

The characteristics of heat transfer are now similar to those of a well charge melter. All the heat transfer to the solids is limited by the conductivity of the molten metal. As shown in Figure 1, the conductivity varies with the difference in temperature. Therefore, the hotter the surface of the bath, the more heat will be transferred to the solids. The primary mode of heat transfer to the flat bath is by radiation. Therefore, it is important that when the furnace reaches this state, the system must have the furnace at the maximum operating temperature.

As shown in Figures 11 and 12, all conditions are right for radiation heat transfer from the refractory, flame and POC.

Flame radiation will vary based on the type of burner. As previously discussed, a high velocity burner is the optimum choice for the first part of the melt cycle. Once the bath goes flat it appears that a slower mixing, more radiant flame burner would be the choice. Slowing the mixing of the air and gas generally produces radiant flames. This produces a long, lazy, luminous flame. At high fire this flame will cover much of the bath. Unfortunately, the burners will probably not be at high fire at this time.

When the furnace is full of cold scrap, it will absorb a tremendous amount of heat. The gross input at this point can be very high. Once the bath goes flat, the amount of exposed surface area for heat transfer is reduced and less energy can be absorbed. Consequently the furnace temperature rises and the burners must cut back. As the typical burner input reduces, the flame
envelope shrinks, decreasing the coverage. In addition, the burner mixing slows even more and the flame tends to lick up toward the roof. This may cause problems with localized hot spotting and possibly roof overtemp alarms.

At this point in the cycle, the primary mode of heat transfer is radiation from the refractory to the bath surface. Looking back at Figure 10, it would appear that the easiest way to finish the melt at this point would be to drive up the bath temperature. Unfortunately, aluminum is very reactive chemically in the liquid state.

Figure 13 shows the effect of high metal temperature on dross formation (Al1203). As the metal temperature exceeds 1420°F, the potential for dross formation escalates rapidly. The more dross that is formed, the more metal that is lost and the more waste from the furnace that must be treated and/or land filled. Although metal temperature is a major factor in dross formation, oxygen must be present and in contact with the metal before the chemical reaction can occur. The primary sources of oxygen are infiltrated air and the burners. It is important to select burners that mix well and turndown sufficiently without requiring excess air. In addition to metal loss, dross formation can have a negative effect on furnace efficiency.

In the past, slow mixing lazy flame burners were used on melters because of the fear of creating more metal loss by scrubbing the surface of the metal with a stream of hot POC. Today high velocity style burners have been used successfully on all styles of melters with no increase in metal loss.
The amount of heat transferred is based on the amount of surface area, refractory temperature, metal temperature and the thickness of the layer of dross covering the metal surface. A thin layer of dross is desirable to cover what would otherwise be a reflective metal surface. The heat radiated to a “shiny” molten metal surface would reflect off rather than be absorbed. If the dross layer becomes too thick, it will act as an insulator. When this occurs, the furnace temperature must be driven even higher to get the heat transfer necessary. Figure 14 shows the potential for increased fuel consumption based on the dross layer.

Dross can be made up of many things but one of the major constituents is aluminum oxide ($\text{Al}_2\text{O}_3$). This is lost metal. The formation of aluminum oxide is basically a time at temperature phenomena with the presence of oxygen. When liquid aluminum is raised in temperature above 1420°F (770°C) and oxygen is present, the potential to create aluminum oxide increases substantially. The longer these conditions exist, the ever-increasing chances for the reaction to occur.

To avoid metal oxidation when the furnace is on a flat bath conditions, it is desirable to:

- keep the furnace temperature as low as possible to minimize the bath surface temperature
- avoid localized hot spots on the metal surface
- transfer the heat as evenly as possible over the entire bath surface area

To avoid having to operate with an elevated bath surface temperature to complete melt cycles in a reasonable time, shallow furnaces are preferred. The deeper the liquid pool that the solids are submerged in, the more difficult to get the energy down to them. It is necessary to raise the surface temperature to get sufficient $\Delta T$ to force conduction to melt the solids. The higher the bath surface temperature, the greater the potential for dross formation. In general, furnaces with greater liquid levels require more energy to operate and can have higher melt loss.

Impinging hot gas (POC) on the bath can increase heat transfer by creating an area of high temperature which increases conduction of heat. This area of very high temperature increases metal loss through oxidation while increasing the insulating affect of the dross cover. The same affect can be seen where a radiating source creates an area of elevated surface temperature. It is difficult to avoid hot spots entirely, but it is best to minimize the potential to create hot spots on the surface especially areas in contact with the refractory lining.

Flame radiation, gas blanket radiation and to some extent convection play a role in the heat transfer to the flat bath. The overwhelming dominant source of heat is the reradiation of energy from the refractory. Once the bath is flat, the goal of the combustion system is to drive the refractory to the operating temperature as fast to uniformity as possible. If the refractory radiates uniformly to the bath surface, the optimum heat transfer can be achieved with a minimum bath surface temperature. This reduces the chance for metal oxidation and dross build up.

The key to uniformity is circulation. Moving the hot POC throughout the furnace insures all the refractory is heated evenly. Hi velocity burners provide excellent mixing of gases to provide a homogenous blanket of gases circulating throughout the furnace chamber. As high velocity burners turndown, the velocity decreases and the flame becomes more luminous. The decreased velocity is still greater than a standard burner while the increased flame luminosity is not as great as flame designed for luminous heat transfer. The total affect provides greater
overall furnace uniformity and heat transfer with very limited potential for creating localized hot spots. (Dual flame burners, pulse firing and regenerative cycling all offer some advantages depending on the operating practices.)

Until recently the main concerns in designing an aluminum melter were melt rate, melt loss, fuel efficiency and capital cost. Today serious consideration must also be given to the stack emissions. With natural gas as the fuel, the emissions of paramount importance are CO, NOx and VOC. (Although CO is a VOC, it is permitted separately having its own regulated limits.) With most natural gases, VOC’s are not a concern.

**Carbon Monoxide**

CO is a by-product of incomplete combustion. It is formed most often by:

1. Poor fuel/air ratio control systems. By operating too close to ratio or with insufficient O$_2$ for combustion. Incomplete combustion occurs and CO is formed instead of O$_2$.
2. Poor mixing burners fired in a chamber with insufficient retention time for completion of the combustion process.
3. Quenching of the burner flame especially in a cold chamber. This happens often in the beginning of the melt cycle when the chamber is cold and the burners are fired into a large pile of cold scrap.

It is important to remember that the combustion process is a chemical reaction that requires heat to start the process. Once started the process consumes some of the thermal energy produced to keep the reaction going. If the heat is removed from the flame envelope too quickly, the chemical reaction is stopped before completion and CO will be formed.

CO formation is minimized by:

1. Fast mixing burners that assure the O$_2$ and carbon are brought in contact with each other. This type of flame has a high temperature.
2. Firing into hot chambers with long retention time for the POC to mix.
3. Operating the burner with significant amounts of excess air. This insures that there is more than enough O$_2$ to react with the carbon.
4. Be sure nothing interferes with the flame envelope.

Unfortunately, most of the methods of assuring minimal formation of CO result in aiding the formation NOx.

**Nitrogen Oxides**

NOx formation occurs mostly at flame temperatures above 2700°F. The major factors for the formation are:

1. Flame temperature. The hotter the flame, the greater the potential for NOx. Preheated air and oxygen enrichment both increase the flame temperature significantly causing a subsequent increase in NOx formation.
2. Gas concentration. The more N$_2$ and O$_2$ available in the high temperature areas, the greater the potential for NOx. The quantity of N$_2$ and O$_2$ available to form NOx is
dependent on the air/fuel ratio the burner is operated at.

**NOx PPM (Mg/NM³)**

<table>
<thead>
<tr>
<th>% Excess Air</th>
<th>60°F (16)</th>
<th>450°F (230)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40 (80)</td>
<td>75 (150)</td>
</tr>
<tr>
<td>10</td>
<td>55 (110)</td>
<td>100 (200)</td>
</tr>
<tr>
<td>25</td>
<td>65 (130)</td>
<td>125 (250)</td>
</tr>
<tr>
<td>50</td>
<td>85 (170)</td>
<td>265 (530)</td>
</tr>
</tbody>
</table>

*NOx Corrected to 3% O₂

**Figure 15**

Figure 15 shows typical changes in NOx formation as the percentage of excess air in the furnace increases. An increase in excess air from 0% to 25% can produce a 53% increase in the NOx formation. It is important to note that the excess air does not necessarily have to come through the burner. It could be air pulled in through the doors and leaks due to poor furnace pressure control.

3) Retention time. The longer the POC containing N₂ and O₂ are held at temperature, the more NOx will be formed. Retention time goes hand in hand with cooling rate. If the flame envelope and POC are cooled fast enough, the formation of NOx is limited.

High flame temperatures, a nominal amount of excess air and long POC retention times are all recognized as favorable design criteria for an aluminum melter. They insure efficient heat transfer while minimizing CO formation. Unfortunately, these same factors are major components in the formation of NOx.

With all this in mind, do not forget the objective is to melt aluminum economically. The question is how to do this and remain in compliance with the environmental regulations for air pollution. Hydrocarbon and oxygen are necessary for the chemical process, which releases the energy used in the melting process. Nitrogen, however, is an extraneous element, which is not only unneeded but also detrimental to the overall efficiency of the furnace. By removing the nitrogen there would be no NOx formation and the system could be designed to assure that a minimal amount of CO was produced. Nitrogen plays no part in the combustion process, but it is a major factor in the overall efficiency of the furnace. The nitrogen enters with the air and passes through the furnace with the POC exiting out the flue at the same temperature as the POC. The N₂ has in fact absorbed some of the heat generated by the combustion process. The combination of the energy lost heating the nitrogen and latent heat lost in the water vapor decreases the amount of heat available in the furnace to do useful work.
Figure 16 shows the % of the gross thermal input to a furnace that is available for useful work based on different flue gas temperature and varying O₂ levels. At 2000°F flue gas, standard air at 21% oxygen, the % of heat available is 46%. That means if the gross input to the furnace was 10 mm btuh, only 4.1 mm btuh are available for useful work. If 100% O₂ is used in the process instead of standard air, the % available heat would rise to 75% or 7.5 million btuh.

The addition of the nitrogen in the process poses not only environmental concerns but also increases fuel consumption. Figure 17 shows that a furnace operating at 2000°F, on 100% oxygen instead of air will consume approximately 38% less fuel. Less fuel burned is not only a decrease in the fuel bill; it also means fewer pounds of flue gas emitted. The decrease in flue gas volume can save in a bag house cost and possibly CO₂. The decrease in fuel consumption also leads to other more subtle benefits.

a) Less POC entering the furnace means that retention time of the POC in the furnace will increase. This aids in completing combustion and increases the overall furnace efficiency.

b) Furnaces are generally set so there is 1-2% excess oxygen in the flue gases. This is done to compensate for the varying calorific value of natural gas. If the excess O₂ is not
consumed by the combustion process, it is available in the furnace for dross formation (AL203). If less fuel is required, then less oxygen is required. This means that the 1-2% excess $O_2$ is in fact less pounds of oxygen which means less available oxygen passes through the furnace for dross formation.

On paper, oxy-fuel appears to be a “no lose” situation. However, there are other considerations before applying it to production furnace…

- a) The flame temperature of a standard ambient air/gas burner is effectively 3200°F. An oxy-fuel flame can reach temperatures in excess of 5000°F.
- b) In the initial part of the melt cycle in a direct charge melter, convective heat transfer through the pile is a must. The transfer rate is based on the volume, temperature and velocity of the gases. With oxy-fuel, the volume of gases is considerably reduced.
- c) A reduction in gas usage of 38% would normally be very appealing. This has to be offset by the cost of the oxygen. What is the utility cost/lb melted?
- d) Will the melt rate be affected?
- e) 0 ppm of NOx is impractical due to the air leakage around doors etc. This air includes nitrogen and this will produce some NOx.

The flame temperature of any burner is very dependent on burner design features. A standard high velocity air/gas burner will have a considerably lower flame temperature than a fast mix burner primarily because of the venturi effect of the high velocity stream of POC. As discussed earlier, this jet stream pulls into its flame envelope a considerable amount of furnace gases. These gases dilute the high temperature POC.

If this same principle is applied to any oxy-fuel burner, similar results can be seen.

<table>
<thead>
<tr>
<th>% $O_2$ in Oxidant</th>
<th>Recirculation Ratio</th>
<th>0</th>
<th>1</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4000 (2200)</td>
<td>3415 (1880)</td>
<td>2917 (1600)</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>4415 (2435)</td>
<td>3710 (2042)</td>
<td>3165 (1740)</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>4750 (2621)</td>
<td>4085 (2250)</td>
<td>3455 (1900)</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>4900 (2714)</td>
<td>4200 (2315)</td>
<td>3625 (1996)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5120 (2827)</td>
<td>4250 (2345)</td>
<td>3750 (2065)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 18**

The chart in Figure 18 shows the effect different levels of recirculation have on oxy-fuel flame temperatures. With a recirc ratio of 3, the flame temperature can be brought down to 3750°F
This would correspond to a standard air/gas burner operating with preheated air at 600°F. Numerous melters have been run for years with preheated air at 800-1000°F which means the 3800°F flame temperature will have no impact on furnace construction or maintenance.

Figure 19

Figure 19 shows that proper burner construction, the oxy-fuel burner can produce a gas stream similar to the standard burner. Even with the low temperature, high momentum flame, the exiting gas volume from an oxy-fuel flame will be less than a standard burner. This may be detrimental in the first part of the melt cycle.

To insure maximum POC circulation through the pile, oxy-fuel burners are placed down the center of the existing air/fuel burners. At the start of the melt cycle, the standard burners are run at a reduced rate. POC from the standard burners is pulled into the oxy-fuel POC, and the higher volume stream impacts the pile. Although the volume will still be less, the temperature of the stream will be higher offsetting the lower volume.

The use of air in the furnace is not as critical at this point in the cycle because the furnace temperature is down and the cold scrap pulls the heat from the flame envelope very rapidly. NOx is dependent on time and temperature for formation, and the low flame and furnace temperatures at this point of the cycle are not conducive to NOx generation. A major gain in heat transfer will come from gas radiation.

The POC stream in a standard air/gas fired system is approximately 26% triatomic molecules. Eliminating the nitrogen POC stream raises the % of triatomic to almost 100% in the furnace atmosphere. Looking back at Figure 6, the radiation transfer shown is based on the 26% triatomic stream. Increasing the concentration of triatomic molecules increases the heat transfer. In a 2000°F furnace, the transfer of energy can double with the same net input to the furnace.

This increase in gas radiation, although effective with the initial cold scrap pile, will be even more effective once the bath has gone flat. Once the bath has gone flat, the operating temperature of the furnace will be at its highest. At this point, the time and temperature profile of the furnace will be very conducive to the formation of NOx. Operating with oxy-fuel burners minimizes the volume of nitrogen available in the furnace atmosphere thus reducing NOx formation.

The efficiency of the furnace will increase along with the melt rate because of the increase in radiation and the circulation provided by the high momentum oxy-fuel jet. The increase in heat
transfer from the flame envelope and the POC throughout the cycle will increase the melting capacity of the furnace. In most cases an increase of 20%-25% in lbs/hr melted would be expected. The 20%-25% increase is based on operating the furnace at temperatures equivalent to a standard air/gas fired furnace. If the roof and metal temperatures are maintained the same, a decrease in the flue temperature will be seen in the oxy-fuel fired furnace. This can be attributed to the better heat transfer characteristics and longer retention time of the POC in the oxy-fuel fired furnace. Any drop in temperature of the flue gases corresponds to an increase in furnace efficiency above the original calculation based on the elimination of the N\textsubscript{2} from the POC.

An additional increase in melt rate is possible if the roof temperature and/or bath temperature is raised from the original set points. This should be done cautiously, because as the previous discussion showed, an increase in bath temperature may cause an increase in dross formation. This is lost metal which must be reprocessed or land filled.

Operating costs are difficult to generalize. The cost of gas and electricity vary greatly and the cost of oxygen is dependent on quantities used where it is produced, how it is transported, etc. These are the easiest factors to evaluate. The savings or benefits for environmental factors and bag house reductions (in operating cost or maintenance) can be more difficult to ascertain.

The first step in evaluating the potential of an oxy-fuel system is to determine what the major problem is to be corrected or what benefit is to be derived.

1) Melt rate
2) NOx reduction (environmental)
3) Fuel savings
4) Bag house savings
5) Capital costs (primarily new construction)

Whatever the specific need, the evaluation should center on resolving that issue. Once it is determined that oxy-fuel is an adequate solution, the additional benefits should be factored into compare overall costs with competing solutions.

Regenerative burner systems can offer similar energy savings as an oxy-fuel system without the added cost of purchased oxygen. Regenerative burner systems make use of the same heat storage and cycling principles as used in large open-hearth steel furnaces and glass tanks. The original purpose for regenerative use was to increase flame temperatures and available heat. This allowed higher process temperatures to be attained. Today the compact regenerative burner systems are used primarily to reduce fuel consumption. Increases in production and environmental benefits are a bonus.

The most common industrial regenerative systems operate with pairs of burners. The minimum installation would have two burners. See Figure 20 A. Each burner would have a compact regenerator containing a bed of alumina and ceramic balls. This bed of alumina balls is the heat transfer medium.
Figure 20 A - Burners are installed in pairs

Figure 20 B shows a typical burner with regenerative. Under the bed there is generally an air/exhaust plenum.
Figure 21 shows the start of a firing cycle. The air valve on the firing burner is open and combustion air is fed up through the bed to the burner head. The burner operates as a normal burner. The exhaust valve is open on opposite burner in pair. Eighty-ninety percent of the products of combustion are pulled down through the heat reclamation bed. The hot gases pass through the bed and are cooled as the bed media heats up. Exit temperatures are typically in the 350°-400° (175°-205°C) range.

Once a certain POC outlet temperature or time period is reached, the burners reverse. The burner that was firing now goes to the exhaust mode and the exhausting burner begins to fire. See Figure 22.
The combustion air passing through the bed strips off the heat built up in the bed while exhausting. This results in an “average” air preheat temperature within 300°F (166°C) of the exhaust gas temperature. The burners continue to cycle generally in 45-60 second intervals. The optimum cycle time for system efficiency is dependent on the size/volume and geometry of the bed. Figure 23 shows the air preheat temperatures estimates available from different heat recovery devices and the corresponding available heat.

<table>
<thead>
<tr>
<th></th>
<th>Air Preheat</th>
<th>Available Heat</th>
<th>Fuel Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Recuperator</td>
<td>700°F (avg)</td>
<td>52%</td>
<td>25%</td>
</tr>
<tr>
<td>Radiation/ Convective Recuperator</td>
<td>1000°F (avg)</td>
<td>60%</td>
<td>33%</td>
</tr>
<tr>
<td>Regenerative</td>
<td>1800°F (avg)</td>
<td>78%</td>
<td>48%</td>
</tr>
</tbody>
</table>

**Figure 23**

In a high temperature process such as aluminum melting, the “available heat” provided by a regenerative system is similar to an oxy-fuel system. At 2150°F (1175°C), the available heat with oxy-fuel is 74%. With a regenerative system 72% can be attained. The corresponding fuel savings is 42% for oxy-fuel and 43% for the regenerative system. Typical fuel savings range in the 40-45% for both systems.

The reduction in fuel consumption reduces the volume of POC that passes through the furnace. Although the N₂ is not minimized as in the oxy-fuel system, the amount of excess O₂ present in the furnace is similar. The less total mass of excess O₂ passing through the furnace, the less is the potential for oxidation of the metal. (A case could be made that the dilution of the atmosphere with N₂ reduces the probability that the O₂ will in fact come in contact with metal. I have never seen any test in this area.)

The high combustion air temperature raises the flame temperature considerably. A typical air/gas flame runs an average temperature of 3200°-3300°F (1760°-1815°C). In a regenerative system, the flame temperature will run in excess of 4000°F (2200°C). The high temperature coupled with the N₂ present in the combustion air can/will increase the NOx formation significantly from a typical 100-140 ppm to as much as 400-500 ppm (could be higher depending on burner design).
Combustion Air Temp 60°F

<table>
<thead>
<tr>
<th>Furnace Temperature °F (°C)</th>
<th>NOx PPM (Mg/NM³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 (535)</td>
<td>55 (110)</td>
</tr>
<tr>
<td>1200 (650)</td>
<td>55 (110)</td>
</tr>
<tr>
<td>1600 (870)</td>
<td>60 (120)</td>
</tr>
<tr>
<td>2000 (1095)</td>
<td>75 (150)</td>
</tr>
<tr>
<td>2200 (1200)</td>
<td>80 (160)</td>
</tr>
<tr>
<td>2400 (1315)</td>
<td>85 (170)</td>
</tr>
</tbody>
</table>

Typical numbers. Actual data depends on burner design.

Figure 24

NOx formation increases with furnace temperature and as the air preheat temperature increases. Figure 24* shows the typical increase in NOx formation as the furnace temperature increases.

**NOx PPM (Mg/NM³)**

<table>
<thead>
<tr>
<th>Combustion Air Temp °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>600 (315)</td>
</tr>
<tr>
<td>1000 (535)</td>
</tr>
<tr>
<td>1600 (870)</td>
</tr>
<tr>
<td>2200 (1200)</td>
</tr>
</tbody>
</table>

Figure 25

As the furnace temperature increases so does the air preheat temperature further increasing the potential to form NOx. Figure 25 shows the typical increase vs air temperature.

The Bloom LumiFlame burner incorporates a baffle and tile design to minimize NOx formation at the high air preheat temperatures. The tile and gas tube design provide an air staged mixing pattern that limits the speed of air mixing with the gas. The result is a controlled mixing pattern that minimizes areas of intense heat release within the flame envelope making the overall flame temperature more uniform.
A conventional burner flame is not equal in temperature throughout the visible envelope. There are areas of intense heat and areas of lower temperature. A low NOx burner is designed to minimize the areas of high temperature as this is where the NOx formation is the highest.

The goal of the Bloom baffle design is to provide a homogenous flame envelope that minimizes NOx formation but still provides superior radiation heat transfer from the flame to the load.

Figure 26

Bloom’s baffle burner recirculates furnace gas into the flame. Its appearance is deceptively simple consisting of a body, gas nozzle, baffle and port. The baffle passages are essentially nozzles which create a jet effect on the exit side. A jet exiting a nozzle creates a recirculation zone and a low pressure area at the exit. The jet phenomenon anchors the flame in the port, ensures thorough mixing of the air and fuel, and provides the energy to recirculate POC into the port.

The ceramic battle provides support to the gas tube and is a radiation shield between the flame and the internal burner parts. Baffle hole and port geometries determine flame characteristics, such as shape and luminosity. Geometry also influences the amount of furnace gases recirculating into the port, a major factor in reducing NOx levels.

The Bloom LumiFlame also incorporates a tile to enhance recirculation of furnace gases into the flame envelope. This provides three important elements to the combustion and melting performance.
1) The reentrainment of inert gases into the flame envelope help to temper the flame temperature further minimizing the potential for NOx formation.
2) In the initial phases of the melt cycle, gas circulation is critical for optimizing the melt rate and the fuel efficiency.
3) A more uniform heat release pattern improving overall furnace uniformity.

As described earlier, pulling the inert gases from the roof and circulating them in the pile of scrap aides tremendously in heat transfer while the load is solid and accepts heat easily. Circulation in the crown (roof) area aids in minimizing the roof temperature keeping the burner system operating at a maximum input.

To further enhance circulation in the early portion of the melt cycle, the LumiFlame burner incorporates a two stage cooling air system on the gas tube.
In the early portion of the melt cycle, the cooling air is increased to create faster mixing and a higher momentum gas stream from the burner tile. This higher momentum stream increases the venturi effect pulling a greater amount of inert gases; therefore, increasing circulation in the furnace. The increase in inert gases in the envelope and the lower furnace and air preheat temperatures early in the cycle results in a minimal, if any, increase in NOx formation. See Figure 28.

When the furnaces reach temperatures of 1500-1600°F (815-870°C), the scrap pile has become a gelatin mass. At this time, radiation heat transfer becomes overwhelmingly dominant. The LumiFlame system then decreases the cooling air flow changing the burner flame to enhance flame to load heat transfer. It is important to note that the high velocity burner has many advantages in the melting process. There are some characteristics that can be a concern.

Looking at high velocity burners, one would think it is a fast mixing burner. In fact it is not. The inherent low NOx operation is due to the delay in combustion brought on by the high velocity of the gas stream from the tile and the high level of recirculated gas. In actual operation, the major heat release from a typical high velocity burner used on an aluminum melter can be 6-10 feet (2-3 meters) from the tile outlet.

In the early portion of the melt cycle, the furnace is at a low temperature and the load can be very close to the burner outlet. In a typical high velocity system this can lead to flame quenching which results in increased CO and aldehyde emissions. In poorly designed systems, this becomes a major problem with today's environmental regulations. In addition, CO emissions are lost fuel.
The LumiFlame baffle/gas tube/tile is designed to provide a uniform heat release pattern. The two stage mixing system minimizes the potential for quenching and a subsequent increase in emissions and fuel consumption. The push/pull designed combines with the gas recirculation provide excellent refractory uniformity in a flat bath condition enhancing efficiency while minimizing the potential for metal oxidation.

When designing a regenerative system, it must be taken into account that the burner will see everything the furnace will see - the temperatures, contaminants and atmosphere changes. The burner must be of a robust design mimicking the furnace construction. The regenerator is a heat transfer device. The efficiency is based on the same principles of a recuperator, the amount of surface area and mass dictates the efficiency. The greater the heat transfer surface area, the greater the efficiency. (All other parameters being equal.) The efficiency of a regenerative system cannot be judged solely on the exhaust gas outlet temperature.

If the operating burner is sending “X” volume into the furnace, the question that need asked is what % of “X” is the exhausting burner removing? The Bloom system is design to exhaust 80-90% and still provide effective heat transfer in the regenerator. Ten percent is left in the furnace to go out the flue and other opening in order to have optimized furnace pressure control. A smaller regenerator may operate at the same temperature but not provide the same furnace efficiency because 25-40% of the products of combustion are exiting through the auxiliary flue with no heat reclaiming.

Applying regenerative burners to direct charged melters and realizing the maximum benefit requires experienced planning and engineering.

1) Burner placement
2) Total gross input – cold and hot
3) Flue location
4) Accessibility for cleaning and maintenance
5) Furnace pressure control
6) Melt cycle control to meet furnace production requirements

High efficiency regenerative systems cannot make up for poor system design.

Bed Cleaning

When evaluating a furnace for application of a regenerative burner system, thought must be given to providing sufficient access around the burners to allow for removal of the bed material for cleaning. The time required between bed cleanings is dependent on the type of scrap and the amount of fluxing and cleaning done in the furnace. Even with clean scrap and minimal fluxing, etc., the bed should be cleaned once or twice a year just to remove aluminum oxides, etc., that can plug areas of the bed and limit air flow and bed effectiveness.

Bed cleaning consists of removing the bed material (alumina balls) and screening them to remove oxides and other particulate. The furnace layout must allow sufficient room for insertion and removal of heat storage material. Each burner can have as much as 3,000 pounds of bed material. A trained crew of two can remove the heat storage material and replace it with clean material in 20 to 30 minutes. System design allows bed cleaning while other burners direct fire
as conventional burners. Direct fire is described later in this paper. Bed cleaning does not require a furnace shutdown.

Control of Regenerative Cycles

The LumiFlame system cycles at intervals between 40 and 60 seconds, the time depending on the bed temperature of the exhausting burner in the pair. When the burners begin to cycle the PLC selects the burner with the highest bed temperature to fire first. While that burner fires, the exhausting burner’s bed temperature is measured. Firing/exhausting is switched when the exhaust header temperature reaches a preset temperature, 350° to 400°F (177° to 204°C). Switch over cannot occur before 40 seconds and must switch at 60 seconds even if the bed has not reached the temperature set point.

Furnace Pressure Control

Although the flue handles 10-20% of POC during regenerative firing, it can be designed to accept the full exhaust flow of the burners when the burners fire direct. Any of the burners can be placed in direct fire and operated as a standard cold air burner. The burners run on ratio at full input on cold air with flue gases exiting out the flue rather than through the regenerator exhaust system. A fouled bed can thus be cleaned while the other burners fire to maintain furnace operation. In many furnaces, the auxiliary flue is designed for 35-50% of rated input. This allows the furnace to operate at a reduced rate during bed cleaning. A special 2 stage damper system is used for furnace pressure control.

![Image of Furnace Roof](image)

**Figure 29**
Figure 29 shows a typical 2-stage combination air/mechanical damper. The mechanical damper has open and closed stop switches and limit indicating switches. Standard operation has the mechanical damper at the minimum position. This would be with an opening of 6-8", 150-200 mm. This is the “full closed” position. The air damper then modulates the air curtain over the 6-8", 150-200 mm, opening to maintain furnace pressure.

By maintaining the air gap and not allowing the damper to close completely, there is a natural pressure relief set up. Should bed plug or surges develop due to cycling high capacity burners, the furnace pressure will only build to certain point before it blows through the air damper.

The mechanical damper opens fully if:

a) furnace goes to purge
b) operator selects bed cleaning mode
c) furnace pressure exceeds safe limit (alarm sounds)
d) optionally – when furnace door opens

Furnace pressure control is critical for operating an efficient furnace with low emissions. Figure 30 shows typical lab test data for Bloom regenerative burners with different baffle designs. The bottom line is the typical operating level for the LumiFlame model.
Flue Gas Volume

As with the oxy-fuel system, the reduction in fuel consumption reduces the amount flue gases from the furnace. The overall volume from an oxy-fuel system is considerably less than a regenerative system. This would appear to be a significant advantage if the POC must be taken to a post treatment system such as a bag house. These devices generally have temperature limitations that can require air cooling. Figure 31 shows the typical flow to a bag house from a standard, regenerative and oxy-fuel system.

Required Available Heat: 10 mm btuh (2930 kw)
Inlet Temperature @ the Bag House: 350°F (175°C)
Fuel: Natural Gas w/ 10% excess air (2% O₂)

### TYPICAL FLUE GAS FLOW

<table>
<thead>
<tr>
<th></th>
<th>Ambient Air</th>
<th>Oxy Fuel</th>
<th>Regenerative</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Available Heat @ 2100°F (1150°C)</td>
<td>10 mm btuh (2930 kw)</td>
<td>10 mm btuh (2930 kw)</td>
<td>10 mm btuh (2930 kw)</td>
</tr>
<tr>
<td>Gross Fuel Input</td>
<td>25 mm btuh</td>
<td>13.5 mm btuh</td>
<td>140 mm btuh</td>
</tr>
<tr>
<td>Combustion Air (10% excess air or 2% O₂)</td>
<td>4,585 scfm (124 NM³/min)</td>
<td>2,570 scfm (70 NM³/min)</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td>460 scfm (12.4 NM³/min)</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>25,000 scfh (676 NM³/hr)</td>
<td>13,500 scfh (365 NM³/min)</td>
<td>14,000 scfh (378 NM³/hr)</td>
</tr>
<tr>
<td>Total Flue Gas Flow</td>
<td>5,000 scfm (135 NM³/min)</td>
<td>685 scfm (18.5 NM³/min)</td>
<td>2,800 scfm (75.6 NM³/min)</td>
</tr>
<tr>
<td>Flue Gas Temperature</td>
<td>2150°F (1176°C)</td>
<td>2100°F (1150°C)</td>
<td>800°F (426°C)</td>
</tr>
<tr>
<td>Approximate Flue Gas Flow to Bag House Filter @ 350°F (175°C) (60°F Air Mix)</td>
<td>39,580 scfm (1070 NM³/min)</td>
<td>5,420 scfm (147 NM³/min)</td>
<td>7,170 scfm (194 NM³/min)</td>
</tr>
<tr>
<td>Actual Flow</td>
<td>61,650 acfm</td>
<td>8,400 acfm</td>
<td>11,115 acfm</td>
</tr>
</tbody>
</table>

**Figure 31**
Conclusion

When designing a combustion system for a direct charge melter, there are many factors that need to be considered.

a) Melt rate while the most important, achieving this goal does not insure long term success/profitability.

b) Fuel efficiency should be looked at as the total utility cost to operate the furnace – fuel, electricity and oxygen if used. This operating cost rarely decreases in the future and can have a major impact on the overall cost of operating the furnace.

c) Type of material to be charged at the present and whether that will change in the future. Metal loss can be the major factor in a profitable operation. The type of alloys to be produced can have an impact on determining prudent melt rates and efficiency.

d) Environmental regulations. What are the existing limits and what is the potential for tighter limits in the future? Taxes for CO, NOx or CO\textsubscript{2} emissions. Limits on particulate emissions.

e) Future maintenance costs.

f) Total installed cost.

The final system design should consider all of these points along with the particular site requirements. The system chosen needs to fit the budget while being flexible in design to allow for future upgrades as operating conditions change.