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**Testing and Modeling of Ultra Low NO<sub>x</sub> regenerative systems  
for Aluminum Melting with Hydrogen Fuel**

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**Abstract**

Hydrogen is one of several mediums being considered for the storage of green energy as institutions around the world begin to plan for a future that is free from net carbon dioxide (CO<sub>2</sub>) emissions. As hydrogen becomes more common, so could its use in high temperature industrial heating applications where direct electrification is not practical. One such heating application might be the melting of aluminum scrap for recycling. Unfortunately, there are concerns about how hydrogen will compare to traditional fossil fuels such as natural gas for this application. For a given gross energy input, will the same amount of heat be transferred to the products given hydrogen's relatively low luminosity when burned? Will hydrogen negatively impact product properties? How about NO<sub>x</sub> emissions, will they increase and put many furnaces out of compliance with their existing air permits?

In this paper Bloom will share the results of our own research on the practicality of using hydrogen for melting aluminum scrap and give data backed insights into the questions listed above. The data we share will be pulled from physical testing performed in our regenerative R&D test furnace using 100% hydrogen and from our computational fluid dynamics (CFD) modeling analysis. Following our data and its analysis, we will outline the logical next steps to complete concept verification and move into real world validation with a focus on minimizing risk to any producer(s) who plan to take a leading role into the future of low carbon combustion.

## 1.0 Introduction

In the United States, availability of fossil fuels as efficient energy sources has resulted in an extensive distribution infrastructure making carbon-based fuels, such as natural gas, a cost-effective primary energy choice for industry. In 2022, industrials accounted for thirty-two percent of natural gas use, 10.44Tcf, in the United States, only being surpassed by power generation.[1] The combustion of these fossil fuels emits large volumes of CO<sub>2</sub> gas, contributing to global greenhouse gas (GHG) emissions. Scientific observations show CO<sub>2</sub> in the atmosphere increasing at higher rates and at elevated concentrations levels never before seen when compared to data from the past.[2] These studies, coupled with geothermal observations, have raised concerns amongst scientists and the general public leading governments, organizations and corporations around the world to action. Governments have instituted and continue to consider legislation to influence the behavior of fossil fuel users with the intent on significantly reducing human based contributions to global CO<sub>2</sub> emissions. This includes providing funding for new technology, 'green' energy incentives, in addition to enacting regulations that impose taxes and/or fines. Nations are also aligning to discuss and jointly address the concern with commitments to reduction policies or even net-zero GHG long term strategies (Paris Agreement, 2016). Investors and activist groups further influence corporations as their decision matrix now often involves examination of environmental and social impact factors. Corporations and governments around the world are actively re-evaluating their processes considering ways to reduce environmental impacts and improve global sustainability. Many industries across the United States and Europe have taken action to lead in improving their processes to provide a sustainable and climate secure future via decarbonization.

More specifically, the aluminum industry has been aggressively discussing pathways to reduce its carbon footprint by displacing the use of fossil fuels with 'Green' energy sources. Global aluminum production was said to contribute to two percent of global human based CO<sub>2</sub> generation.[3] The International Aluminum Institution projects global demand for aluminum to grow eighty percent by 2050. With the evolution of light weight cars, increasing air transportation demand and urban construction continuing to expand, CRU International forecasts aluminum demand in North America alone to increase over forty percent by 2030.

Primary aluminum production is very carbon intensive as it typically uses carbon anodes and consumes large amounts of electricity, often generated from fossil fuels. Due to higher relative electricity costs in the US, almost seventy eight percent of domestic

aluminum production was from secondary production sources in 2021.[3] The production of secondary recycled aluminum is typically fueled by natural gas, only consuming approximately five percent of the energy when compared to primary production processes, therefore emitting significantly less CO<sub>2</sub> emissions. Data collected concerning recycled can feedstock showed that in the US only forty five percent of aluminum beverage cans get recycled. This data is leading governments to consider legislation and programs to promote increased aluminum recycling activity. It is estimated that consumer participation could be easily improved to over a sixty percent can recycling rate with small changes to recycling programs and sorting technology. Analysts estimate this improvement would yield nearly 300,000 tons in additional recycled aluminum production.[4]

Aluminum is said to be infinitely recyclable, making it a very sustainable material source with growing uses. One can see how these types of programs, coupled with increased understanding of sustainability and public responsibility, will increase domestic demand for secondary recycling facilities and thereby assist in reducing Aluminum industry energy use emissions. In 2022 alone, US producers announced plans to spend over \$5 Billion in investments towards adding or improving secondary recycled aluminum production.[5]

One secondary recycling process of interest is aluminum melting in furnaces. These melting furnaces typically utilize fossil fuel gas fired burners to heat the chamber and melt the product effectively. These fuels are often natural gas, as well as other high hydrocarbon fuels commonly available. These furnaces have high connected thermal inputs thereby creating a large CO<sub>2</sub> footprint during operation. Considering a partial or full transition to a non-carbon-based fuel, such as green hydrogen, as an alternate heating fuel for these furnaces could provide a unique way to decarbonize this process. Green hydrogen is considered a clean 'energy carrier' that could serve as a transition fuel in the future scope of energy use. It provides a great way to 'transform' green electricity, produced from non-carbon sources such as hydro, wind or solar, into a non-carbon fuel source, via electrolysis, suitable for high temperature industry applications that currently utilize natural gas. Other process studies considering hydrogen fuel adoption are also underway. The stoichiometric products of combustion are water and N<sub>2</sub>, when burning via air, free of CO<sub>2</sub>. Hydrogen can possibly be generated locally using green energy sources, minimizing the need for new infrastructure. Furthermore, governments appear to be incentivizing industry to move towards this 'carrier fuel', specifically the US congress recently passed the Inflation Reduction Act of 2022 including many clean energy initiative incentives.[6] Many companies within the industry have publicized corporate goals to

attain reduced or net zero GHG emissions and are investigating this exciting opportunity to reduce the carbon emissions of their processes.

There are many factors that influence the process of recycling aluminum in a natural gas fired melting furnace. Understanding how each affects the efficiency and quality of the process and product is critical to success if any transition is to be considered. When just one input or parameter of the process is changed, we must study and understand what impacts are realized in the process as well as in downstream processes.

This paper's focus will be to analyze the use of hydrogen on a regeneratively fired aluminum melting furnace. The basis is to evaluate the fuel's general impact, in comparison to natural gas, on process performance. Specifically, as it relates to heating, emissions and thereby product quality. The methods and tools utilized to analyze these areas of concern are CFD modeling of the combustion reactions and thermodynamics within the furnace, coupled with laboratory testing data from a furnace system matching the CFD model.

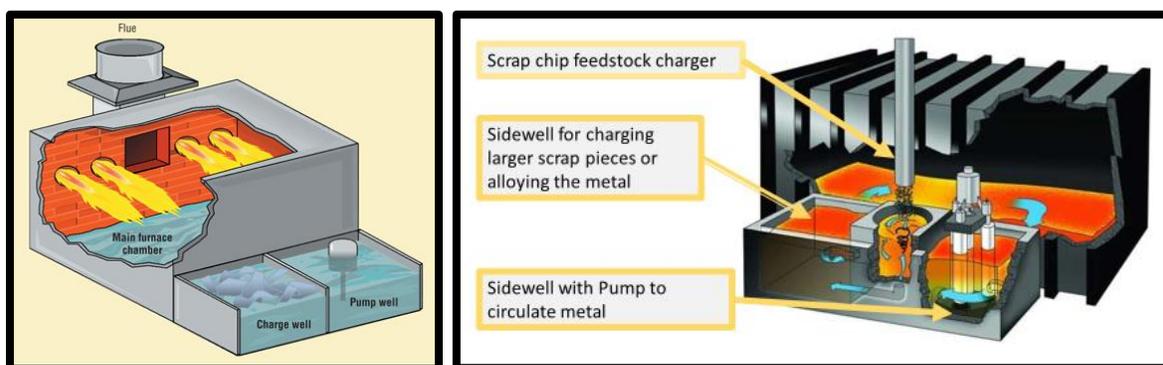
## **2.0 Technical Basis of Analysis**

### *2.1 Furnace Application*

Let's begin with a brief description of the process we are evaluating. Aluminum melters have various designs and modes of operation. Many melting furnaces are operated as batch processes, but some are designed for continuous operation where product is fed into a side well. In a batch operation, the charging process can vary based on operator loading pattern as well as scrap product shape/size. This becomes difficult and resource consuming to model accurately. For more broadly useful results and to simplify modelling, we chose to consider a rectangular side well type continuous process aluminum melter. In this process the furnace is full of a flat molten aluminum bath and operates at a constant furnace temperature condition. This process suits steady-state modeling well and can also be easily replicated in a rectangular shaped laboratory test furnace experiment. This setup will provide a good start to understanding our process impacts and gaining valuable experience allowing the study of more complicated examples in the future.

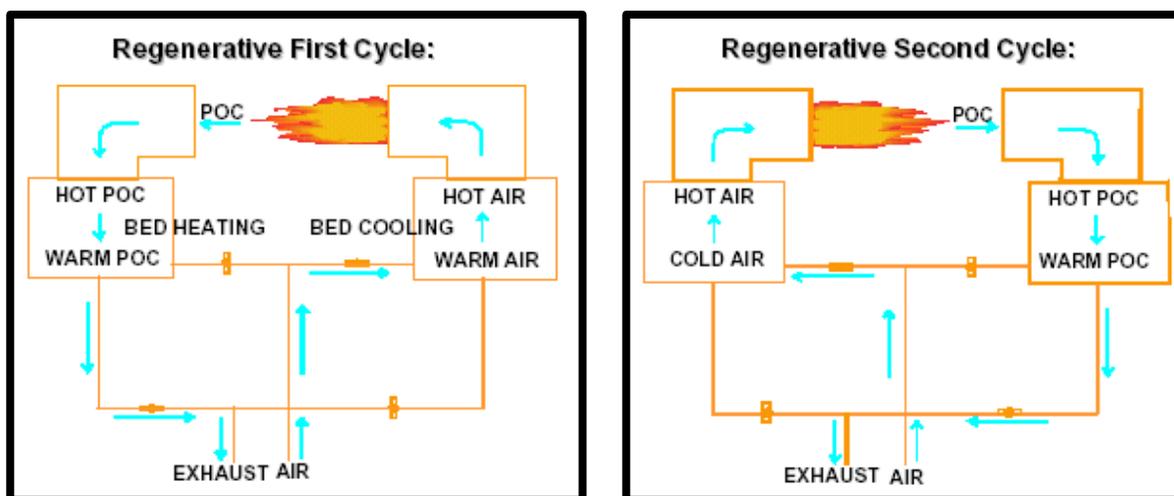
An aluminum side well melter operates as a continuous process where the primary enclosed heating chamber remains full of hot molten product and an adjacent open side well bath of molten aluminum is charged with scrap material for melting. There is a stirrer

or pump mechanism that recirculates the molten metal continuously from the side well into the main heating chamber for reheating and then back into side well for additional charge. The heating chamber is held at a constant temperature transferring needed heat into the circulated molten aluminum to restore lost temperature from melting the charged scrap solids in the side well. Once molten metal reaches the desired capacity a portion of the metal is transferred to a nearby holding furnace or directly to a casting process. Figure one shows concept sketches relating to this type of melting application.



**Figure 1: Side well Aluminum Melter Illustrations, including Lotuss pump [7,8]**

Heat is typically provided by two or more side mounted natural gas fired burners. For improved efficiency and reduced CO<sub>2</sub> emissions, these burners often utilize state-of-the-art ultra-low NO<sub>x</sub> (ULN) regenerative combustion technology. Regenerative burners essentially incorporate very high efficiency internal heat exchangers. The burner assembly consists of a burner head, which mounts to the furnace to combust fuel within the heating chamber. The burner head is mated to a heat exchanger. This heat exchanger, called a media case, is a refractory lined case full of some form of heat exchanging media. For thermal shock longevity and efficient heat transfer, this media is often comprised of many small solid refractory spheres or balls. The combustion system is fed with a series of alternating valves and two blowers. One blower provides forced draft combustion air, while the other provides necessary suction for exhaust extraction. The burners operate in pairs where one burner fires into the furnace chamber combusting fuel to provide necessary heat to the process. See figure 2.



**Figure 2: Simple System Schematic of Regenerative Burner Operation**

During this firing cycle, the second burner operates in a pullback mode, acting as a flue to exhaust a large portion, typically about eighty percent, of the firing burner's products of combustion. This pullback is created utilizing an exhaust blower's force to pull the gases out of the furnace through the second burner head and through its media case, thereby preheating the refractory media balls within it. The remaining twenty percent of flue gases produced by burner one exits the furnace via a traditional flue maintaining necessary positive furnace pressure for good operating practices. After a short period of time, approximately one minute, the burners cycle so that burner two then fires and burner one exhausts. Burner two is supplied with combustion air through its now hot media case achieving high temperature preheated air and efficient flue gas heat recovery to our process. As burner two fires, burner one is pulling hot flue gases through its now cold media bed, storing the flue gas heat in its media in preparation for its next firing cycle. This technology provides highly efficient combustion, typically more than seventy percent (HHV basis), to high temperature processes. This allows for reduced fuel consumption and CO<sub>2</sub> emissions on natural gas fired melters and will enable critical cost control for fuel costs on any transition to hydrogen.

## 2.2 Fuel Comparison

Now that we have established and provided a basic understanding of our process and understand hydrogen can be an effective path to decarbonizing a process, we must understand what affect switching to hydrogen fuel for supplying the necessary melting energy could have on our process. While the combustion of natural gas is well understood in the metals industry, the use of hydrogen is not common due to current

infrastructure and fuel costs. The combustion of hydrogen presents several challenges to end users and their combustion technology suppliers. Let's start by understanding what parameters of our furnace performance are impacted by fuel selection. The fuel is combusted by a burner to release energy into the furnace in a very specific pattern. How that energy is released impacts many parameters of the furnace's thermal performance such as: cycle time, fuel efficiency, melt loss, melt quality, furnace maintenance and emissions produced.

Furnace performance can be affected by changes in fuel but more specifically it's how the burner design handles that fuel change that leads to process impacts. To this extent much burner development has occurred and continues relative to hydrogen combustion. To evaluate burner performance on various fuels, let's compare our base fuel case with the intended future fuel. More specifically, we need to understand the demands of future fuel cases: will the furnace be required to operate on both fuels, just one or even a blend? Some users may want fuel flexibility so costs, productivity and quality can be optimized. We also understand a fuel blend could provide optimized results while minimizing negative impacts, however every user will have different objectives of project outcomes influencing final decisions. As an early stage of exploring, we are simplifying our analysis to using either 100% natural gas or 100% hydrogen fuel. This approach should also help clarify understanding of impacts due to greater contrast in inputs. To further clarify results, our analysis will consider a full natural gas chemical make-up, not just pure methane (CH<sub>4</sub>). Our natural gas analysis for testing and modeling utilized the following volumetric composition: 94.1% CH<sub>4</sub>, 3.9% C<sub>2</sub>H<sub>6</sub>, 0.9% C<sub>3</sub>H<sub>8</sub>, 0.5% higher hydrocarbons, and 0.6% inerts.

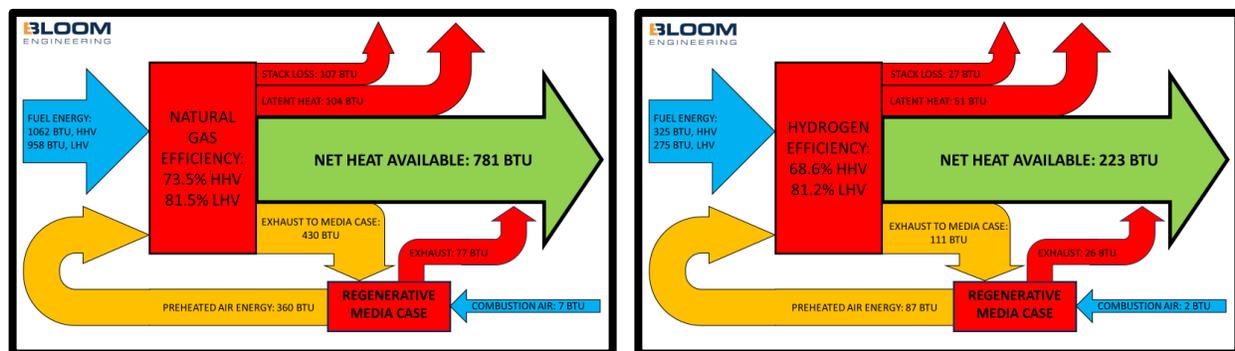
The combustion of hydrogen fuel relative to natural gas has several key differences relative to heating use. We will evaluate and discuss areas of concern and the perceived process impacts. Let's start with a table to quickly point out and compare key differences in the fuels followed by discussion on how they could impact process performance. See figure 3.

Property	Units	Hydrogen	Natural Gas	Ratio or comment
Heating Value, LHV	Btu/scf	275	958	0.29
Flame Speed	ft/s	~9.8	~1.4	~7
Flamability Range	Lean Limit % volume	4	5	More flammable
Flamability Range	Rich Limit % volume	75	15	Much more flammable
Combustion Air-to-Fuel, 1.1 λ	scf/MM Btu, LHV	9520	11482	0.83
POC-to-fuel, 1.1 λ, wet	scf/MM Btu, LHV	11345	12568	0.90
POC-to-fuel, 1.1 λ, dry	scf/MM Btu, LHV	7709	10418	0.74
POC, %H2O, 1.1 λ	% by volume	32	17	
Flame temperature	°F, 1.0 λ, 100°F gas, 100°F air	3872	3533	+339 °F
Flame temperature, Regen	°F, 1.1 λ, 100°F gas, 1800°F air	4454	4105	+349 °F
Flame Color/Radiation		Clear, Lt Blue	Orange, Yellow	Less radiant flame

**Figure 3: Comparison of Fuel Properties important to Thermal Performance**

### Energy Content

Hydrogen has a much lower BTU value per unit volume. So, one will need over three times the supplied volume of hydrogen fuel to meet the energy input of natural gas. More importantly, it has about sixty percent more latent heat loss (~60,000 BTU) per million (MM) BTU burned so if we were to consider energy replacement on a higher heating value (HHV) basis we would supply over six percent less net heat to our process. Figure 4 depicts energy diagrams showing the energy balance for one standard cubic foot of each fuel. Since our analysis uses efficient regenerative burner technology, the energy balance depiction also includes this. We can see on a lower heating value basis that hydrogen appears very much equal to natural gas.



**Figure 4: Sankey Energy Diagrams for Regeneratively Fired Melter (1scf fuel)**

Considering this meaningful higher latent heat loss and overall fuel efficiency of our system, we should evaluate our comparison and any shift to hydrogen fuel on a net heat available energy basis.

$$\frac{\text{Natural Gas Net Available Heat}}{\text{Hydrogen Net Available Heat}} = \frac{781 \text{ BTU}}{223 \text{ BTU}}$$

$$= 3.50 \text{ scf H}_2 \text{ per scf Natural Gas}$$

*Products of Combustion (POC): Constituents and flows*

The stated main reason for exploring hydrogen as a fuel is due to POC constituent differentiation. Green hydrogen POC's leave no carbon footprint (CO<sub>2</sub>) and consist only of water vapor. However, with the absence of CO<sub>2</sub> the hydrogen fired furnace atmosphere will consist of over thirty percent water vapor by volume, nearly double that of natural gas. Will this impact product metal quality or increase melt loss? This can also impact stated NO<sub>x</sub> emissions, discussed in detail later.

Note that Hydrogen has ten percent less POC volume per MM BTU burned. For an existing furnace and flexible fuel burner system, this reduced POC volume, coupled with reduce air-to-fuel ratio, would allow the system to be fired at an increased input on hydrogen fuel to aid in heating without impacting flue design or fan capacity. However, on batch type melting furnaces the lower POC volume could negatively impact convective heating for lower furnace temperatures at the beginning of the batch melt cycle.

Finally, POC volume per unit energy when compared on a DRY basis is twenty six percent less. Therefore, any NO<sub>x</sub> emissions measured on a dry sample volume basis (parts per million - ppm) will be skewed higher relative to a comparison on mass per unit energy basis, lb(#)/MM BTU relative to natural gas.

The explanation for this comes down to the waste gas volumes per unit energy of the two fuels. When sampling is done on a dry basis, as would be the case with most exhaust analyzers, the results are more concentrated by volume (higher ppm NO<sub>x</sub>) for the same amount (mass) of NO<sub>x</sub>. The exaggerated difference in POC volumes on a dry basis is due to the higher volumetric percentage of H<sub>2</sub>O in the wet exhaust gases when firing with hydrogen (~32%) compared to natural gas (~17%) at ten percent excess air.

As an example to illustrate the above point, please consider two furnaces that are being heated by direct combustion, both of which have the same NO<sub>x</sub> emissions equal to 0.1

#/MM BTU. The furnace heated using natural gas has a concentration of NO<sub>x</sub> in its flue gases of 75 ppm (corrected to 3% O<sub>2</sub>) on a dry basis, equaling 0.1#/MM BTU. The second furnace is heated using hydrogen where concentration of NO<sub>x</sub> in its exhaust gases will be about 103 ppm (corrected to 3% O<sub>2</sub>) on a dry basis, 37% higher by volume (ppm) yet still equal by mass per unit energy or 0.1 #/MM BTU. This is very important to note as some air permits include a maximum concentration (ppm) limit and unless amended would unfairly disadvantage hydrogen compared to natural gas and many other common hydrocarbon fuels.

*Burning Properties: Flame Speed, Flammability, Flame Temperature and Flame Luminosity*

The combustion properties of hydrogen are unique and must be considered in burner design. More specifically, hydrogen has a very fast flame propagation, with a flame velocity over seven times that of natural gas. Furthermore, it has a much larger flammability envelope than natural gas. These factors lead to quick, readily occurring combustion when using hydrogen. This makes for improved burner stability and operation but at a possible consequence of shorter flame lengths. In turn, a shorter flame can affect the heat release pattern/distribution within the furnace possibly leading to reduced melt rates. A shorter flame, or more concentrated heat release pattern, could lead to increased melt loss due to higher localized bath temperatures. Finally, a shorter flame releasing the same energy could lead to higher peak flame temperatures, ultimately having the potential to increase NO<sub>x</sub> emissions and make regulatory compliance more challenging.

In addition, the adiabatic flame temperature for hydrogen is nearly 340°F hotter than natural gas. This creates problems for burner designers due to higher flame temperatures and just mentioned challenge of potentially higher NO<sub>x</sub> emissions. Let's point out that though these characteristics could lead to shorter, hotter flames the fact that they allow for more stable combustion, will allow combustion technology developers to aggressively apply known NO<sub>x</sub> reducing techniques with less likelihood to make the burner unstable. This allows for a burner capable of counteracting these combustion phenomena and reducing the potentially negative thermal performance impacts. As we can see, switching to hydrogen combustion runs elevated risks of creating non-compliance regulatory emission issues and the process outcome will be heavily dependent on combustion technology utilized.

A final concern of hydrogen burning properties is the flame luminosity. Due to no carbon, and as a result no soot, present in the POC's the flame lacks the typical bright

yellow/orange flame we are accustomed to observing from hydrocarbon combustion. Hydrogen burns with a light blue to clear color as it only has water molecules to emit light in the visible light spectrum. Low luminosity can impact radiant heat transfer properties of the process thereby potentially reducing melt rates. The risk here is somewhat minimized as developments in ULN burners over the past three decades have greatly reduced the luminosity of hydrocarbon flames. Advances in this technology have even coined the phrase 'flameless' oxidation due to the reduced non-luminous qualities of some ULN burners utilized on today's melting furnaces. So, at this point the concern on flame radiation due to visible luminosity may be less of a risk factor.

Due to the recent strong interest in hydrogen combustion, burner manufacturers have been testing and developing equipment to address these challenges. In addition, suppliers know that many customers will want the equipment to be 'fuel flexible' so they can operate on various fuels, or even blends, to take advantage of lower cost or lower CO<sub>2</sub> fuels available.

Our analysis will utilize a CFD model and lab testing furnace, which will closely simulate that of an aluminum melter, to evaluate and discuss these impacts considering a fuel transition to hydrogen specifically on thermal performance and NO<sub>x</sub> emissions. Let's look at our CFD model and laboratory test furnace in more detail.

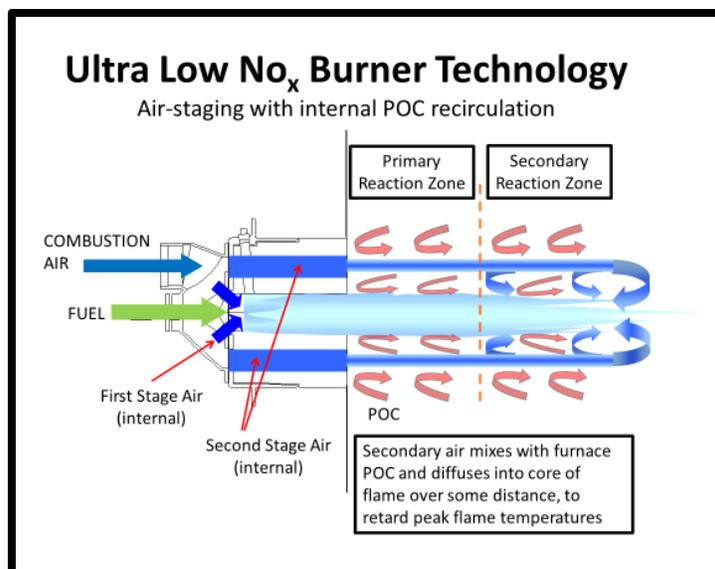
### **3.0 Methods of Analysis**

#### *3.1 Laboratory Test Furnace*

The R&D test facility is located in Pittsburgh Pennsylvania. Included at the R&D center is a fully functional PLC (programmable logic controller) controlled regeneratively fired combustion system. This furnace replicates a single pair regenerative burner system as supplied on an aluminum melting furnace.

Due to the development nature of this furnace, one of the burners is a current technology Bloom 1150 series ultra-low NO<sub>x</sub> burner, while the second burner is the latest development in Bloom's ultra-low NO<sub>x</sub> regenerative burner technology, the Bloom 1650 series burner. Both burners utilize forced draft air staged NO<sub>x</sub> reducing technology coupled with burner port geometries that induce specific volumes of internal flue gas recirculation into the flame further reducing NO<sub>x</sub> emissions. The air staging technology provides a fuel rich primary combustion reaction zone right at the burner port/wall which stabilizes combustion as well as suppresses NO<sub>x</sub> emissions. The burner simultaneously

directs the remaining combustion air downstream (further out into furnace atmosphere) of this primary reaction zone to complete combustion of the fuel at the desired thermally efficient slightly oxidizing overall combustion equivalence ratio. This 'air staged' combustion of the fuel greatly reduced NO<sub>x</sub> emissions from the combustion process while also providing very uniform and efficient heat release within the furnace. See figure below displaying air staged burner concept (not to scale).

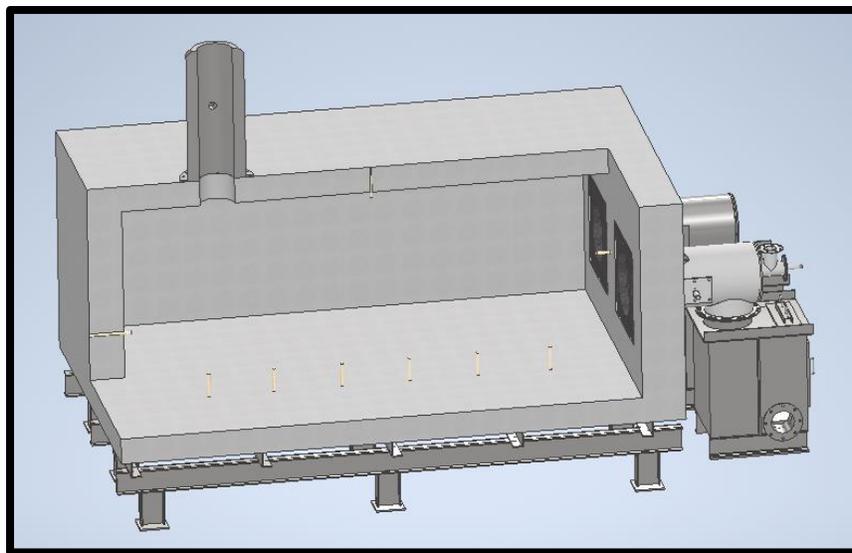


**Figure 5: Test furnace 3D Representation (burner and measurement locations)**

A PLC controlled system monitors and automates all functions of the combustion system, providing NFPA compliant industry standardized safety measures. It also monitors and records pressures, flowrates, temperatures, emissions, status and position of all the combustion equipment. It includes VFD controlled blowers for reduced energy consumption.

The furnace is a dense firebrick construction which insulates the process similar to dense cast field refractory and doubles as a suitable load to allow reasonable warm-up periods with sufficient data acquisition time. The firing chamber is a simple rectangular shape similar in design to our desired side well melting chamber application. Unfortunately, the furnace firebrick wall structure makes the design not suitable to hold and melt aluminum, so actual aluminum interaction cannot be physically tested. The interactions along the 'bath' will need to be solely analyzed via CFD modeling and field testing. The furnace includes flue damper pressure control and has type k ceramic sheathed thermocouples mounted in the walls, roof and hearth to record representative furnace temperatures as

well as flame temperature profiles. The furnace temperature is conservatively (for emissions measurements relative to furnace temperature) measured at a location on the burner wall centrally between the two burners protruding two inches into the furnace atmosphere. This location avoids flame impingement which could create the potential for 'false high' furnace temperature readings. The hearth thermocouples are specific to the 1650 series burner location. These hearth thermocouples are positioned approximately nine inches above the hearth to capture approximate flame envelope boundary temperature measurements. At a minimum, these provide POC gas blanket temperatures just above our simulated 'bath' surface (hearth). There are observation ports to allow engineers and customers alike to observe burner flame performance. The flue is in the roof, on the furnace centerline. A water-cooled stainless probe is located near the flue exit to extract hot POC samples from the combusted furnace atmosphere for emissions measurements. The flue damper is controlled by the PLC to always maintain positive furnace pressure. The furnace regularly fires natural gas fuel and is retrofittable to fire any other gaseous or liquid fuel mixture. The piping and PLC control system incorporate concentric gas orifice assemblies combined with HART differential pressure transmitters to calculate the air, fuel, and burner pullback volumetric flow rates. The furnace combustion atmosphere is controlled to 1.1 -1.15 lambda ratio as would be typical for good furnace practice and to minimize thermal emissions. The figure below shows a 3D representation of the furnace geometry, burner location, flue location and thermocouples.



**Figure 6: Test furnace 3D Representation (8ft W x 14ft L x 5ft H, internal)**

The figure below shows pictures of the test furnace system.



**Figure 7: Pictures of R&D Test Furnace**

One final limitation of the laboratory test facility is continuous long-term firing on hydrogen fuel. Hydrogen is not available via any pipelines currently feeding the facility. Hydrogen supply is sourced via a header fed by a combination of bottled gas cylinder banks. Due to the high connected thermal input of the test system, approximately 4MM BTU/hour, firing and data acquisition on hydrogen is done in short intervals at key furnace temperatures. Therefore, the burners have been designed to be fuel flexible such that heating could occur on natural gas with intermittent switchover to hydrogen firing to capture data. We believe this design suits the needs and current desire of our industry customers such that switching to or from hydrogen is both simple and reversible if desired.

In summary, our physical lab furnace testing will demonstrate:

1. Burner flexible fuel capability
2. Heating effectiveness
  - a. Luminosity via visible flame observations
  - b. Comparative flame profile patterns via hearth thermocouples in-line with the burner
3. Regulatory compliance
  - a. NO<sub>x</sub> emission recordings

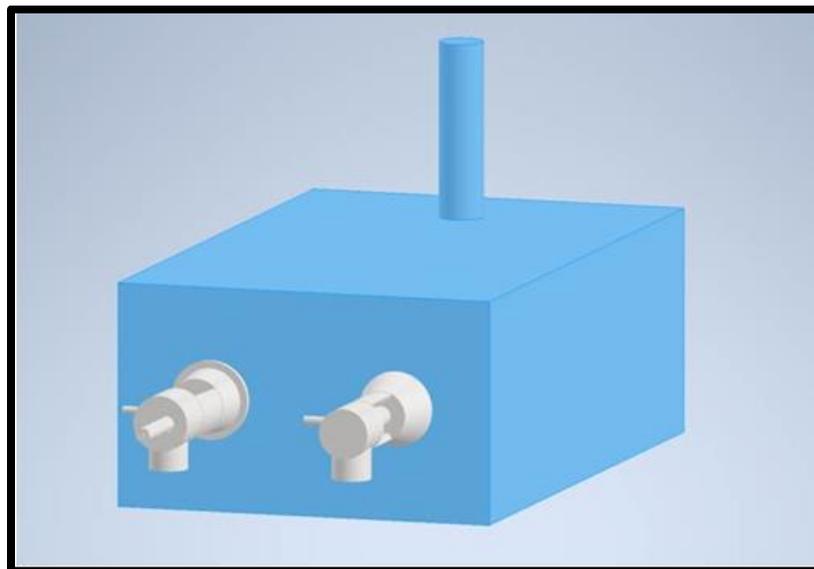
### 3.2 CFD Modeling Analysis

Bloom Engineering has been utilizing CFD to aid in burner design and furnace performance evaluations for over 30 years. It is used to predict performance variations

on many furnace applications including aluminum melters, forge furnaces, steel reheat furnaces, steam methane reformers, ore pelletizing furnaces and thermal oxidizers to name a few. This experience has helped improve accuracy, speed up development and reduce risk on many projects.

The comparison modeling was carried out using Ansys-FLUENT with a steady-state PDF combustion model. A 13-species non-adiabatic PDF scheme was used for the hydrogen fuel cases. Some prior cases had been run with an Eddy-dissipation model, which yielded similar results but was more computationally expensive. Boundary conditions were applied to match the lab test data, such as average furnace wall temperature.

Figure 8 below is the furnace model used for our analysis. It is a replica of the R&D test furnace geometry and burner technology, like an aluminum side well melting chamber. The model simulation was evaluated at steady state nominal burner firing rates of approximately 4MM BTU/hour (LHV). The furnace walls were simulated at 2100°F temperature. When analyzing hydrogen firing the fuel was assumed to be 100% pure H<sub>2</sub>. The natural gas analysis used was as stated earlier in section 2.2. The air to fuel ratios were set at good practice target of 1.1 lambda ratio (10% excess air). The regenerating burner was modeled at 80% flue gas pullback with the remainder of flue gases exiting the furnaces at the damper controlled stack location.



**Figure 8: CFD Furnace Model**

We will present the following comparative (natural gas versus hydrogen) analysis from our CFD model simulation results:

1. Heating effectiveness
  - a. Flame shape via chemical composition of flame envelope in the furnace at the burner centerlines
  - b. Flame temperature profile at the burner centerline
  - c. Heat flux plots at the bath surface
2. Melt loss
  - a. POC flow paths within the furnace
  - b. POC increased water vapor, specifically at the metal bath surface
3. Regulatory compliance
  - a. NO<sub>x</sub> emission predictions

## 4.0 Analysis Data and Discussion

### 4.1 Heating effectiveness

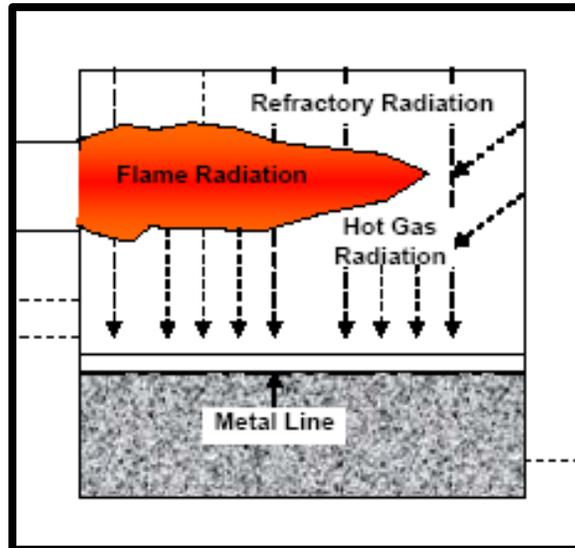
#### *Flame Shape*

A key concern we have discussed is whether the transition to hydrogen fuel will impact the process heating effectiveness. Heating effectiveness impacts melt rates and cycle times, which are key concerns to an end user operating as productively and efficiently as possible. Heating effectiveness is driven by the overall thermal performance of the combustion system transferring heat to the process. A factor to consider in optimizing heating effectiveness is flame shape as it relates to 'bath coverage'. Due to the highly effective heat transfer properties of radiant heat, we desire to 'cover' as much of our desired load with our combustion flame envelope to optimize heating performance. At elevated process temperatures such as our application modelled, radiation dominates the heat transfer occurring exponentially as it relates to the temperature difference. Radiation heat transfer is also linearly dependent on emissivity of the source and area which it radiates from. Optimizing radiation will yield ideal heating performance.

$$Q_{radiation} = \sigma(Emissivity)(Area)(T_{flame}^4 - T_{product}^4)$$

Our process energy receiver is the molten bath, our entire hearth area of the furnace in our model. What sources radiate energy to our bath at the highest temperatures? The flame ( $T_{flame}$ ), POC gases within the furnace and the furnace's inner surfaces (roof and

walls), typically hard refractory. However, when we consider surface area and emissivity ratings, the roof and walls are the largest energy emitters. See the figure below.



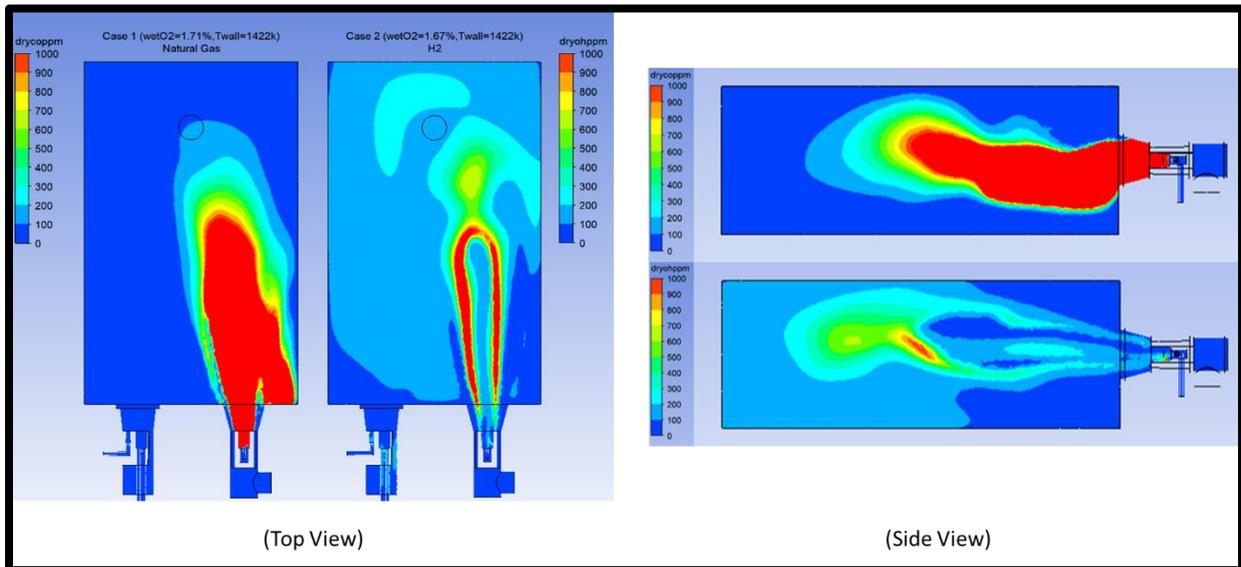
**Figure 9: Radiation occurring within a Side well melting aluminum furnace**

Again, with the evolution of ULN 'flameless' burner technology, and understanding that in our process where radiant heat is highly driven from radiant refractory surfaces, experience has shown melt rates unchanged or improved with ULN burner's less luminous flames. This is due in part to ULN burners having longer flame profiles. These longer flames provide more heat release area and consequently more uniform furnace heating profiles, but also show us how heat transfer from radiant refractory surface areas dominate heat transfer to our load. The primary heat transfer inside well type melters is re-radiation from the refractory surfaces to the bath. This re-radiation accounts for 85%-90% of the energy transferred to the product. Efficient and productive well melters are designed to optimize these radiation heat transfer mechanisms. [9]

Since experience in converting to 'flameless' combustion systems in these processes have not shown to be hurtful to heating effectiveness, we can be less fearful of this risk. However, we see that even with less radiant ULN flames, flame shape (radiant source area) over the bath plays an important part in optimizing overall thermal performance of these systems and should be considered. So, it is prudent to compare our flame shape to mitigate risk. Simply stated, flame footprint transfers energy effectively to our load and improved or maintained bath flame coverage tends to yield optimized melt rates.

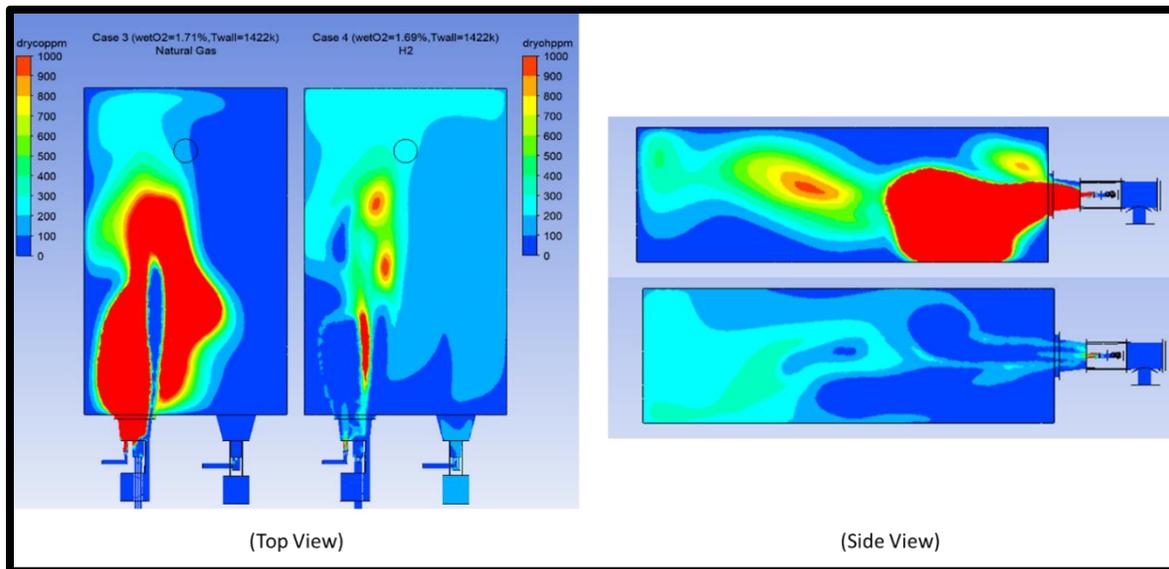
One must now define flame shape. Some industries differ on the definition, but for the purposes of this analysis, we are considering a natural gas flame envelope to be fully combusted where our POC's have CO concentrations of 1000 ppm or less. Since our hydrogen combustion POC's do not contain CO, we must consider another partial combustion radical, in this case OH. When the POC concentration of OH is 1000ppm or higher, we will consider that region part of our on-going hydrogen combustion or the flame envelope. See slides comparing these parameters below. Let's also point out that each slide is labeled with a case number. The following describes each case:

- Case 1: 1150 series ULN burner firing on natural gas fuel
- Case 2: 1150 series ULN burner firing on hydrogen fuel
- Case 3: 1650 series ULN burner firing on natural gas fuel
- Case 4: 1650 series ULN burner firing on hydrogen fuel



**Figure 10: Flame Shape Comparison of ULN 1150 burner: NG vs Hydrogen**  
(Views shown at burner horizontal & vertical centerlines)

When comparing the flame shapes presented in the slides above, we can see the flame lengths are essentially equal when considering 1000ppm flame envelopes (red regions). These slides support that the flame coverage (flame radiation heat release) on hydrogen is nearly equal to natural gas when considering flame length. Note that the hydrogen flame side view shows flame tail buoyancy and pulls away from the bath towards the roof.

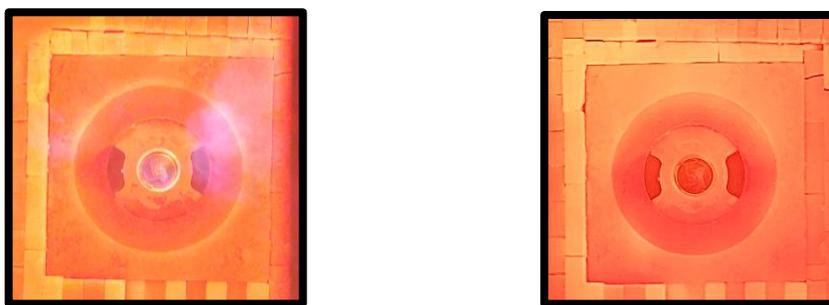


**Figure 11: Flame Shape Comparison of ULN 1650 burner: NG vs Hydrogen  
(Views shown at burner horizontal & vertical centerlines)**

When analyzing the 1650 series burner results, it is important to note that the burner air/fuel mixing is non-symmetrical in nature relative to burner centerlines. This creates a flame that is more offset from our burner centerlines, making our flame views shown above (on vertical/horizontal centerlines) a little less obvious when compared to the symmetric 1150 series shown first. The slides show improved staging of the fuels leading to a larger flame envelope relative to the 1150 series. When comparing the 1650 series on the two different fuels, the noticeable flame length, as indicated by the 1000ppm (red) regions appear similar again. So, even though hydrogen has higher flame speeds that typically lead to shorter flames our model shows that the staging effect of the ULN burner technology negates that phenomenon, providing equal flame shape when changing our fuel type. Note that the hydrogen flame side view shows the flame tail pulling towards bath. Melter's often have their burners angled down towards the bath to overcome buoyancy effects and keep the flame closer to the bath for better heat transfer. The R&D furnace has burners mounted horizontal (no angle), so we modelled accordingly. Later results will show the effect that not tilting the burners down has on our heat flux.

Let's consider the R&D test furnace now for the opportunity to observe the flame appearance, both luminosity and shape. Flame emissivity, or luminosity, contributes to the radiant heat transfer from flame linearly. When ULN burner technology is implemented, visible flames become very difficult to observe and accurately measure due

to their low luminosity characteristic, resulting from reduced peak flame temperatures. As furnace temperatures increase and the refractory surfaces become more luminous approaching ULN flame luminosity, therefore flame visibility becomes even more difficult. As a result, flame shape and length at our process temperatures were not visually recordable in the test furnace, however luminosity could still be considered. The figure below shows representative pictures of the natural gas and hydrogen 'flames' observed from the ULN burners on our furnace at 2000°F temperature, slightly lower than our process, to aid visibility. It is apparent that flame luminosity is minimal at temperatures like our application. The natural gas flame exhibits noticeable but very faint light blue flames anchored to the burner. These dissipate in color and are unnoticeable within a few feet of the burner hot face. The hydrogen flame is clear except for a very faint, extremely light blue flame right at the burner face, not even visible in the photograph. There is no observable flame pattern within the furnace when firing hydrogen fuel.

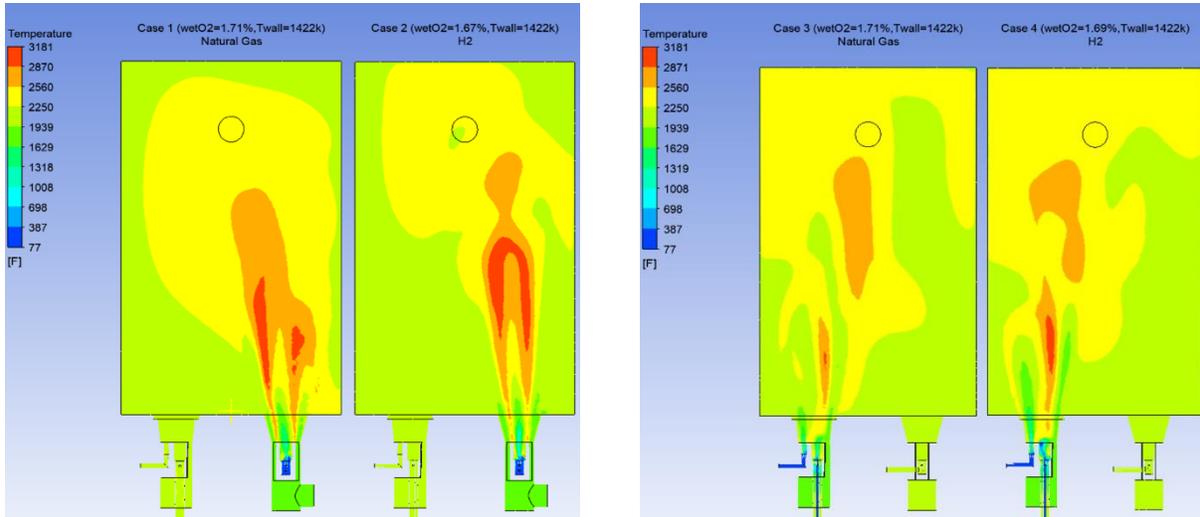


**Figure 12: R&D furnace ULN burner flames: natural gas (left) and hydrogen (right)**

These comparisons show the burner flames on either fuel exhibit no significant flame luminosity. These observations support the notion that our concerns of hydrogen flames impacting our heating effectiveness due to low luminosity (emissivity) are a very minimal risk to our process performance.

The major contributor to flame radiation heating is peak flame temperatures ( $T_{\text{flame}}^4$ ). Unfortunately, peak flame temperatures also lead to increased  $\text{NO}_x$  emissions within the burner POC's. The key is to optimize flame temperatures across the flame envelope to maximize radiant heat transfer while minimizing thermal  $\text{NO}_x$  creation. The CFD model was used to analyze flame and POC temperatures within the furnace. The figure below is the model's comparison of temperatures along a horizontal plane at the burner centerline. These figures provide insight into whether any expected difference in radiation heat transfer should be expected based on peak temperature concentrations, as well as overall

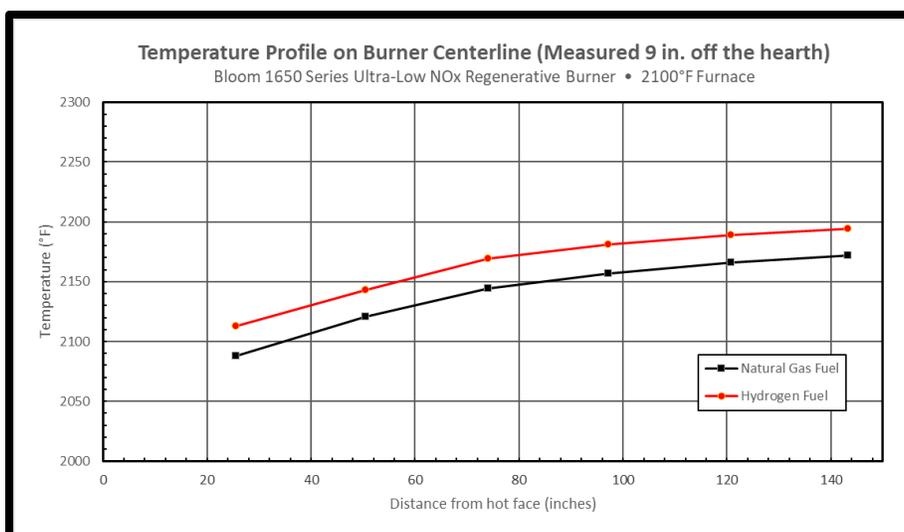
temperature profiles. The left image is the 1150 series technology, whereas the right image is the 1650 series ULN burner simulation.



**Figure 13: Temperatures along the burner centerline: 1150 (left) and 1650 (right)**

In all cases we see very similar heating profiles on both fuels fired. The hydrogen cases both show slightly larger regions of maximum flame temperatures, as expected due to its higher adiabatic flame temperature discussed earlier. The 1650 series burner shows increased heating to the far end of the furnace due to improved burner staging properties. This leads to improved uniformity and an expected increase in performance. These results indicate that radiation energy from the hydrogen flames should be maintained or improved relative to natural gas. It also indicates a possible concern for increased challenge of higher  $\text{NO}_x$  emissions, more so for the 1150 series, due to larger regions of peak flame temperatures. This will be evaluated further in the emissions results, specifically those obtained from the test furnace.

The test furnace hearth thermocouples positioned along the burner centerline show relative heating profile comparisons as well. The location of the thermocouples, 9" above hearth or 21" below burner centerline, put them just under the flame envelope but provide us with valuable relative heating performance of the flame/POC's near the product. The chart below compares recorded temperatures on the thermocouples in-line with the 1650 series burner.



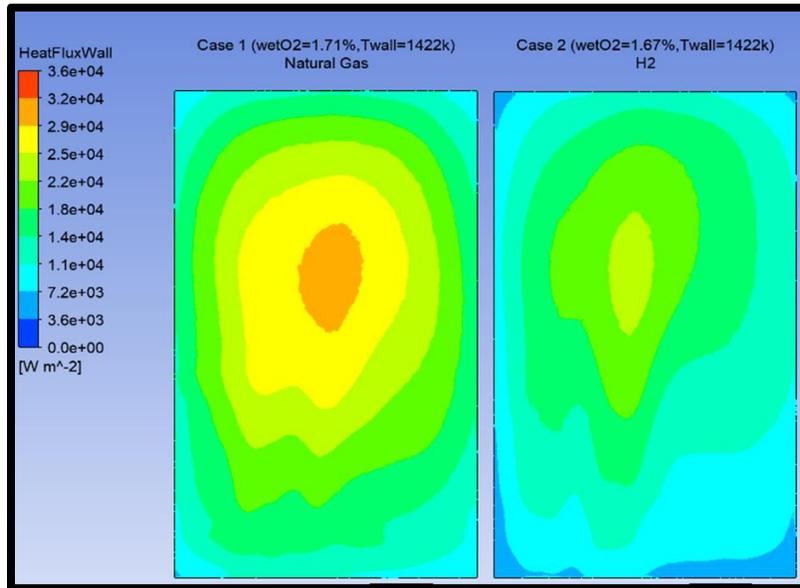
**Figure 14: R&D Furnace Temperature Profile on 1650 Series Burner Centerline**

All thermocouples showed a relative temperature increase of approximately 25°F. The thermocouples are shielded in ceramic sheaths to minimize destruction of the equipment. The sheath dampens the heat transfer, muting the results some, but it is still obvious that flame/POC temperatures have increased with the fuel change from natural gas to hydrogen firing. The heating profile continues to rise further away from the burner, agreeing with CFD model results for the 1650 series, showing good burner staging properties.

All our comparisons of flame shape made above indicate that a switch to hydrogen fuel will not negatively impact the flame radiation process performance parameter.

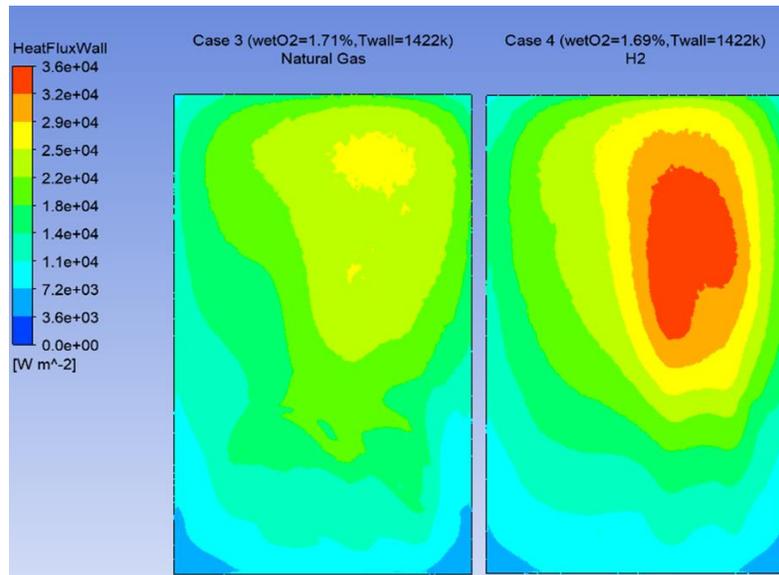
#### *Heat Flux at the bath surface*

Another key performance metric to consider in furnace heating effectiveness is optimized heat flux. Our process productivity is driven by heat flux into our product. If heat flux is optimized across the bath, we expect to maintain or improve productivity (melt rates). See the CFD results below detailing simulated heat flux plots at the bath surface. The first figure shows the expected heat flux of the 1150 series burner.



**Figure 15: Heat flux at furnace floor/bath: 1150 series NG (left) and H<sub>2</sub> (right)**

The 1150 series hydrogen heat flux results at the product surface (hearth) were reduced by 5-10% in most regions. As mentioned earlier, the 1150 hydrogen flames displayed some buoyancy which is negatively affecting heat flux at the bath surface. Even with increased peak flame temperatures and maintained flame length, the heat flux at the bath surface is reduced since the flame is further from the surface. Prior experiences conducted in real world modeling of customer furnaces showed similar results, which were overcome by adjusting the burner angle down towards the bath, so the flame sweeps closer to the bath surface, solving this concern. Again, since the lab furnace burners are mounted horizontally the modeling was conducted to replicate its setup with these results not being a surprise. Adjusting the lab burners to downward firing was time prohibitive for the purposes of this study and would also further limit the furnace's future use for other testing applications. Typical studies would involve further adjusting the CFD model's burner geometries to determine the ideal downward angle needed to optimize this performance metric. Since the purpose of this exercise was to provide an initial study showing comparative results to the lab furnace, this was not done at this time. Studies considering real world process analysis would be done in further detail with iterative computations to refine and optimize results for each processes unique characteristics and parameters.



**Figure 16: Heat flux at furnace floor/bath: 1650 series NG (left) and H<sub>2</sub> (right)**

The 1650 series hydrogen heat flux results at the product surface (hearth) improved by 10-15% for a majority of the bath surface. The heat flux is specifically improved near the far end of the furnace which is ideal for the process as that product is then pulled into the charging well to melt freshly charged scrap aluminum.

#### 4.2 Melt Loss

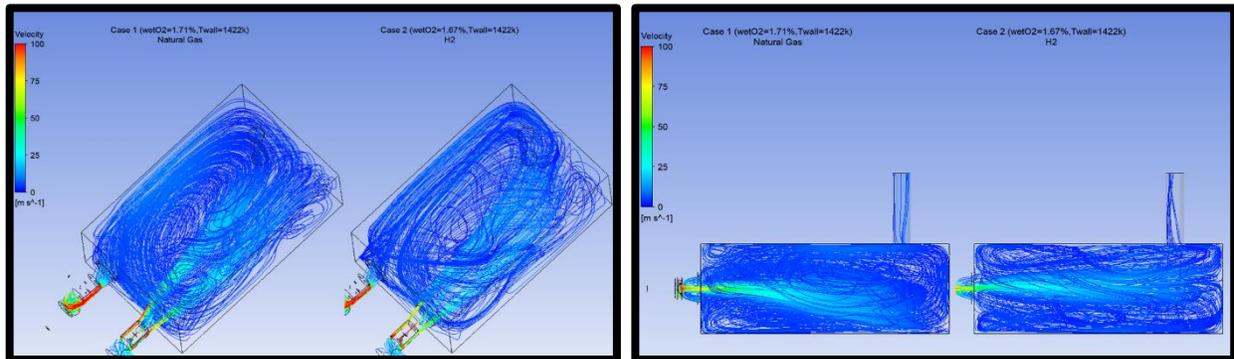
Melt loss is primarily driven by oxidation of the aluminum. Oxidation of a metal is a function of time, temperature, and oxidant availability. Oxidant availability is limited primarily by good furnace maintenance and operating practices. That is, operate the combustion system at minimal excess air combustion ratios, maintain optimum burner performance through maintenance upkeep, maintain positive furnace pressure control through damper control and proper furnace seal maintenance. Our analysis is based on controlling these variables properly, so the remaining concerns that our combustion system impacts are POC velocity and chemical constituency at the bath surface. The POC velocities are critical with aluminum melting due to the possibility of moving the bath surface layer and exposing more aluminum to potential oxidation. If furnace air/fuel ratio is controlled properly our concern for oxidation results from increased concentrations of POC water vapor experienced on hydrogen firing.

#### *POC velocity profile at the bath surface*

Let's recall that for hydrogen combustion the POC's are about ten percent less by volume than natural gas. This translates into lower POC velocities exiting our burner into the

furnace chamber for a dual fuel burner application. Therefore, we would expect to not see any concerns related to velocity at our bath, however as we saw earlier hydrogen combustion can change the flame behavior or direction. It is of note to mention that if this were a batch type direct charged melting furnace, this reduced POC velocity on hydrogen could result in slower initial melting of the solid scrap charge due to reduced convection heat transfer.

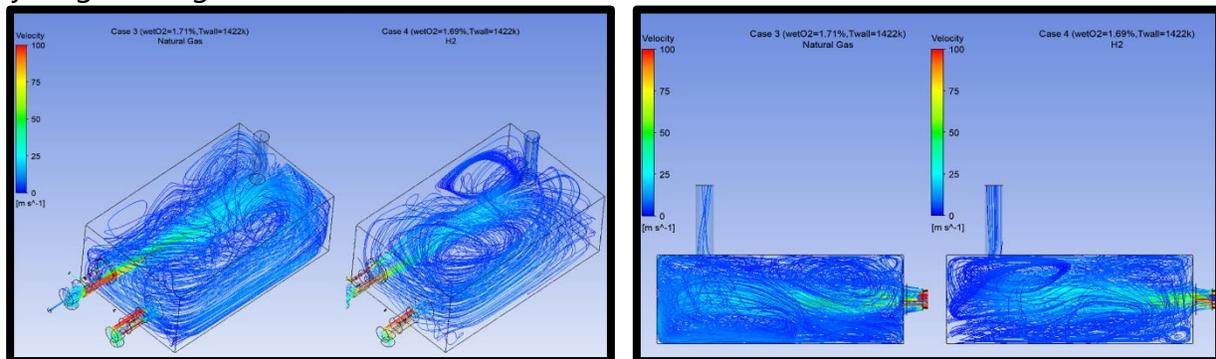
The plots below show POC path lines and their associated velocity profile with respect to the bath surface.



**Figure 17: POC Flow/velocity profile within the furnace: 1150 series**

The plots above show POC volume and velocities reduced on hydrogen as expected. The flow concentrations remain in line with the burners and predominately away from the furnace hearth.

For the 1650 series burner shown in the figure below, we again see POC volume and velocities reduced on hydrogen as expected. The flow concentrations remain in line with the burners and predominately away from the furnace hearth when converting to hydrogen firing.

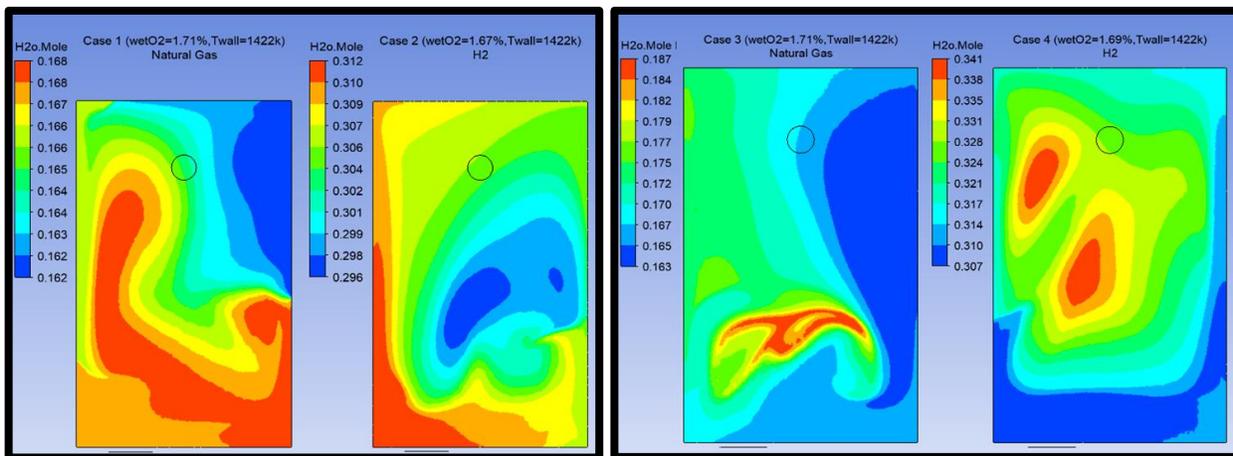


**Figure 18: POC Flow/velocity profile within the furnace: 1650 series**

Based on the above representations, there is no observation that would provide a reason for increase in observed melt loss upon transition to hydrogen fuel firing based on POC velocity or flow paths.

*POC constituents at the bath surface*

POC reactions with the aluminum bath are a consequence of a direct heating process. The composition of the gases that interact with the metal will influence reactivity. From prior discussions, we know the hydrogen POC's contain no CO<sub>2</sub> but elevated levels of H<sub>2</sub>O. The CFD simulation confirms the elevated water concentrations, as expected. The figure below shows water concentrations of the POC at the bath surface. Note that the scale is varied since the concentrations vary by a factor of nearly two. Due to ongoing exploration and refinement by CFD simulating software, accurate and field verified hydrogen combustion aluminum reaction simulations are not yet reliable. Therefore, the impact of this concern will need lab or field verified.



**Figure 19: POC water mole fraction at bath surface: 1150 (right) and 1650 (left)**

Since our lab furnace cannot hold or process aluminum, researching other studies on this subject was prudent, else field testing would be required to understand this impact clearly. With the current interest in reducing CO<sub>2</sub> emissions via hydrogen combustion, many studies are currently being conducted. One such study was recently completed in a joint effort by several producers and suppliers. This paper was recently published with the conclusion shown below.

This study showed that hydrogen can be used as a substitute fuel for natural gas or LPG in aluminum melting furnaces without increasing the oxidation of most molten aluminum alloys. [10]

More results are surely forthcoming, however initial tests optimistically show no adverse impacts from increased concentrations of water vapor that occur when transitioning to hydrogen fuel from natural gas.

#### 4.3 *Regulatory Compliance*

Now that we have evaluated productivity and quality-related concerns of our potential fuel transition, we must ensure it operates responsibly with equal or improved regulatory compliance. The evaluation of furnace emissions performance can often be initially evaluated through CFD model analysis. The relative impact of burner or process changes can often be quickly assessed, adjusted, and optimized through our model simulations. This allows physical lab verification to be streamlined to a final prototype design. Lab verification of emissions should always be quantified to mitigate risk of a product for contract guarantee of NO<sub>x</sub> emissions.

The following table quantifies the emissions performance of the burner series included in our evaluation. Again, the 1150 series burner has an existing large installed base where ULN retrofits to hydrogen fuel are being heavily explored. The alternative 1650 series burner is next generation ULN technology providing a reduced emissions option for hydrogen firing. NO<sub>x</sub> emissions in the North American metals markets are often reported on a dry basis in ppm, corrected to 3% oxygen in the POC. As previously discussed, reporting hydrogen emissions on a dry basis in ppm creates a biased result and should be considered on a more equal basis of mass of NO<sub>x</sub> emitted per unit energy (#/MM BTU). Again, in our local market this #/MM BTU method is typically done on an HHV basis. Therefore, our tabulation provides both standardized volumetric (ppm) and mass (#/MM BTU, HHV) comparisons of the relative NO<sub>x</sub> emissions produced. (Note: Results shown may not be representative of all situations. NO<sub>x</sub> emission levels are heavily dependent upon each furnace application's unique geometry and burner placement. Actual results will vary with each application.)

Regenerative Burner Series	Fuel Type	Furnace Temperature	Relative 1150 NO <sub>x</sub> Emissions (PPM Basis)	Relative 1150 NO <sub>x</sub> Emissions (#/MM Btu Basis)	Relative Emissions NG vs H <sub>2</sub> (PPM Basis)	Relative Emissions NG vs H <sub>2</sub> (#/MM Btu Basis)
		°F	%	%	%	%
Bloom 1150	Natural Gas	2100	100	100	100	100
Bloom 1150	Hydrogen	2100	54	33	54	33
Bloom 1650	Natural Gas	2100	88	86	100	100
Bloom 1650	Hydrogen	2100	44	31	50	36

**Figure 20: NO<sub>x</sub> Emissions from test furnace results**

Recall we had concerns for NO<sub>x</sub> emissions when transitioning to hydrogen fuel use due to higher adiabatic flame temperatures with hydrogen combustion. The test furnace emission results show substantial reduction in NO<sub>x</sub> emissions when firing hydrogen. This improved emissions performance is a result of the advanced ULN burner technologies implemented in the burners tested and good system air-to-fuel ratio control. Results will vary based on burner and control technologies, as well as system air-to-fuel ratio tuning. Also note that emissions improvement with the 1650 series burner latest technological improvements. We see that implementation of best available burner and control technologies allows the possibility for transitioning to flexible fuel (natural gas or hydrogen) firing capabilities while maintaining regulatory compliance with existing permits in place.

Furthermore, we see if regulatory compliance is conducted on an equal net energy basis consideration (LHV), further real reductions are realized on a mass emissions emitted basis.

Our CFD model predicted NO<sub>x</sub> results on the 1150 series technology within 10% of the test furnace results when considering natural gas. The hydrogen model showed a reduction as observed in the test furnace; however, the CFD predictions were about 25% higher than lab test results. The CFD software provider was contacted, and discussions had concerning hydrogen emissions modeling details. Due to limited use of pure hydrogen combustion in industry, exploration and refinement of hydrogen modeling algorithms from CFD software providers are being refined and validated with real world field data. This validation is ongoing, and accuracy of NO<sub>x</sub> modeling is improving.

## 5.0 Conclusions and Next Steps

### 5.1 Conclusions

This simplified study compared transitioning from natural gas to hydrogen combustion on a regeneratively fired side well type aluminum melter with easy-to-understand results. We reviewed key concerns with combusting hydrogen and how they could possibly impact key parameters of the process. We then systematically evaluated those concerns via CFD modeling of the system and laboratory test furnace firing results. These results provided confirmation and confidence that hydrogen is a viable low risk, GHG reducing transition fuel opportunity for gas fired aluminum melting processes. One can see that through accurate modeling of the process and utilizing available ULN burner technology, a properly designed system can provide confidence that a real-world transition to hydrogen has high probability of providing equal or better performance when compared to existing natural gas fired melting solutions. By iteratively modeling system enhancements in detail, key heating parameters can be refined and optimized to mitigate risk when considering low carbon fuel source transitions for each process's unique application. Furthermore, this transition to hydrogen firing can likely be pursued without negatively impacting regulatory NO<sub>x</sub> compliance.

### 5.2 Next Steps

With key concerns of heating effectiveness, melt loss and NO<sub>x</sub> emissions being addressed, the next step needed to prove out the viability of successful hydrogen transition on an aluminum melting furnace is to conduct detailed modeling of the actual application and verify results via a field implementation. Several field test projects are in progress. These tests will provide critical insight confirming several key issues which our analysis provided limited insight to. Specifically, our analysis of flame luminosity impacts as they relate to maintaining melt rates based upon our application of less luminous ULN burner flames. Furthermore, field testing will hope to confirm other sources findings that most aluminum alloys will be unaffected by increased concentration of water vapor in the POC's coupled with the absence of CO<sub>2</sub>.

Burner technology developers are already proactively testing burner improvements to further address hydrogen firing concerns discussed in this paper. For example, if furnace effectiveness were to decrease due to reduced luminosity, offering to boost the luminosity of burners running on hydrogen with a "luminosity lance", which would introduce a hydrocarbon fuel, in a small amount, to the combustion envelope. A further example of ongoing developments aimed at hydrogen combustion is improvements in

media case technology that increase heat recovery and overall thermal performance of the process. A final area of assistance some offer is many years of application knowledge and expertise in aluminum melting. This experience allows other options to address potential decreased effectiveness such as modifying the burner locations, firing angles and/or inputs to heat the chamber more effectively. Experience combined with skilled CFD modeling of a customer's exact furnace geometries allow analysis and implementation of low-risk combustion solutions to the process that optimize thermal performance.

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