Final Technical Report

Development of Next Generation Heating System for Scale Free Steel Reheating

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1 EXECUTIVE SUMMARY

The primary objective of this program is to develop and test a scale free heating system that reduces scale formation in the steel reheating process resulting in a substantial reduction in energy use, improvement in steel quality, and significant cost advantages for the U.S. steel industry. The program is divided in two phases. This report describes work performed, results, and conclusions for Phase II with specific reference to commercial application of the scale free heating technology in the steel industry.

Phase I of the project included following tasks: (1) Development and technical analysis of options, study of process and options for energy use optimization; (2) Study and definition of current and future industry needs (3) Selection of priority concepts based on analysis in the above activities; (4) Technical Economic Analysis of the Selected Concepts; (5) Selection of the most attractive concept in consultation with the steel industry; (6) preparation of Phase I report and (7) Project management. These activities were carried out by a team consisting of (i) a major steel company, Steel Dynamics, Inc.; (ii) a U.S. reheat furnace supplier (ACL-NWO previously known as A.C. Leadbetter, Alchas Inc.); (iii) an industrial gas supplier, Air Products and Chemical Company; (iv) a steel industry organization, The Steel Manufacturing Association – SMA; (v) a forging industry organization, Forging Industry Association – FIA; and (vi) an energy and environmental management company (E3M, Inc.) with extensive R&D and project management experience. Activities of Phase I of the program demonstrated that it is possible to develop and apply a scale free reheating process that offers major competitive advantages to the U.S. steel industry while offering significant reduction in energy used by the steel industry.

Phase II of the program was initiated in later part of the year 2006. The program team added a major burner supplier Bloom Engineering and a furnace supplier Danieli as additional team members. This phase had the following tasks: (8) Scale free heating tests on a pilot scale furnace using commonly used steel using process parameters defined in Phase I; (9) Testing of samples to verify acceptability of the samples to meet the steel industry needs.; (10) Heating (Combustion) system definition to meet scale free requirements and specifications for critical components; (11) Preliminary design - sizing of the system for a typical application; (12) Detail energy, economic and environmental performance analysis, and modeling for evaluation of options; and (13) Review of the analysis by industry participants, required revisions, and final decision on the scale free reheating system design; (14) Final report

The Phase II activities have resulted in preliminary design of a scale free reheating system that can be applied to a new furnace application as well as retrofit design that allows conversion of an existing steel reheating furnace. The system and components are developed to meet requirements of 76% of the US steel industry applications.

The development work has resulted in the following components and knowledge base that will enable us to reheat steel with substantial reduction in scale formation and energy savings during the reheating process. Scale reduction also results in additional energy savings associated with higher yield from reheat furnaces. Reduction in scale reduces need for energy used in producing steel that is wasted as scale. Energy used for steel production ranges from 9 MM Btu/ton to 16.6 MM Btu/ton or the industry average of approximately 13 MM Btu/ton. Hence reduction in scale at reheating stage would represent a substantial energy reduction for the steel industry. The actual reduction in scale and associated energy use for the steel industry depends on several factors related to the design and operating practices and allowable economics for the process.

Specific accomplishments of the program include:

- a. Construction and operation of sample testing facility that allows testing of steel samples under conventional heating conditions as well as the scale free heating conditions with the desired time-temperature and furnace atmospheric conditions (gas compositions) as experienced by the steel during the reheating process. This facility was used to test samples and verify effectiveness of the predicted furnace conditions to achieve large (as much as 97%) reduction in scale formation.
- b. Development of natural gas fired burners capable of operating under highly fuel rich combustion as well as under excess air conditions to allow furnace operation for conventional heating as well as scale free heating operation using the same burners and an appropriate control system. Application of scale free operation for new and retrofitted furnaces required development of three different types of burners: (i) conventional axial flame burners that can be operated with 1000 deg. F. preheated combustion air; (ii) conventional axial flame burners that can be used with modestly preheated air with oxygen enrichment to achieve the desired sub stoichiometric operation; and (iii) flat flame burners that can be used with modestly preheated air with oxygen enrichment to achieve the desired sub stoichiometric operation.
- c. Preliminary drawings that indicate required changes for application of scale free heating in a new furnace. These drawings and available cost data base are used to prepare cost comparison between a conventional reheat furnace and a furnace designed for scale free operations. This information is used in a preliminary economic model.
- d. Development of a preliminary economic analysis model that allows estimates of cost savings and payback period based on the given data for the cost and scale reduction for any application. The payback analysis has been carried out for three different types of furnaces using the available data and the results indicate less than 1 year payback period in a new furnace application.
- e. Analysis of energy savings that allows estimate of energy savings with application of scale free heating. The analysis, includes energy savings resulting from improvements in reheat furnace technology (higher preheat temperature and better furnace design with controls) and reduction in energy use related to elimination of scale and thus reduction in energy use for producing that amount of steel at the reheating stage of the production cycle. Average energy reduction is 0.375 MM Btu/ton or, at a national level, approximately 28.5 Trillion Btu (TBtu) per year added on 76 MM tons/year steel production using scale free heating.
- f. Two potential applications, one for a new furnace and one for retrofit case, are being pursued for scale free heating system at two separate steel plants in USA.
- g. The steel industry is being kept informed through Steel Manufacturing Association (SMA) as well as Forging Industry Association (FIA).

This final report gives details of the development activities as well as actions being pursued for commercial application of the scale free steel reheating process in the steel and forging industries.

Based on the accomplishments in development of the required components, pre-engineering work and the interest generated in the industry, we consider this development as a success.

2 INTRODUCTION

The purpose of this Project was to develop the heating and combustion process and the required burner hardware to achieve the heating of steel to rolling temperatures while forming little or no scale. This process technology and the related burner hardware had to not only allow a furnace to operate in what is hereby termed the "Scale Free Heating Mode" (or SFH) of operation but also allow the furnace to return to the normal mode of heating steel in a state of the art reheat furnace. This normal mode of heating is hereby termed the "Conventional Heating Mode" (or CH).

The dual mode capability was considered a critical requirement in order to promote and advance scale free heating into the steel industry. The risk of designing, manufacturing and installing a new furnace or retrofitting a furnace at the cost of millions of dollars that could only achieve scale free heating would not be accepted by the industry. There are very few industrial applications of scale free heating and they are in a very narrow range of steel forming. These few applications are in the forging industry and do not provide a risk free extrapolation of the scale free heating process to the heating and rolling practices of hot strip mills, merchant bar mills, SBQ mills, structural mills, etc. Therefore, the ability to fall back to the proven conventional heating (if necessary) has to be an integral part of the scale free heating process and equipment development.

The normal or conventional heating (CH) mode of heating steel products to rolling temperatures is to heat steel in a furnace that is being fired by burners operating at or slightly above the stoichiometric ratio of the fuel being used. The 100% stoichiometric ratio is defined as the air/gas ratio that yields perfect combustion of the fuel and yields a flue gas atmosphere that is made up of only N_2 , CO_2 and H_2O . Combustion at an air/gas ratio slightly above 100% stoichiometric would result in a small percentage of O_2 also in the flue gasses.

All burners in all furnace zones would be operating at or slightly above 100% stoichiometric combustion levels and the resulting time, temperature and atmosphere profiles as the product passes through the furnace would be represented by the following graph.

Exhibit 1: Conventional heating time, temperature, atmosphere profile.

The flue gas constituents of CO_2 , H_2O and O_2 are all oxidizing to steel when the surface temperature of the steel is above about $1400^{\circ}F$.

The scale free heating (SFH) mode of heating steel products to rolling temperatures is to heat steel in a furnace that is being fired by burners operating well below the stoichiometric ratio of the fuel being used. This will be in the range of 50% to 60% of the stoichiometric ratio and the flue gas atmosphere will contain CO and H_2 as well as N_2 , CO_2 and H_2O .

In the SFH mode only the burners in the soak and heat zones would be operated at these sub-stoichiometric air/gas ratios and air would be added into the front end of the furnace to burn down the combustibles (CO and H_2). The resulting time, temperature, and atmosphere profiles as the product passes through the furnace would be represented by the following graph.

Exhibit 2: Scale free heating time, temperature atmosphere profile.

The CO and H₂ flue gas constituents are reducing to steel and when considered with the other flue gas constituents of CO₂, H₂O and N₂ the flue gas mixture is either reducing or oxidizing to steel depending upon the ratio of CO/CO₂ and H₂/H₂O and depending upon the surface temperature of the steel. This relationship is demonstrated in the following graph.

Exhibit 3: Effect of temperature and "atmosphere" on Steel oxidation

This graph defines the scale free heating combustion process that needs to be followed in order to heat steel to forming or rolling temperatures without creating scale.

The CO/CO₂ and H₂/H₂O ratios are inversely proportional to the % stoichiometric ratio of combustion. Therefore the reducing/oxidizing boundaries as related to the % stoichiometric combustion ratio is represented by the following graph.

Exhibit 4: Reducing/oxidizing boundaries and % stoichiometric combustion

2.1 Process

A major portion of this Project was focused on relating the required scale free heating combustion process to the actual combustion processes that could be accomplished in a conventional reheat furnace geometry. In order to do this an actual operating furnace at a Project Team Member's steel plant was used as a simulation basis for laboratory sample heating tests that simulated both conventional and scale free heating time, temperature and atmosphere profiles. The first set of tests focused on simulation of the CH mode. Small steel coupons provided by the Project Team Member were heated at numerous time, temperature and atmosphere profiles that represented the actual furnace operating at various conventional heating production levels and/or delay conditions. The amount of scale formed on the samples was measured for each of the CH simulation. This Process work has been reported extensively in Appendix A: Conventional Heating Sample Report

In the second set of tests similar heating and/or holding simulations were done with samples now being exposed to the sub-stoichiometric atmosphere profiles that could be achieved in the same furnace operating at the same time/temperature profiles as that used for the above described conventional heating simulations. As in the conventional heating simulations, the amount of scale formed on the samples was measured for each of the SFH simulation. The SFH atmosphere profiles that were used in these SFH simulations was determined through rigorous heat balances to determine what the actual atmosphere profile would be within an actual furnace. This Process work has been reported extensively in Appendix B: Scale Free Heating Sample Report

2.2 Hardware

The requirement that a furnace that could perform product heating in an atmosphere profile that developed very little or no scale had to also be capable of heating the steel in the conventional heating mode required the development of special burner hardware.

A burner that can provide the needed combustion ratios or % stoichiometric levels for both CH and SFH has to perform over a much larger range of % stoichiometric operation and input than a burner that provides either only CH combustion conditions or only SFH combustion conditions. For example, consider a burner in the soak zone of a CH furnace. Typically these burners are relatively small in size and input because they only need to provide the heat required to soak the product out to some final temperature. Most of the heat to the product has already been provided in the upstream charge and heat zones by much larger burners.

Therefore, the typical input range of CH heating soak zone burners is in the range of 1.0 to 3.0 MMBtu/hr per burner and the burners will be operated at or slightly above the stoichiometric combustion ratio of the particular fuel being used. The required burner turndown rate for these soak zone burners is defined by the input needed to provide the maximum required product heat divided by the input needed to provide only holding losses during delays or long holds of the soak zone at some operating temperature but with no product passing through the zone. This turndown ratio is typically in the range of about 8/1.

But, if the furnace is required to also heat products in the SFH mode these same soak zone burners will be required to operate at about 50% of the stoichiometric range of the particular fuel being used in order to provide a scale free atmosphere to the very hot products that are in the soak zone. The combustion efficiency of the burner operating at 50% stoichiometric is much lower than the combustion efficiency of the same burner operating at 100% stoichiometric. Therefore the required input to the burner will be much higher. In fact, CH and SFH heat balances will quickly determine that the SFH burner input will be 6 to 10 times greater than the CH burner input and will also require the same type of 8/1 turndown as that of the CH burner because they are both seeing the same zone variations between operating and holding conditions.

The net result of this wide range in input demands for a given burner operating in both the CH and SFH mode is that the overall turndown range of the burner increases from a typical 8/1 turndown if the burner was required to operate in only the CH or only the SFH mode to a turndown ratio in the order of 35/1 if the same burner has to operate in both the CH and SFH mode.

An actual example of the input variation and turndown variation of burners in the soak zone of a particular furnace is shown in the table below.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	7.924 MMBtu/HR
MINIMUM SFH RATE	1.016 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	1.931 MMBtu/HR
MINIMUM CH RATE	0.248 MMBtu/HR
CH TURNDOWN	7.8
OVERALL SFH to CH TURNDOWN	31.95

Exhibit 5: Soak zone burner turndown

In the SFH mode the burner has to provide 7.924 MMBtu/hr as opposed to only 1.931 MMBtu/hr in the CH mode. Although both the SFH and CH turndown is 7.8/1 the total turndown the burner has to be capable of over both the CH and SFH mode is 31.95/1.

Not only does the performance range of the burner become much more complex when it must perform in both the CH and SFH modes but also the type of burner required can vary depending upon the type and condition of the furnace. The following table outlines the type of burner that will be needed as opposed to the furnace market that the a CH/SFH burner might be applied to.

SCALE FREE HEATING BURNER MARKET				
BURNER TYPE	COMBUSTION AIR	MARKET	MARKET OF 76MM TPY	BURNER TEST/DEVELOPMENT PRIORITY
Longitudinal	Preheated to 1000°F	New Furnaces	10%	1
Longitudinal	Exiting preheat (750°F) plus O ₂ Enrichment to 1000°F Equivalent	Retrofit	90%	2
Flat Flame	Exiting preheat (750°F) plus O ₂ Enrichment to 1000°F Equivalent	Retrofit	50% of 90%	3

Exhibit 6: Scale free heating burner market.

The Project Team estimated that the total USA reheating furnace capacity was about 100 MM TPY of which about 76 MM TPY was potential capacity for either replacement with or conversion to a CH/SFH furnace. The remaining 24 MM TPY was either hot charge reheat furnaces or thin slab tunnel furnaces where the level of hot charge into the furnace rendered SFH inefficient.

Of the 76 MM TPY potential SFH heating market, only about 10% could be expected to be new furnaces based on the historical replacement rate of reheat furnaces. A new furnace could be supplied with the recuperator and special burner capable of either CH or SFH that was to be developed as part of this Program. That is, a longitudinal fired burner designed to achieve CH/SFH combustion requirements with 1000°F preheated air.

The remaining 90% of the 76 MM TPY furnace capacity open to CH/SFH would be retrofits of existing furnaces. The Project Team concluded that the footprint of an existing furnace could preclude the ability to replace an existing, undersized recuperator with a new recuperator that could supply the required 1000°F preheat in order to achieve the CH/SFH combustion requirements. Additionally, based on a Project Team market survey, it was concluded that 50% of the retrofit market were furnaces that had flat flame burners in one or more top zones.

Therefore, there was a need to develop two additional types of burners;

- A longitudinally fired burner that could operate with the existing preheat air temperature with the addition of oxygen enrichment to the combustion air in order to achieve the CH/SFH combustion requirements.
- A flat flame fired burner that could operate with the existing preheat air temperature with the addition of oxygen enrichment to the combustion air in order to achieve the CH/SFH combustion requirements.

Each of the above defined three burners were successfully developed and tested in the Hardware Development portion of this Project.

The development of the longitudinally fired burner operating with 1000°F preheat air temperature has been reported extensively in Appendix C: Preheated Air Burner Report.

The development of the longitudinally fired burner operating with less than 1000°F preheat air temperature (750°F) with oxygen enrichment in order to achieve the required CH/SFH combustion requirements has been reported extensively in Appendix D: Oxygen Enriched Burner Report.

The development of the flat flame fired burner operating with less than 1000°F preheat air temperature (750°F) with oxygen enrichment in order to achieve the required CH/SFH combustion requirements has been reported extensively in Appendix E: Scale Free HTR Burner Report.

2.3 Market Potential

As discussed above, the Project Team conducted a Market Survey in order to determine the size of the potential SFH Market as well as the type of burner hardware that would be needed to address furnaces that were candidates for SFH through retrofitting the existing furnace with the burner and combustion hardware needed to achieve CH/SFH combustion requirements. The size of the potential SFH Market is summarized below.

Exhibit 7: Scale free heating: USA market

The only reheat furnace applications that are not automatically adaptable to CH/SFH are furnaces that have some level of hot charge products. This includes all of the existing Tunnel Furnace applications in thin slab mills where the slab enters the reheat furnace at 1800°F plus temperature for final heating and temperature equalization prior to final rolling into strip. Such high product preheat levels precludes the efficient application of SFH. The above table shows a relatively smaller percentage of hot charge products that are not adaptable to SFH for

conventional hot strip mills and long product mills. The net result is that of the projected 100 MM TPY USA reheat furnace market, about 76 MM TPY is adaptable to SFH as either new furnaces or furnaces retrofitted from CH to CH/SFH.

2.4 Energy Savings Potential

Scale free reheating of steel offers energy savings from two major areas of energy savings. One is related to energy savings during the reheating process where steel is heated to approximately 2100 de. F. and energy is used for raising temperature of the steel being reheated. The other area of energy saving is related to reduction in scale formation. The scale is iron oxide that is similar to the iron ore that is used to produce steel. Production of scale reduces the product yield that needs to be compensated by steel produced from the iron air through primary iron and steel production. Thus scale reduction would result in reduction in energy use that is required to produce steel equivalent to the amount of steel lost in scale.

Energy reduction during reheating process depends on several factors related to the type of heating system used and the furnace design. A review of energy use for reheating furnaces indicates that average energy use for modern reheating furnaces under production condition is 1.5 MM Btu/ton. Improvements made during application of scale free heating can result in energy savings of 12% or 0.180 MM Btu/ton.

Scale reduction related savings can be estimated by using an average energy use of 13 MM Btu/ton that is required to produce steel from iron ore and bring it to a condition where it is reheated. An analysis of potential reduction in scale formation using scale free process is 1.5% of the total steel reheated. Use of scale free reheating would result in energy saving of 0.195 MM Btu/ton of steel being reheated.

Total energy savings potential with application of scale free process would be equal to sum of the savings resulting from the above mentioned areas of energy savings or 0.375 MM Btu/ton. As mentioned in section 2.3 above, for USA, 76 million tons of steel is adaptable to scale free reheating using new furnaces or retrofit of currently sued furnaces. Based on this total energy savings potential is 28.5 Trillion Btu/year.

2.5 Commercialization Status

The Project Team is currently in commercialization of SFH in:

- A new reheat furnace being proposed to a major steel producer for a rebar mill.
- Upgrade and retrofit of existing rotary furnace(s) in a piercing operation.

The Project Team has evaluated potential applications for SFH in a few other applications that have proven to not be potential applications for SFH retrofits. These applications were;

- Two rebar mill furnace retrofits
- One forging operation
- One piercing operation with a rotary furnace

3 BACKGROUND

A basic requirement in the development of SFH process and hardware has been that SFH capability must be compatible with CH requirements. That is, the SFH mode of operation has to be superimposed upon a basic furnace operation that is considered to be "state of the art" for a conventional heating (CH) furnace that either is existing (therefore a retrofit situation) or for a new furnace. So it becomes necessary to define what "state of the art" is in terms of a CH furnace. A "State of the art" furnace is defined as a furnace that accomplishes the efficient heating of steel from charge temperatures to rolling temperatures. "Efficient heating" is accomplished due to furnace design and construction that provides for minimum heat losses, high preheat air temperatures combined with a long furnace with an unfired preheat section (UFPH) for additional efficiency. Additionally, the furnace is controlled by process controllers and PC's at level 1 to effect temperature and combustion control as well as the control of mechanical equipment. The level 1 system extracts vital product and cycle information from the Plant or Mill Level II system to determine product positioning in the furnace, heating capacity and zone set point determination as a function of heating capacity and product type. This assures efficient operation over a wide range of furnace production rates as well as efficiently accounting for the commencement and ending of planned or unplanned delays.

All of above is contained and/or accomplished in a state of the art furnace that is operating in the Conventional Heating Mode (CH) which is hereby defined as the burners operating at or slightly above stoichiometric conditions. Therefore scale will be formed on a product heated in this state of the art furnace due to the existence of an oxidizing atmosphere around a product that is at high temperature.

This Project was therefore concerned with eliminating or minimizing the scale formed during the heating process. This was expected to be accomplished by firing the burners at sub-stoichiometric conditions when the product surface temperature was high and then burning the flue gasses back to stoichiometric conditions in the charge end of the furnace where the surface temperature is low and scale will not readily form. This method or mode of heating is referred to as Scale Free Heating Mode (SFH).

The Project objective was to first determine the combustion process required to achieve scale free or minimum scale during the reheating process and then to develop the burner hardware needed to achieve the sub-stoichiometric ratios that are required for SFH. The burner hardware had to be capable of performing in the current "state of the art" furnace so that the furnace would be capable of operating in both the CH and SFH mode of operation.

The required combustion process was developed by heating sample products in various time, temperature and atmosphere profiles in order to determine the level of scale created. These time temperature profiles were exact simulations of the time temperature profile that a product would be experiencing in an actual reheat furnace. The time temperature profiles were combined with various atmosphere profiles in an attempt to minimize or eliminate scale formation while retaining the state of the art thermal efficiency of the furnace in both CH and SFH modes.

A Project Team was organized that consisted of a group of companies covering a wide range of knowledge and experience in of steel making (SDI), combustion and furnace equipment (Bloom

Engineering, ACL, Danieli., Air Products), scale free heating knowledge and experience (E3M) and the metals industry (SMA, FIA).

4 BODY OF THE REPORT

The process and development work that was defined for this Project has been completed and reported upon in detailed reports issued at the completion of each body of work. These detailed reports are included in the Appendices of this Project Final Report and are listed below for reference and definition:

Appendix A: Conventional Heating Sample Report

Appendix B: Scale Free Heating Sample Report

Appendix C: Preheated Air Burner Report

Appendix D: Oxygen Enriched Burner Report

Appendix E: Scale Free HTR Burner Report

Each report address the methodology used in the work development and includes all of the data recorded and analyzed within the body of work encompassing the report.

This section of the Project Final Report is intended to only briefly summarize the extensive work accomplished in each area and highlight conclusions made and accomplishments achieved. The reader is advised to read each report for detailed information on the work involved in each report.

4.1 Process Development

The work on process development conducted in this Project was concerned with defining the combustion and heating process encountered in heating steel products in a state of the art furnace that was operating in either a conventional or scale free heating mode. This was accomplished by simulating the time, temperature and atmosphere profiles that a product would see as it was heated in a typical reheat furnace in either the conventional or scale free heating mode.

Two distinct test programs were conducted. The first test program consisted of conventional heating simulations and the detailed report is included in Appendix A. The second test program consisted of scale free heating simulations and the detailed report is included in Appendix B.

A summary of each report follows.

4.1.1 Conventional Heating Sample Report Summary (Appendix A)

In both the CH and SFH sample heating tests very small steel test coupons were heated in a test furnace designed by the Project Team and constructed and operated by Bloom Engineering Project personnel. The samples were small coupons approximately one inch square by 1/4" thick that were provided by SDI as representative of some of their major product chemistries.

The sample(s) were lowered into the test furnace and heated in accordance with a time, temperature and atmosphere (t/t/p) profile that duplicated the t/t/p profile that SDI's BB3 product would incur as it was heated in their Medium Section Mill furnace at Columbia City, Indiana. The BB3 product was selected as the reference product by the Project Team since it represented a major product of SDI and a product where SDI and the Project Team had substantial background and data from the reference reheat furnace. The BB3 is a very large structural shape having the general outline of a dog bone and is used as the rough cast product for structural beam rolling and forming. The BB3 product dimensions are provided below.

BB3 PRODUCT SHAPE

Exhibit 8: BB3 product shape.

The BB3 product as well as all of the other cast products of SDI are heated to rolling temperatures in a state of the art top and bottom fired walking beam furnace that is about 80' long and 50' wide. The products are charged into the furnace (typically cold but sometimes with some preheat) walked through the furnace while being heated to about 2250°F and then discharged to the rolling mill. A typical heating curve (time/temperature) for a BB3 heated in this furnace is provided below.

Exhibit 9: Temperature profile for 200 TPH (100% capacity) conventional heating.

All of the burners in the SDI furnace are operating slightly above stoichiometric so that the atmosphere within the furnace is made up of nitrogen, carbon dioxide, water vapor and a small amount of oxygen.

A typical sample heating test conducted by Bloom Engineering would be simulating this same t/t/a profile on a test coupon heated in the test furnace. The test coupon was weighed before the heating simulation and also after heating and shot blasting to determine the amount of scale created during the heating process.

Simulation tests were conducted for the furnace operating at 100%, 75%, 50% and 25% of the SDI furnace rated capacity (200 tph) and the results of the scale formed are summarized in the following graph.

Exhibit 10: BB3 % scale vs. % capacity (all data).

Simulation tests were also conducted to address holding conditions where the products are held for long times at various temperatures due to mill break downs, scheduled down time or product rolling change overs. This information was needed in order to eventually determine when and if scale free heating conditions can be maintained during scheduled or unscheduled holds or delays. Typical results of holding the sample coupons at various temperatures for 2 hours in a conventional mode atmosphere (1.7% oxygen) is provided in the following graph.

Exhibit 11: % scale vs. temperature at fixed 2 hours at 1.7% oxygen in flue gases.

This body of work provided the reference data needed to evaluate the effectiveness of scale free heating which was to be the next series of heating and holding simulations. For additional detail and information on all of the tests and analysis accomplished in these conventional heating sample tests please refer to the Appendix A, Conventional Heating Sample Report.

4.1.2 Scale Free Heating Sample Report Summary (Appendix B)

Upon completion of the conventional heating sample tests the same lab test furnace was used to conduct a series of sample heating tests where a scale free time, temperature and atmosphere (t/t/a) profile was superimposed on the sample coupons. Actually, the time/temperature profile (t/t) for any given capacity simulation was exactly the same t/t profile as used for that capacity in the conventional heating tests that were conducted earlier. The t/t profile for conventional heating and scale free heating in a given furnace has to be the same if one is to hold to the basic premise of this development which was that one furnace must be capable of operating in either the CH or SFH mode. To accomplish this basic premise the furnace must be able to heat any product at any capacity to the same time versus temperature profile regardless whether the furnace is operating in a CH or SFH mode. Only the atmosphere profile would differ from the CH to the SFH mode.

A heating model is used to determine the time/temperature profile of a particular furnace heating a particular product. The resulting graph below shows the FURNACE TEMPERATURE profile from the charge end to the discharge end that the heating model used in calculating the resultant WORK TEMPERATURE profile.

Exhibit 12: conventional heating time-temperature-atmosphere (t/t/a) profile.

The ATMOSPHERE profile does not affect the heating of the product but it is added to the graph to show that atmosphere within the furnace would be equivalent to that of 100% stoichiometric combustion from the charge end to the discharge end of the furnace in the CH mode t/t/a.

The same t/t profile would be used for the same furnace if it was to be operated as a SFH furnace as shown below.

Exhibit 13: Scale free heating time-temperature-atmosphere (t/t/a) profile

The difference in the SFH t/t/a profile is the atmosphere profile. The t/t profile for the furnace and work is exactly the same as that of the CH t/t but as the work temperature increases in the SFH heating mode the atmosphere profile is made reducing by lowering the % stoichiometric.

In practice it will be seen that this is achieved by firing the burners in the discharge zone (soak zone) at about 50% stoichiometric and then gradually increasing the % stoichiometric toward the charge end of the furnace by injecting burn down air into the furnace and/or by firing burners at a higher % stoichiometric ratio.

It is important to emphasize that the very same t/t is used for both the CH and SFH mode. In effect, this assures that the furnace is basically designed as a CH furnace since the CH t/t profile is imposed on the SFH t/t/a. As long as the burners can achieve the required CH and SFH firing conditions throughout the furnace and as long as the combustion control systems can provide either the CH or the SFH modes of operation than the furnace is essentially transparent to CH or SFH and will operate and perform in both modes.

The remaining challenges are to determine what is the SFH atmosphere profile that is generated by the CH t/t profile and once this SFH atmosphere profile is defined, does it indeed result in scale free or low scale heating? The SFH atmosphere profiles were able to be defined by first generating heat balances for the furnace and heated product with a conventional heating combustion mode and then generating a heat balance for the same net furnace and product demands but using a scale free heating combustion mode. This scale free heating combustion mode heat balance defined the atmosphere portion of the SFH time, temperature, atmosphere (t/t/a) profile that was used for the sample heating tests. With the atmosphere profile thus defined, SFH sample testing was done to determine what level of scale would be developed by the SFH t/t/a.

The calculation of a conventional heating heat balance is quite detailed and complicated. The calculation of a scale free heating heat balance is very similar to that of a CH heat balance

except that the available heats in the various zones are determined at the sub-stoichiometric combustion levels of the zones and therefore the input in a sub-stoichiometric zone is much higher than if that same zone was to be operated in the CH mode.

The entire CH versus SFH heat balance development will not be duplicated in this Section of this Report since it is presented complete and in detail in Appendix B of this Report. It is recommended that the reader refer to Appendix B for more detail on the development of CH and SFH heat balances and their resultant atmosphere profiles.

As noted earlier, with the SFH atmosphere profile being defined by the SFH heat balance, SFH sample testing was done to determine what level of scale would be developed by the SFH t/t/a. Numerous coupon heating tests were conducted to simulate heating the BB3 reference product at various heating capacities. The scaling rate data from these tests could then be compared to the scaling rate data from the CH simulations in order to determine the % scale savings with SFH. The results of these heating simulations are plotted against the results of the conventional heating simulations discussed earlier.

Exhibit 14: Scale free heating vs. conventional heating simulation results

Significant reduction in the % scale formed is achieved when the furnace is operating in the SFH mode. The Appendix B Report explains that SFH performance drops off at lower furnace capacities due to the inability to achieve reasonable heat balances at the lower furnace capacities. As will be discussed next, the type of furnace and the type of product significantly effects the overall application range and the performance level of a furnace operating in the SFH mode.

Heating simulations were conducted with the reference SDI furnace heating an 8" thick slab. Both a CH and SFH heating model and heat balance were done for the furnace heating the

slab at 100% of rated capacity and the resulting t/t/a profiles were used for the coupon heating tests. The results of the coupon tests are summarized in the following table.

CONVENTIONAL VERSUS SCALE FREE HEATING OF A SLAB			
TEST #	HEATING MODE	FURNACE CAPACITY	% SCALE
22A	CH	100%	0.63%
22B	CH	100%	0.57%
26A	SFH	100%	0.05%
26B	SFH	100%	0.07%

Exhibit 15: Scale formation: conventional vs. scale free heating of a slab.

The slab heating simulations resulted in the CH scale being reduced from about 0.6% to about 0.06% when the furnace was operating in the SFH mode. This is about a 90% reduction in the scale level for the slab product versus about a 75% reduction for the same furnace heating the BB3 product. The Appendix B report discusses in more detail how the furnace type and product type can affect the overall performance of the SFH mode. Scale reduction offers additional energy savings that would amount to approximately 0.195 MM Btu/ton of steel reheated. Hence accurate prediction of scale reduction is very important. The Integral Analysis method, discussed below, allows us to predict reduction in scale formation and hence the associated energy savings with use of scale free heating system.

An Integral Analysis (IA) method was developed that reliably predicted % scale savings by comparing the predicted t/t/a profiles developed from CH and SFH heat balances only. This allows one to estimate the expected scale savings for any given furnace and product. The results of the IA method are summarized in the following table for all of the BB3 CH and SFH coupon heating tests conducted.

Exhibit 16: Integral analysis of BB3 heating tests.

The IA method was used to determine predicted scale savings for other types of furnaces and products in order to generate cost comparisons and Payback Analyses of the cost and performance of a SFH furnace as compared to a CH furnace. This Payback Analysis work was done during the application and marketing stages of the Project and after the Appendix B Report was issued and will therefore be covered in a later Section of this Report.

The CH and SFH heat balances and sample heating simulations not only defined the % scale in each mode but also defined the required % stoichiometric ratios and input levels needed by the burners in the CH and SFH modes. This data and information was required in order to define the CH/ SFH Burner Specifications for the burners that were to be developed in the burner development portion of this Project.

4.2 Burner Development

The hardware development portion of this Project involved developing burners that could meet the demands of a furnace that could heat products in either a CH or a SFH mode. As discussed previously, a matrix of required types of burners had been decided upon based on results of a survey addressing new and existing furnace designs and burner types. This summary matrix is repeated below for reference.

SCALE FREE HEATING BURNER MARKET

BURNER TYPE	COMBUSTION AIR	MARKET	% MARKET OF 76MM TPY	BURNER TEST/DEVELOP PRIORITY
Longitudinal	Preheated to 1000°F	New Furnaces	10%	1
Longitudinal	Exiting preheat (750°F) plus O2 Enrichment to 1000°F Equivalent	Retrofit	90%	2
Flat Flame	Exiting preheat (750°F) plus O2 Enrichment to 1000°F Equivalent	Retrofit	50% of 90%	3

Exhibit 17: Scale free heating burner market.

The three separate burner development programs were required in order to address the entire new furnace and retrofit furnace market.

As each of the three development programs were completed the work was documented in a detailed Report. Each of these comprehensive Reports are included in the Appendices of this Project Final Report and are listed below for reference and definition:

Appendix C: Preheated Air Burner Report

Appendix D: Oxygen Enriched Burner Report

Appendix E: Scale Free HTR Burner Report

Each report address the methodology used in the burner development and includes all of the data recorded and analyzed during the development work. This section of the Project Final Report is intended to only briefly summarize the extensive work accomplished in each area and highlight conclusions made and accomplishments achieved. The reader is advised to read each report for detailed information on the work involved in the individual development program.

4.2.1 Preheated Air Burner Report Summary (Appendix C)

This burner series was to be developed for application to a new CH/SFH Furnace where the furnace geometry and zone layout could be designed for an axial fired burner style. The burner development work was to be done by Bloom Engineering (Bloom) in their combustion labs. The

first order of business for the Project Team was to develop a Burner Specification that would define to Bloom the entire operating range of the CH/SFH burners required for a reference furnace size. The existing SDI Structural Medium Section Mill furnace was again used as the reference furnace. The previous work in the sample heating portion of this Project had resulted in heat balances on this furnace for both CH and SFH modes and therefore the basic information needed to define the burner sizes was already available.

It needs to be pointed out that the heat balances completed in the sample heating work were all based on a preheat air temperature at the burner of 1000°F. This is a relatively high preheat air temperature even for a "state of the art" furnace featuring modern design and technology levels. However, the Project Team members E3M, Bloom and ACL, all had previous experience in SFH heating burner designs and all agreed that a minimum of 1000°F preheat air temperature was required in order to achieve complete combustion with natural gas burners operating in the 50% stoichiometric range. Therefore the Burner Specification for this first burner development, an axial fired preheated air burner capable of both CH and SFH combustion, was based on the burner having 1000°F preheated air. As mentioned above, the CH and SFH heat balances developed in the sample heating work of this Project was the basis of the Burner Specification developed by the Project Team and submitted to Bloom.

The Burner Specification is presented below.

SCALE FREE HEATING BURNER SPECIFICATION: PREHEATED AIR											
ZONE	CONNECTED			DESIGN			TURNDOWN			ZONE	NUMBER OF BURNER
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G		
SOAK	39,619	7,924	5	30,476	6,095	5	5,079	1,016	5	SOAK	21
HEAT	56,622	8,089	7	43,556	6,222	7	7,259	1,037	7	HEAT	18
CHARGE	63,886	0	NA	49,143	0	NA	8,190	0	NA	CHARGE	0
										FURNACE	39
											312

Fuel: Natural gas @ 1027 Btu/cf (East Ohio Natural Gas)

Burner Notes: No burners are required for Charge Zone. Number of burners shown for Soak and Heat Zones are for both top and bottom heating zones.

Preheat Air Temperature: Background suggests that the minimum preheat air temperature required for 5/1 combustion is 1000°F. Burner Supplier to note if higher preheat air temperature is required.

Air and Gas Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

CONVENTIONAL HEATING BURNER SPECIFICATION: PREHEATED AIR											
ZONE	CONNECTED			DESIGN			TURNDOWN			ZONE	NUMBER OF BURNER
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G		
SOAK	19,314	1,931	10	14,857	1,486	10	2,476	248	10	SOAK	21
HEAT	46,800	4,680	10	36,000	3,600	10	6,000	600	10	HEAT	18
CHARGE	104,000	10,400	10	80,000	8,000	10	13,333	1,333	10	CHARGE	18
										FURNACE	57
											312

Fuel: Natural gas @ 1027 Btu/cf (East Ohio Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 1000°F

Air and Gas Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 18: Scale free heating burner specification: preheated air.

From this specification Bloom developed a Test Burner Specification that would allow the development program to work in a burner capacity range that fit their burner test facilities, equipment sizes and utility capacities. The Test Burner Specification for the SFH heating mode was based on the soak zone burner sizes of the furnace specification since the soak zone burners needed to operate at the lowest level of % stoichiometric (in the order of 50%

stoichiometric). This series of burners would be the most difficult to develop and would therefore be the reference specification for the test burner.

The SFH and CH mode Test Burner Specification is shown in the table below. These specifications lists the performance levels and capacity required for burners in the soak zone of a CH and SFH furnace as well as the performance levels and downsized capacity required for the test burner being tested and developed in the lab facilities.

BURNER SPECIFICATION / TESTING: 50% STOICHIOMETRIC SOAK ZONE											
BURNER FOR	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A / G	AIR (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	GAS (scfh)	A / G	T / D
FURNACE	39,619	7,924	5	30,476	6,095	5	1.3	5,079	1,016	5	7.8
TESTED	22,000	4,400	5	16,923	3,385	5	1.3	2,821	564	5	7.8

BURNER SPECIFICATION/TESTING: 105% STOICHIOMETRIC SOAK ZONE											
BURNER FOR	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	T/D	AIR (scfh)	GAS (scfh)	A/G	T/D
FURNACE	19,314	1,931	10	14,857	1,486	10	1.3	2,476	248	10	7.8
TEST	10,725	1,073	10	8,250	825	10	1.3	1,375	138	10	7.8

Exhibit 19: Burner Specification/testing: 50% and 105% stoichiometric in soak zone.

The following table summarizes the specified minimum and maximum furnace burner capacity and required turndown for both the furnace burner and tested burner.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	7.924 MMBtu/HR
MINIMUM SFH RATE	1.016 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	1.931 MMBtu/HR
MINIMUM CH RATE	0.248 MMBtu/HR
CH TURNDOWN	7.8

OVERALL SFH to CH TURNDOWN	31.95
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Exhibit 20: Soak zone burner turndown.

Although each mode of operation only required a 7.8/1 turndown within the mode the overall turndown of a single burner in the soak zone that has to perform both in the CH and SFH mode was 31.95/1.

The specified turndown for the CH mode was achieved in the burner development program but the specified turndown for the SFH mode could not be met as summarized in the following table.

BURNER TURNDOWN CH MODE	
REQUIRED	7.8
ACTUAL	8
BURNER TURNDOWN SFH MODE	
REQUIRED	7.8
ACTUAL	1.5

Exhibit 21: Burner turndown: CH and SFH modes.

The burner testing and demonstration results concluded that the burner fell well short of specified operating ranges for the 50% stoichiometric operating ranges required. Project Team discussions and meeting were held to determine future direction. The concern was that two additional burners still needed to be developed in order to address the significant retrofit furnace market. It was pointed out by Bloom that “pulse firing” could eliminate the need for the currently specified turndown ranges and if so, the existing burner may be applicable as is. “Pulse firing” utilizes the burner firing at maximum capacity all of the time and effects turndown by shutting the burner off in “pulses”. Bloom currently had multiple installations of pulse-fired Cyclops burners in soak zone applications.

The Project Team agreed that pulse firing was an acceptable method to effect turndown in a CH/SFH furnace. Therefore the Project Team concluded and recommended that the development/testing of the preheat air CH/SFH burner be terminated and a burner development Report be written and issued. Burner development/testing work would immediately be directed to the preheated air burner utilizing additional oxygen enriched air to achieve the required CH/SFH operating ranges.

The above synopsis is only a brief summary of the extensive work, data collection and analysis that is reported upon in the detailed report Preheated Air Burner Report contained in Appendix C of this Final Report. The reader is advised to read this report for detailed information on the work involved in the development program.

4.2.2 Oxygen Enriched Burner Report Summary (Appendix D)

A Burner Specification for this preheated air/oxygen burner needed to be issued to Bloom similar to the Burner Specification for the preheated air burner. This oxygen enriched CH/SFH burner was to be used in retrofitting existing CH furnaces that had less than 1000°F preheat air available. The approach would be to enrich the existing preheat air with oxygen to an oxygen enrichment level that would make it equivalent to 1000°F preheat air in terms of combustion efficiency in the soak zone of the existing furnace. The expectation was that a burner utilizing this level oxygen enrichment and preheat air would be able to achieve the wide range of combustion performance required for the CH/SFH modes of operation.

The first order of business was to decide upon the level of initial preheat (prior to enrichment) that the burner development would be based on. The Project Team created a questionnaire that was submitted to SMA member companies. Among other things, the questionnaire asked what was the typical preheat air temperature the member had on his existing reheat furnace. The resulting average preheat of the respondents to the questionnaire was 750°F. This level of preheat air was therefore used as the starting point of the oxygen enriched burner development.

To this point, the intention was to now enrich 750°F preheat air with sufficient oxygen so that it had the same soak zone available heat as that achieved with combustion of 1000°F preheated air at the sub stoichiometric ratio required in the soak zone of a SFH furnace (typically in the order of 53% of stoichiometric ratio based on the SFH sample heating tests). But at this point the Project Team decided to reconsider the 1000°F preheat level as the design point. Based on the difficulty in achieving the SFH mode combustion requirements in the previous preheated air burner development it was decided to increase the equivalent air preheat level to 1200°F. This of course would require a higher oxygen enrichment level than that required for 1000°F equivalency but it was expected that this higher effective preheat level would also make it easier to achieve the CH/SFH mode combustion ranges.

The following table provides the 750°F preheat air/oxygen enrichment level that is equivalent to standard air preheated to 1200°F combusted in a SFH furnace's soak zone that is operating at 2372°F, (the soak zone flue gas temperature of the SDI reference furnace).

Temperature F	Air Preheat Temp F	% O2	% of Stoichiometric	Air/Fuel Ratio	Available Heat	CO/CO2 Ratio	H2/H2O Ratio
2372	1200	21.0	53%	5.208	12.48%	3.54	1.22
2372	750	29.7	53%	3.692	12.60%	3.50	1.21

Exhibit 22: Equivalency of preheated air and oxygen enriched air for scale free heating

Standard air preheated to 1200°F and burned at 53% of stoichiometric ratio at an ambient temperature of 2372°F will have a thermal efficiency of 12.48%.

If 750°F preheated air is enriched with oxygen so that the mixture level increases from 21% to 29.7% the resulting air/oxygen mixture will have virtually the same thermal efficiency as 1200°F standard air combusted at 53% stoichiometric ratio and 2372° ambient temperature.

It is interesting to note that the resulting CO/CO₂ and H₂/H₂O ratios are also virtually the same for the both combustion air considerations. This assures one that the SFH characteristics of both combustion processes will be the same in terms of scale formation as a function of the t/t/a profiles.

It should also be pointed out that the mixture of 3.28 scfh of air at 750°F with the required 0.408 scfh of oxygen at 77°F (required to attain 29.7% oxygen in the mixture) results in a mixture temperature of 675°F being delivered at the burner.

With the preheat/oxygen enriched levels of 750°F/29.7% oxygen now being defined the following Burner Specification was developed by the Project Team and submitted to Bloom.

SCALE FREE HEATING BURNER SPECIFICATION: PREHEATED, 29.7 % OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	26,022	3,233	7,924	3,692	20,016	2,487	6,095	3,692	3,336	415	1,016	3,692	SOAK	21	166
HEAT	35,084	4,359	8,089	4,876	26,987	3,353	6,222	4,876	4,497	559	1,037	4,876	HEAT	18	146
CHARGE	43,073	5,351	0	NA	33,134	4,116	0	NA	5,523	685	0	NA	CHARGE	0	0
													FURNACE	39	312

Fuel: Natural gas @ 1044 Btu/ft³ (Pittsburgh Natural Gas)

Burner Notes: No burners are required for Charge Zone. Number of burners shown for Soak and Heat Zones are for both top and bottom heating zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

Percent Stoichiometric: Soak Zone Fired at 53% of Stoichiometric, Heat Zone at 70% Stoichiometric, Charge Zone Burndown to 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

NOx: Burners should be equivalent to EFACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

CONVENTIONAL HEATING BURNER SPECIFICATION: PREHEATED, 29.7% OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	12,566	1,561	1,931	7.31	9,666	1,201	1,486	7.31	1,611	200	248	7.31	SOAK	21	41
HEAT	30,448	3,783	4,680	7.31	23,422	2,910	3,600	7.31	3,904	485	600	7.31	HEAT	18	84
CHARGE	67,662	8,406	10,400	7.31	52,048	6,466	8,000	7.31	8,675	1,078	1,333	7.31	CHARGE	18	187
													FURNACE	57	312

Fuel: Natural gas @ 1044 Btu/ft³ (Pittsburgh Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Percent Stoichiometric: All zones fired at 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to EFACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 23: Conventional heating burner specification: preheated vs. 29.7% oxygen enriched air.

The test burner sizing was developed by Bloom and the specification of the test size and testing range of the burner was re-submitted to the Project Team for review and approval. The Project Team took under consideration the possibility of not using oxygen enrichment in the burner when the burner was to be operated in the CH mode. After further review and discussion by the Project Team it was decided that oxygen enrichment would only be utilized during SFH firing for several reasons. First and foremost, by eliminating oxygen enrichment during conventional firing, the overall burner turndown requirements through SFH and CH would be greatly improved. Turndown performance, as stated previously, was a large concern based upon previous testing. Consequently, CH burner development and testing would be performed with 750°F combustion air only.

The Bloom Engineering then developed a corresponding Demonstration Burner Specification based upon the supplied Burner Specification, taking into account the reduced percentage of available heat (~49%) associated with the non-enriched CH combustion air as compared to the original 29.7% O₂ enriched specification (~57% available heat). The revised Burner Specifications is presented below.

DEMONSTRATION BURNER SPECIFICATIONS: PREHEATED, 29.7% OXYGEN ENRICHED AIR													
MODE	ZONE	CONNECTED				DESIGN				TURNDOWN			
		AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G
SFH	SOAK	14,450	1,795	4,400	3.692	11,115	1,381	3,385	3.692	1,853	230	564	3.692
	HEAT	19,482	2,421	4,492	4.876	14,986	1,862	3,455	4.876	2,498	310	576	4.876
CH	SOAK	12,476	0	1,248	10	9,997	0	960	10	1,599	0	160	10
	HEAT	30,230	0	3,023	10	23,254	0	2,325	10	3,876	0	388	10
ZONE	MODE												
SOAK	SFH	14,450	1,795	4,400	3.692	11,115	1,381	3,385	3.692	1,853	230	564	3.692
	CH	12,476	0	1,248	10	9,997	0	960	10	1,599	0	160	10
HEAT	SFH	19,482	2,421	4,492	4.876	14,986	1,862	3,455	4.876	2,498	310	576	4.876
	CH	30,230	0	3,023	10	23,254	0	2,325	10	3,876	0	388	10

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)
 Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.
 Preheat Air Temperature: 750°F
 Air and Gas Pressure: To be provided by Burner Supplier.
 NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu
 Zone Temperatures: Say 2250°F

Exhibit 24: Revised burner specifications for preheated, 29.7% oxygen enriched air.

It should be pointed out that oxygen enriched CH might actually be favorable in certain retrofit considerations. For example, if the cost of oxygen is considerably less than the cost of natural gas it would be advantageous to utilize oxygen enrichment for both the CH and SFH modes. In any such case the resulting burner performance associated with oxygen enriched CH firing will have to be reviewed on a case by case basis. This is because there could be a possibility of high NO_x emissions with the combination of preheated, oxygen enriched air in the CH mode. The test burner specification was developed from the above furnace burner specification and is provided in the following table.

SPECIFIED VERSUS TESTED BURNER SIZE		
ZONE @ % STOICHIOMETRIC	SPECIFIED (MMBtu/hr)	TESTED (MMBtu/hr)
SOAK @ 50% STOICHIOMETRIC	7.924	4.400
SOAK @ 105% STOICHIOMETRIC	1.931	1.248*

*Value corrected for available heat variance due to non-enriched combustion air during CH.

Exhibit 25: Specified vs. tested burner size.

The overall range of turndown required in the soak zone of a CH/SFH furnace is provided in the following table. While within either the CH or SFH mode the burner turndown only needed to be 7.8/1, when consideration is made that one burner has to perform in both modes the overall turndown of that burner is 27.5/1.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	4.400 MMBtu/HR
MINIMUM SFH RATE	0.564 MMBtu/HR
SFH TURNDOWN	7.8

MAXIMUM CH RATE	1.248 MMBtu/HR
MINIMUM CH RATE	0.160 MMBtu/HR
CH TURNDOWN	7.8
OVERALL SFH to CH TURNDOWN	27.50

Exhibit 26: Soak zone burner turndown.

Testing and development work encountered the same problem that the preheated air burner development met in that the desired turndown for the SFH mode could not be achieved. This is demonstrated in the following table.

BURNER TURNDOWN 50% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	1.33
BURNER TURNDOWN 100% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	8

Exhibit 27: Burner turndown test results at 50% and 100% stoichiometric firing

Again, as was the case in the preheated air development work, pulse firing was accepted as a way to attain turndown and thereby allow the burner to achieve the overall 27.5/1 turndown when applied to a CH/SFH furnace retrofit. This allowed the Project Team to move on to the development of the third and final burner type, a flat flame type burner that could perform in both the CH and SFH mode.

The above synopsis is only a brief summary of the extensive work, data collection and analysis that is reported upon in the detailed report Oxygen Enriched Burner Report contained in Appendix D of this Final Report. The reader is advised to read this report for detailed information on the work involved in the development program.

4.2.3 Scale Free HTR Burner Report Summary (Appendix E)

Burner development/testing work was then directed to the flat flame burner that would also utilize preheated oxygen enriched air to achieve the required CH/SFH operating ranges. Remember that an analysis of the retrofit market conducted in the early stages of Phase II had pointed out that about 50% of the potential retrofit furnace market utilized flat flame burners in at least one zone of the furnace. This statistic emphasized the additional need for a flat flame burner that could also meet the CH/SFH requirements of a furnace converted from CH to

CH/SFH. A Burner Specification for this burner was largely based off of the Burner Specification already provided for the longitudinal oxygen-enriched preheated air burner. The same level of preheat air (750°F) and the same level of oxygen enrichment (29.7% total oxygen in air) was used for the Burner Specification to Bloom which in turn was sized down to a test burner size and performance range summarized in the following table.

SPECIFIED VERSUS TESTED BURNER SIZE		
ZONE @ %	SPECIFIED (MMBtu/hr)	TESTED (MMBtu/hr)
STOICHIOMETRIC		
SOAK @ 50% STOICHIOMETRIC	8.273	5.220
SOAK @ 105% STOICHIOMETRIC	2.016	1.480*

**Value corrected for available heat variance due to non-enriched combustion air during CH.*

Exhibit 28: Burner size: specified vs. tested burner size .

Testing and development work encountered the same problems that the preheated air burner and oxygen enriched burner development work met previously in that the desired turndown for the SFH mode could not be achieved. But again pulse firing was accepted as a way to attain turndown and thereby allow the burner to achieve the overall 27.5/1 turndown required when applied to a CH/SFH furnace retrofit.

The above is only a brief summary of the extensive work, data collection and analysis that is reported upon in the detailed report Scale Free HTR Burner Report contained in Appendix E of this Final Report. The reader is advised to read this report for detailed information on the work involved in the development program.

5 ACCOMPLISHMENTS

Numerous accomplishments were attained within this Project which have been described in the previous Sections of this Report.

- A scale free heating process was developed and tested. This process substantially reduces the amount of scale formed while heating products from room temperature to rolling and forming temperatures. The amount of scale reduction is dependent upon the specific furnace design, product and heating profile being considered but can easily reach scale reduction levels of 90% or more.
- An integral analysis method was developed to reliably predict the relative amount of scale generated in a furnace operating in the SFH mode.
- The burner hardware needed for either a new furnace capable of both CH and SFH or a retrofit of an existing furnace to CH/SFH was developed and tested.

- The developed process and combustion hardware are currently being marketed by the Project Team to a major USA Steel Company. Other potential applications are being pursued in the specialty steel market and forging industry.
- Five technical Reports have been completed that fully describe the work completed in the SFH process development and the SFH burner development.

All of the above have been addressed within the context of this Final Report and/or in the detailed reports included in the Appendices of this Final Report.

The marketing of the developed SFH process and technology has afforded the Project Team the opportunity to oversee the potential application of the SFH technology to many different types of furnaces and product production cycles. In addressing these potential applications the Project Team developed additional tools and analytical methods to more quickly and more accurately evaluate the benefits SFH brings to a specific application. An improved and more accurate method to do a CH and SFH heat balance was developed and the Integral Analysis method was used to project annual scale savings and project Paybacks for different types of mills and reheat furnaces. These are discussed in the following.

5.1 Improved Heat Balance Procedure

A procedure for extending a conventional heating furnace heat balance to a scale free heating heat balance applicable to the same furnace geometry and product heating level was developed in the Scale Free Sample Testing phase of this Project. This heat balance procedure is discussed briefly in Section 4.1.2. of this Final Report and reported upon in great detail in the Scale Free Heating Sample Report which is included as Appendix B of this Final Report.

During the marketing work of this Project the Project Team had to evaluate many potential applications of SFH applied to existing or proposed CH situations. In doing so, the Project Team developed and applied a more streamline and exactly accurate method to extrapolate a SFH heat balance from the base CH heat balance. Before describing this method it is necessary to briefly review the CH and SFH heat balance method and procedures used in the earlier Project work.

The original procedure required time consuming re-iterations of the % stoichiometric combustion levels in the soak and heat zones in order to arrive at a final heat balance that allowed all the combustibles generated in the heat and soak zones to be burned completely down in the charge zone, prior to entering the furnace flue system. The re-iteration process seldom arrived at a perfect SFH heat balance. The heat balance designer was forced to error slightly on the safe side which resulted in sacrificing some potential scale savings in favor of avoiding exhausting rich gasses into the flue. It also often resulted in slightly higher MMBtu/ton for the SFH mode as opposed to the CH mode of heating.

The original heat balance procedure started with a conventional heating heat balance which is summarized in the following table.

CONVENTIONAL HEATING HEAT BALANCE SUMMARY											
Structural Dynamics Inc.		200 tph Walking Beam									
FURNACE CAPACITY		200 TPH									
PIECE THICKNESS		BB3 IN									
PIECE WIDTH		28.75 IN									
PIECE LENGTH		47.5 FT									
PIECE SPACING		45.3 IN									
PREHEAT TEMP		1000 °F									
EXCESS AIR		10 %									
FLUE GAS MASS		856 #/HR/MMBTU									
% TOP HEATING		55 %									
% INSULATION		100									
HEATING CURVE INFORMATION											
		SOAK		HEAT		PREHEAT		UFPH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM		
SET POINT	°F	2250	2250	2225	2225	1950	1950	OFF	OFF		
WALL TEMP	°F	2250	2250	2225	2225	1950	1950	1755	1755		
FG TEMP	°F	2350	2350	2325	2325	2050	2050	1560	1560		
TIME IN ZONE (MIN)		26.25	26.25	31.5	31.5	22.5	22.5	8.75	8.75	89	
HEAT TO WORK BTU/#		8.8	N/A	98.8	N/A	165.7	N/A	70.8	N/A		
Q TOTAL	MMBTU/HR	3.52	N/A	39.52	N/A	66.28	N/A	28.32	N/A	137.64	
FURNACE NET HEAT BALANCE CALCULATIONS											
		SOAK		HEAT		PREHEAT		UFPH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM		
WORK	MMBTU/HR	1.94	1.58	21.74	17.78	36.45	29.83	15.58	12.74	137.64	86.43%
WALLS	MMBTU/HR	0.502	0.496	0.565	0.408	0.361	0.342	0.153	0.116	2.94	1.85%
RAILS	MMBTU/HR	0.00	2.624	0.000	3.054	0.000	1.503	0.000	0.431	7.61	4.78%
POSTS	MMBTU/HR	0.00	1.083	0.000	1.043	0.000	1.160	0.000	0.293	3.58	2.25%
SLOTS	MMBTU/HR	0.00	1.845	0.000	1.778	0.000	1.729	0.000	0.411	5.76	3.62%
MISC	MMBTU/HR	0.653	0.654	0.000	0.000	0.000	0.000	0.201	0.201	1.71	1.07%
NET-TOT	MMBTU/HR	3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20	159.25	100%
Overall Furnace Available Heat =										70.81%	
Overall Furnace Gross Input =										224.88 MMBtu/hr	
Conventional Heating MMBtu/ton =										1.12 MMBtu/ton	

Exhibit 29: Conventional heating heat balance summary.

As noted, this heat balance is for the reference SDI furnace heating the BB3 product at the design capacity of 200 tph. This is the base reference heat balance used in the CH and SFH sample tests discussed and is reported upon in much more detail in the Appendix B Reports.

As discussed in the Appendix B Report, this base CH heat balance was then used to generate the corresponding SFH heat balance. By making the SFH mode adapt to this CH heat balance the furnace designer was assured that this furnace would be able to operate in both the CH and SFH mode of operation which was one of the basic premises of this Project. The Appendix B Report explains how the above CH heat balance is converted into the following SFH heat balance.

SCALE FREE HEATING HEAT BALANCE SUMMARY										
Structural Dynamics Inc. 200 tph Walking Beam										
FURNACE CAPACITY 200 TPH										
PIECE THICKNESS BB3 IN										
PIECE WIDTH 28.75 IN REFERENCE IS bb3 200 tph conventional(1)										
PIECE LENGTH 47.5 FT										
PIECE SPACING 45.3 IN										
PREHEAT TEMP 1000 °F										
EXCESS AIR 10 %										
FLUE GAS MASS 856 #HR/MMBTU										
% TOP HEATING 55 %										
% INSULATION 100										
HEATING CURVE INFORMATION										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
SET POINT °F		2250	2250	2225	2225	1950	1950	OFF	OFF	
WALL TEMP °F		2250	2250	2225	2225	1950	1950	1755	1755	
FG TEMP °F		2350	2350	2325	2325	2050	2050	1560	1560	
TIME IN ZONE (MIN)		26.25	26.25	31.5	31.5	22.5	22.5	8.75	8.75	89
HEAT TO WORK BTU/#		8.8	N/A	98.8	N/A	185.7	N/A	70.8	N/A	
Q TOTAL MMBTU/HR		3.52	N/A	39.52	N/A	66.28	N/A	28.32	N/A	137.64
FURNACE NET HEAT BALANCE CALCULATIONS										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
WORK MMBTU/HR		1.94	1.58	21.74	17.78	36.45	29.83	15.58	12.74	137.64 86.43%
WALLS MMBTU/HR		0.502	0.496	0.565	0.408	0.361	0.342	0.153	0.116	2.94 1.85%
RAILS MMBTU/HR		0.00	2.624	0.000	3.054	0.000	1.503	0.000	0.431	7.61 4.78%
POSTS MMBTU/HR		0.00	1.083	0.000	1.043	0.000	1.160	0.000	0.293	3.58 2.25%
SLOTS MMBTU/HR		0.00	1.845	0.000	1.778	0.000	1.729	0.000	0.411	5.76 3.62%
MISC MMBTU/HR		0.653	0.654	0.000	0.000	0.000	0.000	0.201	0.201	1.71 1.07%
NET-TOT MMBTU/HR		3.09	8.25	22.30	24.07	36.82	34.56	15.93	14.20	159.25 100%
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
Net Heat Required @ Zone Exit =		11.38		MMBTu/hr						
AH @ 50% =		8.21%		%						
Firing Rate Required =		138.65		MMBTu/hr						
Furnace Total Net Heat Required @ Zone Exit =				57.75		MMBTu/hr				
				AH @ 80% =		35.14%				
				Firing Rate Required =		164.34		MMBTu/hr		
				Firing Rate from Previous Zones =		138.65		MMBTu/hr		
				Firing Rate Required =		26.69		MMBTu/hr		
				Furnace Total Net Heat Required @ Zone Exit =		159.25		MMBTu/hr		
						AH @ 110% =		70.81%		
						Firing Rate Required =		224.88		MMBTu/hr
						Firing Rate from Previous Zones =		164.34		MMBTu/hr
						Firing Rate Required =		60.54		MMBTu/hr
						Total Furnace Input =		224.88		MMBTu/hr
						SFH MMBtu/ton =		1.124		MMBTu/ton
						CH MMBtu/ton =		1.124		MMBTu/ton

Exhibit 30: Scale free heating heat balance summary.

Numerous iterations were done before arriving at this final SFH heat balance. The iterations involved trying to run the Soak and Heat zones as rich as possible, i.e. low % stoichiometric, while still be able to burn down all of the rich carryover gasses in the charge zone.

Exhibit 31: Heat balance calculation methodology example

The above summary schematic shows that in addition to burning the 164 MMBtu/hr flue gasses at 80% stoichiometric down to 110% stoichiometric in the charge zone an additional 61 MMBtu/hr was fired through the charge zone burners at 110% stoichiometric.

The above two CH and SFH heat balances were the basis for the t/t/a profiles that were used for the CH and SFH sample heating tests. The sample heating tests in turn generated the amount of scale formed in the CH mode and the amount of scale formed in the SFH mode when the reference furnace was heating BB3 products at the rated capacity of 200 tph.

But in fact, the above SFH heat balance wasn't truly the optimum SFH mode operating condition because 61 MMBtu/hr was still injected through burners in the charge zone firing at

110% stoichiometric. The optimum SFH mode operating condition would be one where no additional burner input is needed in the charge zone and all heat required in the charge zone is acquired by burning down the carryover gasses from the soak and heat zones. This would be optimum because it would entail the soak and/or heat zones operating at lower % stoichiometric than the 50% and 80% levels that they are operating at in the above SFH heat balance. This in turn would result in the BB3 product seeing lower % stoichiometric flue gasses in the soak and/or heat zones as well as in the burndown section of the charge zone and therefore forming less scale.

The Project Team developed many tools to assist in the analysis of how sub-stoichiometric combustion affected the thermal efficiency of the combustion process and how sub-stoichiometric flue products affected the scale level of steel at elevated temperatures. The latter tool was used in the Integral Analysis work described in Section 4.1.2. of this Final Report and in more detail in the Appendix B Report.

The thermal efficiency of sub-stoichiometric combustion was addressed by use of an equilibrium program that generated the thermal efficiency of a given % stoichiometric level and temperature of sub-stoichiometric combustion. While evaluating many potential applications of CH/SFH in the marketing phase of this Project the Project Team used the equilibrium program to streamline the SFH heat balance procedure and to more accurately calculate a SFH heat balance from the base CH heat balance. Instead of re-iterating the level of % stoichiometric combustion through the soak, heat and charge zones until most or all of the sub-stoichiometric flue gasses generated in the soak and heat zones were burned to completion in the charge zone (as described above in the CH and SFH heat balances) the equilibrium program was used to exactly define what level of % stoichiometric combustion was needed in the heat zone to guarantee complete and perfect burndown in the charge zone.

The equilibrium program also generated the products of combustion at the specific % stoichiometric combustion level being considered and therefore the ratio of CO/CO_2 and $\text{H}_2/\text{H}_2\text{O}$ were defined. Executing the equilibrium program over a range of sub-stoichiometric points allowed the development of the adjacent graphs which defined what the gas constituent ratio or the % stoichiometric level needed to be on the scale free line representing the interface between reducing and oxidizing.

Exhibit 32: Effect of steel temperature and furnace “atmosphere” on steel oxidation

Exhibit 33: Effect of steel temperature and stoichiometry of furnace “atmosphere” on steel oxidation

An example of how these tools were applied to generate a heat balance that perfectly optimized the SFH mode of combustion within the furnace is embodied in the following heat balance.

SCALE FREE HEATING HEAT BALANCE SUMMARY

Structural Dynamics Inc. 200 tph Walking Beam

FURNACE CAPACITY	200	TPH																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					</
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Exhibit 34: Scale free heating heat balance summary.

The empirical expression that defined the % stoichiometric ratio required for scale free heating as a function of the product's surface temperature determined that the soak zone had to be fired at 53% stoichiometric in order to remain scale free to a product with a surface temperature

experienced within the soak zone. This empirical expression represented the curve in the following graph.

Exhibit 35: Effect of steel temperature and stoichiometry on steel oxidation

The equilibrium program was used to determine that the available heat of the combustion process occurring in the soak zone was 10.8%. This is the result of combustion at a flue gas temperature of 2350°F, with a preheat air temperature of 1000°F and a combustion ratio of 53% stoichiometric. As shown below, this resulted in the burners in the soak zone firing at an input rate of 105 MMBtu/hr.

Net Heat Required @ Zone Exit =	11.38	MMBtu/hr
AH @ 53% =	10.80%	%
Firing Rate Required =	105.33	MMBtu/hr

Exhibit 36: Soak zone firing rate requirement calculations

The improvement in the heat balance process occurs in the consideration of the heat balance in the Heat Zone which is summarized below.

Furnace Total Net Heat Required @ Zone Exit =	57.75	MMBtu/hr	
Total Firing Rate of CH furnace =	224.88	MMBtu/hr	from the CH Heat Balance above
Therefore % AV of Heat Zone Required =	25.68%		
Therefore % Stoichiometric of Heat Zone Required =	69.40%		
Firing Rate of Heat Zone Required =	119.55	MMBtu/hr	

Exhibit 37: Heat zone firing rate requirement calculations

It is already known from the CH heat balance that the total furnace input required for CH was 224.88 MMBtu/ton. If one now defines the total input fired in the soak and heat zone to be equivalent to the total input of the furnace for conventional heating one would determine that the available heat of the combustion process at this point in the scale free heating heat balance

had to be $(57.75 \text{ MMBtu/hr}) / (224.88 \text{ MMBtu/hr})$ which is equal to 25.68%. That is, the total net heat required by the heat balance at this point divided by the total input expected to be fired into the furnace. That expected total input is the total input fired in the CH heat balance (224.88 MMBtu/hr).

The equilibrium program is then used to determine that combustion at a % stoichiometric ratio of 69.4% will yield the required available heat of 25.68% for the combustion conditions in the heat zone.

Furthermore, since 105.33MMBtu/hr had already been fired through the soak zone burners at 53% stoichiometric it was necessary to burndown these flue gasses to 69.4% stoichiometric and add an additional $224.88 - 105.33 = 119.55 \text{ MMBtu/hr}$ through the heat zone burners firing at 69.4% stoichiometric.

The SFH heat balance is completed in the charge and unfired preheat zone as shown in the following table.

Furnace Total Net Heat Required @ Zone Exit =	159.25	MMBtu/hr
AH @ 110% =	70.81%	
Firing Rate Required =	224.88	MMBtu/hr
Firing Rate from Previous Zones =	224.88	MMBtu/hr
Firing Rate Required =	0.00	MMBtu/hr
Total Furnace Input =	224.88	MMBtu/hr
SFH MMBtu/ton =	1.124	MMBtu/ton
CH MMBtu/ton =	1.124	MMBtu/ton

Exhibit 38: Calculations for heat requirement in terms of Btu per ton of steel

An exact agreement is achieved with the previous CH heat balance since both the total net heat required by the furnace and product and the overall furnace available heat is the same for both the CH and SFH heat balance. No time consuming and approximating iterations were required as was done in the original method used to develop the SFH heat balance from the CH heat balance presented in the Appendix B Report.

The new heat balance method optimizes the t/t/a (time/temperature/atmosphere) profiles for the SFH heating mode because it assures that the soak and heat zones are operating as rich as possible while still meeting the CH heat balance criteria. If the soak and heat zones are operating as rich as possible than they are also developing the least amount of scale on the product being heated in these zones at the t/t (time/temperature) profile dictated by the CH heating profile.

This is demonstrated by comparing the following two combustion schematics.

Exhibit 39: Example of heat balance calculations – case 1

Exhibit 40 Example of heat balance calculations – case 2s

The upper schematic summarizes the furnace firing strategy as deduced from the original heat balance procedure applied during the conventional heating and scale free heating sample heating tests and reported upon in the Appendix A and B Reports.

The lower schematic summarizes the furnace firing strategy deduced from the improved heat balance procedure. The results are summarized in the table below.

COMPARISON OF HEAT BALANCE METHOD							
	SOAK ZONE		HEAT ZONE		CHARGE ZONE		TOTAL
	ORIGINAL METHOD	NEW METHOD	ORIGINAL METHOD	NEW METHOD	ORIGINAL METHOD	NEW METHOD	
INPUT (MMBtu/hr)	138	105	26	120	61	0	225
% STOICHIOMETRIC	50%	53%	80%	69%	110%	110%	225

Exhibit 41: Comparison of heat balance methods.

The new heat balance method maximizes the sub-stoichiometric input in the soak and heat zones and assures that complete burndown is perfectly attained in the charge zone. Therefore the heated product is exposed to the highest levels of sub-stoichiometric combustion levels in the soak and heat zones which in turn will result in the lowest levels of scale possible for this heat balance.

5.2 Payback Analysis

Integral Analysis (IA) was described in Section 4.1.2. of this Final Report and is discussed in more detail in the Appendix B Report. The streamlining of CH and SFH heat balances which assured the minimum scale when a furnace was operated in the SFH mode was discussed in Section 5.1 above. With the improved heat balance procedure and IA capabilities it became possible for the Project Team to accurately predict the reduction in scale when a furnace was either initially designed for CH/SFH capability or was retrofitted from a CH mode so that it could perform in both the CH and SFH mode.

If the predicted performance resulting from CH/SFH modes of operation could be combined with the additional cost required to make a furnace capable of CH/SFH modes it is possible to determine the payback of the cost of SFH. Some Project Team members did have costs for a turnkey supply of a CH furnace from previous commercial projects they had completed. The

Project work had by now clearly defined the hardware and control modifications needed for both CH and SFH heating in one furnace. Therefore it was possible to estimate the costs of what the original CH furnace would be if it had been designed, supplied and installed as a furnace capable of both CH and SFH. Project Team members therefore did Payback Analyses for three types of furnaces and these paybacks are presented in the following Sections.

5.2.1 Walking Beam Furnace Payback

A Project Team member had originally supplied the reheat furnace at SDI's Structural Mill. This is the same furnace that has been utilized throughout this Project to develop time, temperature and atmosphere profiles and heat balances for both CH and SFH modes that were then used to determine the scale savings for SFH (the Process Development work of this Project) and to determine the burner specifications (the Hardware Development work of this Project).

The original CH furnace cost was updated to 2010 costs. The original CH furnace specification was re-specified to define the SFH burner, recuperator, piping, steel, and control hardware and engineering costs that would have been required if this furnace had been originally supplied as a CH/SFH furnace. The original but updated cost was then corrected with the added costs of these material items not only manufactured and delivered but also installed. Therefore a new turnkey cost of a CH/SFH furnace was arrived at.

The difference between the original but updated cost of a CH furnace only and the new cost of that furnace now being provide as a furnace capable of CH/SFH modes of operation would represent the cost of SFH.

The annual amount of scale saved was estimated by reference to the scale savings determined in the SFH sample tests where the scale savings for a wide range of furnace operation had already been determined. The Team Member SDI provided operational data concerning contact time, % delays and hearth coverage. The Project Team then calculated the expected annual scale for both a CH furnace and a SFH furnace. The payback for the premium paid for the SFH furnace based on the annual scale savings is provided in the following table.

STRUCTURAL MILL - WALKING BEAM			
OPERATIONAL DATA			
	CONVENTIONAL	SCALE FREE HEATING	
Cost of Scale =	\$755.00	SAME	\$/ton scale
TPY =	1,000,000	SAME	
% Scale =	1.25%	0.14%	%
Contact Time =	77%	SAME	%
Delays =	18%	SAME	%
Hearth Coverage =	70%	SAME	%
MMBtu/ton =	1.44	SAME	MMBtu/ton
SCALE SAVINGS			
	CONVENTIONAL	SCALE FREE HEATING	
Operating Tons of Scale/yr =	12,500	1,400	tons/yr
Tons Scale Formed Due to Delays/yr =	IN ABOVE	2,513	tons/yr
Total Scale Formed/yr =	12,500	3,913	tons/yr
Cost of Total Scale Formed/yr =	\$9,437,500	\$2,954,638	\$/yr
Cost of Scale Removal/yr =	\$50,400	\$15,779	\$/yr
Total Scale Cost/yr =	\$9,487,900	\$2,970,417	\$/yr
SFH Scale Savings/yr =		\$6,517,483	\$/yr
PAYBACK			
	CONVENTIONAL	SCALE FREE HEATING	
Turnkey Furnace Sales Price =	\$14,500,000	\$17,300,000	
Premium for SFH =		\$2,800,000	
Payback =		0.43	yrs

Exhibit 42: Payback for the SFH furnace based on the annual scale savings.

The CH Operational Data was provided by SDI and was used for the SFH column except for the 0.14% scale which was the result of the sample heating tests. The MMBtu/ton would be the same because the SFH furnace would be designed to provide the same thermal efficiency as the CH furnace.

In the Scale Saving section the Operating Tons of Scale/yr is based on the production of 1 million tons per year at either a 1.25% or a 0.14% scale rate. The Tons Formed Due to Delays/yr was calculated by the Project Team's model and SDI's operational data of Contact Time, Delays and Hearth Coverage.

The annual savings due to scale reduction with the CH/SFH furnace was determined to be \$6,517,483 per year.

The cost premium for the design, supply and install a furnace capable of CH/SFH versus a furnace capable of CH only was \$2,800,000.

This yields a payback for the considered Walking Beam furnace of 0.43 yrs.

5.2.2 Walking Hearth Furnace Payback

The same Project Team member had also originally supplied a Walking Hearth reheat furnace to a major long products supplier to serve a Merchant Bar Mill. The Project was a turnkey

supply that involved engineering, manufacturing, installation and startup so the Project Team member had a complete CH, Walking Hearth Furnace estimate to extrapolate a CH/SFH, Walking Hearth Furnace cost. As in the case of the Walking Beam furnace above, the original CH estimate was updated to 2010 pricing and then the CH furnace specification was re-specified to define the SFH burner, recuperator, piping, steel, and control hardware and engineering costs that would have been required if this furnace had been originally supplied as a CH/SFH furnace. Therefore a new turnkey cost of a CH/SFH furnace was arrived at.

The difference between the original but updated cost of a CH furnace only and the new cost of that furnace now being provide as a furnace capable of CH/SFH modes of operation would represent the cost of SFH.

The Team Member that had originally supplied the CH furnace provided operational data concerning contact time, % delays and hearth coverage since this was information contained in the original Proposal. The original customer provided the estimated CH scale formation and an IA analysis was done to determine the estimated % reduction in scale with SFH.

The payback for the premium paid for the SFH furnace based on the annual scale savings is provided in the following table.

MERCHANT MILL - WALKING HEARTH			
OPERATIONAL DATA			
	CONVENTIONAL	SCALE FREE HEATING	
Cost of Scale =	\$500.00	SAME	\$/ton scale
TPY =	500,000	SAME	
% Scale =	1.00%	0.21%	%
Contact Time =	85%	SAME	%
Delays =	10%	SAME	%
Hearth Coverage =	90%	SAME	%
MMBtu/ton =	1.15	SAME	MMBtu/ton
SCALE SAVINGS			
	CONVENTIONAL	SCALE FREE HEATING	
Operating Tons of Scale/yr =	5,000	1,050	tons/yr
Tons Scale Formed Due to Delays/yr =	IN ABOVE	345	tons/yr
Total Scale Formed/yr =	5,000	1,395	tons/yr
Cost of Total Scale Formed/yr =	\$2,500,000	\$697,403	\$/yr
Cost of Scale Removal/yr =	NA	NA	\$/yr
Total Scale Cost/yr =	\$2,500,000	\$697,403	\$/yr
SFH Scale Savings/yr =		\$1,802,597	\$/yr
PAYBACK			
	CONVENTIONAL	SCALE FREE HEATING	
Turnkey Furnace Sales Price =	\$9,400,000	\$10,800,000	
Premium for SFH =		\$1,400,000	
Payback =		0.78	yrs

Exhibit 43: Payback for the SFH furnace based on the annual scale savings.

The cost premium for the design, supply and install a furnace capable of CH/SFH versus a furnace capable of CH only was \$1,400,000.

This yields a payback for the considered Walking Hearth furnace of 0.78 yrs.

Top Fired Pusher Furnace Payback

A Project Team member was currently quoting a Top Fired Pusher Furnace to a major USA steel manufacturer. The manufacturer had already received a CH Top Fired Pusher Furnace Proposal from the Project Team member and was interested in the cost and performance of a CH/SFH furnace. The Project Team member therefore developed and submitted a Proposal for a CH/SFH furnace and provided the following payback analysis for this Final Report.

WIRE ROD MILL - TOP FIRED PUSHER FURNACE			
OPERATIONAL DATA			
	CONVENTIONAL	SCALE FREE HEATING	
COST OF STEEL	600	600	\$/ton scale
TPY	420,000	420,000	%
% SCALE	0.75	0.225	%
CONTACT TIME	75	75	%
DELAYS	15.00%	15.00%	%
HEARTH COVERAGE	90	90	%
MMBTU/TON	1.00	1.00	MMBTU/TON
SCALE SAVINGS			
	CONVENTIONAL	SCALE FREE HEATING	
OPERATING TONS OF SCALE/yr	3150	945	tons/yr
TONS SCALE FORMED DUE TO DELAYS/yr	In above	473	tons/yr
TOTAL SCALE FORMED/yr	3150	1418	tons/yr
COST OF SCALE FORMED/yr	1,890,000	850,500	\$/YR
COST OF SCALE REMOVAL/yr	57,600	19,200	\$/YR
TOTAL SCALE COST/yr	1,947,600	869,700	\$/YR
SFH SCALE SAVINGS/yr		\$ 1,077,900.00	
PAYBACK			
	CONVENTIONAL	SCALE FREE HEATING	
TURNKEY FURNACE SALES PRICE	Base	Base + \$750,000	
	PREMIUM FOR SFH	Base + \$750,000	
PAYBACK		0.70	YRS

Exhibit 44: Payback calculations for the scale free heating application

The annual savings due scale reduction with the CH/SFH furnace was determined to be \$1,077,900 per year.

The cost premium for the design, supply and install a furnace capable of CH/SFH versus a furnace capable of CH only was \$750,000.

This yields a payback for the considered Walking Hearth furnace of 0.70 yrs.

5.2.3 Payback Summary

The Table below summarizes the Paybacks of the three types of mills and furnaces considered in the above.

TYPE OF MILL	TYPE OF FURNACE	ANNUAL SCALE SAVINGS WITH CH/SFH	COST PREMIUM FOR CH/SFH FURNACE	PAYBACK FOR CH/SFH FURNACE
STRUCTURAL	WALKING BEAM	\$6,517,483/yr	\$2,800,000	0.43 yr
MERCHANT BAR	WALKING HEARTH	\$1,802,597/yr	\$1,400,000	0.78 yrs
WIRE ROD	TOP FIRED PUSHER	\$1,077,900/yr	\$750,000	0.70 yrs

Exhibit 45: Paybacks summary for scale free heating in different applications

6 CONCLUSIONS

The project team has achieved objectives of Phase I and Phase II of the scale free steel reheating system development program.

Phase I of the program was focused on preliminary feasibility analysis of the potential benefits and market applicability of the scale free steel reheating process and indicated that it is possible to develop and apply a scale free reheating process that offers major competitive advantages to the U.S. steel industry while offering significant reduction in energy used by the steel industry.

Phase II activities included further analysis and testing of the process parameters to accomplish scale free heating, laboratory demonstration of feasibility of scale free heating through sample testing, development of the critical components (burners and control system), engineering analysis and preliminary economic analysis model. These activities together with contacts with the potential users and active marketing efforts by an international furnace supplier resulted in proposals to one steel company for application of scale free reheating in the US steel industry.

The process analysis indicates that it is possible to use natural gas fired combustion system that is capable of generating process atmosphere (mixture of gases) that can be used for scale free heating of steel and at the same time maintain or reduce energy use in the reheating process. The process requirements can be met by using preheated air for combustion of natural gas or a mixture of preheated combustion air and oxygen enrichment of the combustion air. The combustion process can be maintained to avoid soot formation and achieve the required "flame" temperature to allow efficient heating rates in various zones of a reheating furnace.

The program activities included development and extensive testing of the burners which are considered as the most critical component of a reheat furnace. The burner testing demonstrated that it is possible to operate the burners at 50% sub-stoichiometric combustion condition, at excess air firing condition and at all other air-fuel ratios between these two conditions. This performance is achieved for three important operating conditions: (i) conventional axial flame configuration with use of highly preheated (between 1000 deg. F. and 1200 deg. F.) combustion air; (ii) conventional axial flame configuration with use of lower temperature preheated (750° F. and lower) combustion air with oxygen enrichment as required; and (iii) flat flame configuration with preheated air (750° F. and lower) and oxygen enriched air as required. Availability and successful testing of these burners allows us to offer application of scale free heating for large percentage (about 76%) of the steel reheating capacity in the USA.

The most important advantage offered by the current scale free heating system using the burners developed under this program is the ability to operate a furnace under scale free condition or conventional (excess air firing) and the ease of switching operations from one type to another without any significant time delay. This feature allows optimization of operations under different production conditions or production rates and reduces any risk of adapting scale free heating.

A simple analysis methodology developed under this program allows us to predict reduction in scale formation with use of scale free heating. The prediction is based on the time-temperature-gas composition used during the heating process and the current level of scale formation. In most cases it is not possible to use theoretically required time-temperature-atmosphere conditions, especially under off-design production. Use of the predictive model can be very useful for a detail economic analysis in which scale reduction is a major and often controlling parameter. Comparison of the model results with the test results show a very good agreement and provides high level of confidence in its validity.

A major internationally active furnace supplier, Danieli Corporation completed a set of proposal or pre-design drawings to analyze application of scale free heating for a pusher furnace. This was done for a steel company and a formal proposal was submitted using the analysis discussed below for a pusher furnace. Hence the following conclusions are derived based on the experience on a real commercial application. The design and its analysis included consideration of important design and operating issues. They include: (i) effect of the time-temperature-atmosphere cycle on scale formation and energy use (MM Btu/ton) under conventional and scale free heating operations; (ii) issues related to use of sub-stoichiometric combustion in various furnace zones under different operating conditions related to safety and hazard analysis; (iii) piping and controls related issues; and (iv) preliminary cost analysis that shows incremental cost associated with use of scale free heating compared to a furnace designed for conventional steel reheating. The conclusions were reached that it is possible to design and expect a safe operation under different operating conditions during scale free heating. It is also possible to control the furnace operation that can be changed from scale free to convectional heating and vice-versa for a reheat furnace. The preliminary cost analysis for a new furnace application shows less than one year payback period for added investment for the scale free design. The analysis also indicated that it is possible to reduce scale formation by approximately 70% during reheating process. This level of scale reduction was acceptable to the steel company.

Preliminary economic analysis covering the additional cost to supply a furnace with scale free heating capability in addition to the basic conventional heating capability was completed for a walking beam furnace, a walking hearth furnace and a pusher hearth furnace. The payback analysis indicated that it is possible to expect less than one year payback of the added cost for making the furnace capable of scale free heating. Actual payback depends on various factors such as the operating practices, production variations, air preheat temperature and the availability and cost of oxygen when oxygen enrichment is used.

Scale free reheating can be applied in the forging industry for continuous furnaces with high production (usually greater than 10 tons/hr) furnaces. The smaller furnaces are usually batch type and use of scale free heating would result in higher energy use measured in terms of MM Btu/ton. However scale formation and its effects on downstream equipment is very important economic consideration in the forging industry. For example reduced scale or absence of scale on the hot steel to be forged can extend the tool life, reduce maintenance on the tools, and extend die life. Cost reductions associated with reduction in costs for downstream equipment may justify increased energy use, most likely in continuous operations. Use of scale free heating for batch furnaces is very doubtful unless the exhaust gas heat can be used in some other application such as heating water, or air or preheating other parts before they are placed in the forging furnace. We were not able to find such appellations during our efforts in locating a suitable application in forging industry.

A summary of the conclusions is listed below.

- a. We have developed sufficient knowledge and methodology to define the required process and design parameters that can be used to design a scale free heating application for the steel industry.
- b. All necessary burners and associated components such as air preheaters or oxygen enrichment is now commercially viable. The burners can be used for scale free as well conventional operations and can use preheated air or a combination of preheated air and oxygen enrichment when the existing air preheat temperature is lower than 1000° F.
- c. The hardware and controls allow a furnace user to select the type of operation with “a flip of a switch” and optimize energy use or scale formation. The operational changes required due to changes in operating conditions or production requirements can be accomplished without changing hardware or extensive time delays associated with adjustments in the hardware.
- d. It is possible to predict scale reduction with reasonable accuracy for a given time-temperature - atmosphere conditions and use it for optimization of the process parameters and cycle.
- e. The scale free heating can be applied to most commonly used furnace system such as a walking furnace, pusher hearth furnace, rotary furnace etc.
- f. The technology is now available for application to any one of the most commonly used reheat furnaces from a US based international furnace company. They can conduct the required process and feasibility analysis for application of scale free heating in a new furnace or retrofit to an existing furnace.
- g. Preliminary economic analysis for three major furnace categories indicate that payback periods for added cost of hardware and engineering can be one year or lower when the furnace operations are carried out at near design conditions.
- h. The project team has worked very closely with the industry organizations, Steel manufacturing Association (SMA) and Forging Industry Association (FIA) to communicate the program objectives, status of the program and end results to their member companies.
- i. The program results have exceeded the originally stated objectives of the process and hardware development with preliminary engineering considerations. We actually have prepared and submitted a proposal for a potential application of scale free heating on a new furnace for a major steel producer. The final decision on the purchase and installation of the proposed systems is pending.

7 RECOMMENDATIONS

Based on results of Phase I and Phase II of this program and feedback from the steel industry furnace users, we recommend that the Department of Energy continue to support additional efforts in extended application of scale free heating technology for selected segment of the

steel industry which has not been considered in this program. It will also help to support efforts in commercialization of the technology and measurement and verification (M&V) of one or more industry applications when the system is installed and operational at one or more steel companies. Specifically we make following recommendations.

Program scope extension

- i. Program scope extension to study to extend application of scale free heating to growing market segment of the steel reheating processes where steel is charged at higher temperature, varying from approximately 1200 deg. F. to as high as 1800 deg. F. These systems include preheated steel (slabs, billets etc.), thin slab casting and direct strip casting processes where steel shapes are directly introduced into the reheating or “equalizing” furnaces. The scale free heating process can be more effectively used for some of these applications since it will be necessary to discharge the flue gases with large amount of combustibles at high temperature. This would increase the furnace heat requirement unless the flue gas heat is used productively. It is possible to use these gases for power generation through use of Combined Heat and Power systems such as boiler-steam turbine generator. The exhaust gases are very clean and are easy to combust due to their composition as well as temperature. We had not included investigations and process engineering of such a system to keep the current program more focused on the demonstration of scale free heating concept. Now that the concept and related hardware have been developed and pre-engineered, we believe that extension of the system is beneficial. The economics of such a system look more attractive in view of the lowered natural gas price, higher electricity cost and need for a “back up” power for many mini mills during the high peak power rates and perceived power cut backs during the summer months as experienced 5 years ago when the steel industry was operating under “normal” production levels. The extension will help growing sector of the steel market where the EAF mills are now going more and more toward direct reheating and rolling. Also a number of integrated as well as EAF steel plants are practicing hot charging by avoiding cooling of the charge or preheating it.
- ii. Study of possible methods of using and justifying scale free application for the forging industry where the project justification is largely based on economic benefits associated with beneficial effects of scale free operation on the tools life, maintenance, product quality etc. In such cases increased energy use during the furnace operations may be compensated by energy and other cost reductions associated with improved product quality, higher yield, production interruptions and associated “holding losses”, maintenance of tools used for hot parts forging etc. Benefits of use of scale free heating for small continuous forging furnaces have been demonstrated for many years however it is necessary to study extension of its application to batch furnaces. This would help the forging industry compete with the foreign competition and improve opportunities for exports.
- iii. Support measurement and verification (M&V) activities to monitor performance of one or more scale free heating applications. This will include establishing a base line for current values of scale formation during the

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Exhibit 42: % scale vs. time at fixed 1800F & 1.7% - 5% oxygen. 36

1 INTRODUCTION

This report describes the testing and results of a series of tests intended to document the scale characteristics of steel products subjected to conventional heating. Conventional heating is defined as the typical time, temperature and atmosphere histories experienced by steel products heated in a conventional reheat furnace. A conventional reheat furnace is considered to be a furnace that is fired at or slightly above stoichiometric combustion while it heats a steel product from room temperature to rolling temperature.

The reference steel product for this series of tests was the BB3 dog bone section that is currently heated in SDI's Medium Section Mill furnace at Columbia City, Indiana. A cross section of this product is shown in the sketch below.

Exhibit 1: BB3 product Shape.

This furnace was designed and installed by ACL NWO Inc. (ACL) in 2000. ACL has extensive design calculations, drawings and performance reports to substantiate the design and performance of this furnace in its everyday operation. ACL's Heating Model was used to determine the original size and shape of the reheat furnace in order to heat the various specified steel products at the specified heating rates. This same Heating Model was used to generate the time temperature profiles of the BB3 steel product that was used as the reference product for these tests.

The Heating Model was used to generate the time temperature profiles for a BB3 that was heated at 100%, 75%, 50%, and 25% of rated capacity. The rated capacity of the SDI furnace on the BB3 product was 200 tph when the furnace was charged with full length BB3 products, that is, 100% hearth coverage. Therefore, the time temperature profiles that were generated represented 200, 175, 100 and 50 tph production rates.

A typical time temperature profile generated by the model for a BB3 heated at 200 tph (100% capacity) is provided in the adjacent graph.

Exhibit 2: Temperature profile for 200 TPH, (100% capacity). Conventional heating.

This temperature profile represents the top surface temperature of a BB3 product as it proceeds from the charge door to the discharge door of the SDI furnace while it is being heated at rate of 200 tph (100% capacity). The laboratory sample testing consisted of heating the surface temperature of the test sample at this same time temperature profile. Therefore, the test sample was experiencing the same time temperature history of the actual BB3 production product and would be developing scale at the same rate as the production product.

In addition to heating the test samples at the prescribed time temperature profiles it was also necessary to provide an atmosphere around the test sample that was equivalent to a conventional heating furnace. That is, a furnace that is fired with natural gas at a controlled combustion ratio of typically 10% excess air. The specific air/gas ratio and % oxygen, CO₂ and H₂O in the flue products for Pittsburgh Natural Gas that was used for the conventional heating tests is provided in the following table.

PITTSBURGH NATURAL GAS AT 10% EXCESS AIR			
AIR/GAS	% O ₂	% CO ₂	%H ₂ O
10.86/1	1.7	8.9	16.9

Exhibit 3: flue gas composition (dry) for Pittsburgh natural gas at 10% excess air.

In addition to simulating the conventional heating time, temperature and atmosphere profiles of a BB3 heating from cold to rolling temperatures (called Heating Tests) it was also necessary to simulate the product being held at various temperatures for various times. These types of tests

were referred to as Holding Tests and were intended to determine the effect on scale formation when holding products at various conditions. This data would be needed in order to determine if and under what conditions does scale free heating become uneconomical due to energy cost incurred by trying to maintain a scale free atmosphere while holding products for long times.

In short, scaling data from both the Heating and Holding Tests was intended to not only establish the base line for the amount of scale formed in a conventional heating furnace but to also provide the basic empirical parameters that could be used in a scaling model that determined the limits of scale free heating in day in and day out operation.

2 DESCRIPTION OF TEST FACILITY

The project team met and reviewed the basic requirements of a general test facility to simulate both conventional heating (CH) and scale free heating (SFH) conditions. The test facility not only had to simulate the heating cycles from low to high production rates but it also had to simulate holding conditions that occur during normal day in and day out operation of a rolling mill. The size of the test sample, the sample test furnace, and test instrumentation was generally agreed upon and are described in detail in the following sections.

2.1 Test Sample Size

The test sample size was chosen as a result of a variety of considerations. From the conception of this portion of the project, it was well documented that the SFH process would require very particular heating and atmospheric conditions. In order to best simulate the desired heating scenarios, it was quickly determined that a smaller test setup would allow for greater procedural flexibility and modification. This of course dictates sample size to a suitably smaller dimension than say a common industrial bloom. Given that a smaller setup was desired, a review of fitting electric furnaces also revealed limited power capabilities and set process tube diameters associated with such designs, which further diminished the possible testing sample layout. An additional factor was the inherent need for multiple test samples due to the strong emphasis on data collection. By choosing an appropriate test shape, testing runs could involve more than a single test sample and provide greater amounts of data, which also allows for better result comparisons and more accurate conclusions. A final consideration for sample size, and perhaps the most important, was the realization that a small sample with a larger surface area to weight ratio would allow for the scale formation observed during testing to be effectively amplified thus enhancing the data collection. With all these interests in mind, a test piece size guideline was set that would require all samples to be roughly 1"-2.0" x 0.5"-1" with a thickness of approximately 0.25".

Exhibit 4: Example of test samples

Due to the obvious variance in shape and size of industrial products, a method of scaling the results for comparison was created. Since the formation process of scale is largely based upon surface area and heating curve, a rather simple mathematical conversion was able to be used assuming similar heating curves were followed. For each test run conducted, a ratio of weight loss due to scale versus sample surface area was developed. Then this calculated ratio was

used to project weight losses associated with scale formation for a common industry product “dogbone” known as a BB3, given the known surface area. The BB3 was used since this product was chosen as the benchmark for heating curve simulation by the project group and provided for a common product reference point. The table below illustrates the conversion application for percentage of scale formed on a test sample.

Scale Formation Conversion					
Steel Description	Initial Weight	Surface Area	Metal Loss	% Weight Loss	Metal Loss V.S. SA
	Lbs.	ft ²	Lbs.	%	Lbs./ft. ²
Test Sample	0.0706	0.020	0.0104	14.76%	0.5285
Industry Product	Initial Weight	Surface Area	Metal Loss V.S. SA	Projected Metal Loss	Projected % Weight Loss
	Lbs./ft. Length	ft ² /ft. Length	Lbs./ft. ²	Lbs./ft. Length	%
BB3	598.73	8.51	0.5285	4.50	0.75%

Exhibit 5: Scale formation conversion.

10.2 Furnace Facility

The electric test furnace chosen was a Carbolite Model STF 15/450-V/301 Single Zone Solid Vertical Tube Furnace. The furnace selection was driven by two main factors. First, as briefly mentioned previously, a smaller furnace was desired to allow for greater testing manipulation. This furnace was specified with a 3.5” OD process tube which matched up well with the discussed sample size. The vertical set up would also remove the need to develop a complex sample support structure during testing, allowing a simple hanging design to become feasible. Second, the furnace temperature capacity was listed well above the desired testing temperatures with a maximum of 2732°F with a power rating of 5.5 kW, seemingly meeting the heat demands discussed at that point in time. The furnace also made use of an 8-step programmable controller which allowed for adequate flexibility for process curves and providing for desirable testing repeatability. As a final consideration, previous transactions with Carbolite had resulted in quality equipment and an established business relationship.

Exhibit 6: Photographs of the test furnace facility

Along with the actual furnace, a large consideration for the furnace facility was the actual process tube material. After consulting with Carbolite, the initial choice was a standard mullite tube due to physical characteristics described as “impervious and resistant to flux, sulphurous & carbonaceous atmospheres”, while having a maximum operating temperature of 2732°F. However, after initial testing resulted in material failure, an alumina tube of 99.8% concentration was chosen due to high material resistance to thermal shock. The alumina tube was also prescribed for both oxidizing and reducing atmospheres while being capable of operating

temperatures up to 3542°F. As a result, all sample testing was successfully conducted without further incident while using the alumina process tube seen below.

Exhibit 7: Alumina process tube used in the test furnace

The final test setup included several additions and key features in order to facilitate testing. Starting from ground up, the furnace made use of a Bloom standard 030 pilot (30,000 Btu/Hr rating) attached to an internally insulated section of 309 stainless steel. This pilot was the source for products of combustion during conventional heating testing. In order to attach this assembly to the process tube, a floating seal was created which made use of a 4" OD section of stainless steel and a pair of flanges. The flanges used fiber rope to create the actual seal. Internally, a single radiation shield was installed on top of the poured insulation. This allowed for improved gas mixing, necessary for later SFH testing, while also aiding the electric furnace by reducing the required heating input during testing.

Exhibit 8: Flow straightner and floating seal design for the test furnace

Continuing upwards, the process tube ran vertically through the electric furnace as previously seen. At the tube exit another floating seal of similar design was used to attach a vertical run of stainless steel pipe. Located in this section of pipe was a flapper gate and Nitrogen injection port used during the quench phase of sample testing. This section was also the placement for the emissions port which made use of stainless tubing to connect to a water-cooled emissions probe.

Exhibit 9: To area of the heating furnace facility

Residing atop of the aforementioned vertical run was a 3" stainless steel tee which provided for an access point to insert test samples as well as a diverging path for flue gases. The tee, in combination with the connected vertical run, provided the nitrogen quench chamber. Testing samples were hung vertically by a beaded Type K thermocouple through this tee, serving as support for the samples as well as monitoring chamber temperature during testing. The thermocouple was centered and sealed by running through an appropriately drilled out 3" stainless steel cap.

Exhibit 10: Sample positioning arrangement

In order to retract the samples out of the furnace chamber into the quench chamber, a horizontal arm was installed directly above the sample insertion point. During the quench phases, the thermocouple wire was secured to this arm to properly align the samples in the quench chamber.

Exhibit 11: Another view of sample locating arrangement

Extending horizontally from the tee, a section of stainless steel pipe provided for the flow of flue gas. Installed in this section was an additional Type K thermocouple in order to monitor flue temperatures during testing. Threaded together at the other end of this pipe, a final vertical run

served as the actual exhaust leg, where a burn-off pilot was attached for later SFH testing. During actual testing, a stainless steel damper plate was placed partially over the exhaust in order to maintain positive pressure. As a closing note on the furnace facility, a schematic detailing the overall furnace layout can be found on the following page.

Exhibit 12: Thermocouple location and arrangement

Exhibit 13: Schematic description of furnace layout.

2.2 Instrumentation

The test furnace instrumentation covers a large variety of devices used to accurately monitor testing conditions and is perhaps best discussed by breaking the test setup into several key areas of interest.

Products of Combustion Pilot

In the interest of producing consistent and accurate products of combustion flow rates, the following instrumentation was used to set up and monitor the POC pilot during each test run:

- *US Gauge 0-15 psig Pressure Gauge* – This device monitored inlet pressure of natural gas in 0.5 psig increments and was located upstream of the in line gas meter.
- *Weksler Instruments 20-240°F Temperature Gauge* – This gauge provided the inlet temperature of natural gas and was located upstream of the gas meter.
- *Rockwell S-190 Gas Meter* – Natural gas flow was measured by this device which was rated for 190 CFH at 5.0 psig inlet pressure. Each dial revolution corresponded to 0.1 cubic foot of gas flow.
- *Dwyer Series 475 Mark III Digital Manometer* – This unit was used to measure static pressure at the POC pilot which indicates the pilot firing rate. The manometer is rated for a maximum of 40" water column (W.C.) with measurements being displayed to tenths of an inch of W.C.
- *NTRON Model C5 %O₂ Analyzer* – Oxygen content of the pilot air and gas mixture was provided by this analyzer and indicated how close the POC pilot was to stoichiometric firing. The analyzer displays % O₂ to a tenth of a percent.

Furnace Monitoring & Compressed Air/Nitrogen Injection

During testing, the following components were used to track the various conditions of the furnace setup as well as manipulate the oxygen content of the sample atmosphere.

- *Omega Type-K Sheathed Thermocouples* – These were used on the furnace setup and provided real-time temperature data converted to °F. One was located 9.5" above the POC pilot for monitoring gas temperature with another one installed into the horizontal gas leg providing exhaust temperature.
- *Carbolite Programmable Controller* – The controller read-out was used during testing to monitor furnace element temperature and power output during testing. These measurements provided useful information while developing proper heating programs.
- *Meriam Instruments U-Tube Oil Manometer* – This manometer measured exhaust leg static pressure during testing with a range of 10" W.C. measured in 0.1" W.C. increments.
- *Fischer & Porter Rotameter* – Regulated flow control of compressed air during oxygen manipulation required in holding tests. This rotameter was designed for 0-1.0 SCFM of Propane scaled in 0.05 SCFM increments and was re-rated for Air flow.
- *Dwyer Rotameter* – Regulated flow control of Nitrogen to the quench chamber during the quench phase of testing. This rotameter was designed for 0-3.0 SCFM of Air scaled in 0.1 SCFM increments and was re-rated for Nitrogen flow.

Emissions

The various pieces of equipment described below were used to analyze and monitor the process chamber atmosphere during testing.

- *Stainless Steel Water-Cooled Emissions Probe* – All emissions samples were drawn through this probe by a pump station which forced the gases through a water chiller and on to the various analyzers at a constant 12 psig. Just prior to the analyzers, the gases were run through a Drierite-filled canister in order to remove all undesirable moisture, which resulted in all readings and measurements being recorded on a “dry” basis.
- *Rosemount Analytical Model 951A NO/NO_x Analyzer* – This unit provided Nitrous Oxide measurements in parts per million. During testing the analyzer’s range was set to 0-100 ppm providing for +/- 5.0 ppm error.
- *Rosemount Analytical Model 880A CO Analyzer* – This analyzer measured Carbon Monoxide emissions in parts per million, the preferred unit during conventional heating testing. The unit operated on a 0-5000 ppm range resulting in +/- 20.5 ppm error.
- *Teledyne Brown Engineering Portable Oxygen Analyzer* – This piece of instrumentation provided emissions content of Oxygen on a percent by volume basis during testing.
- *California Analytical Model 602 NDIR Analyzer* – This unit provided both Carbon Monoxide and Carbon Dioxide measurements based upon volumetric percentage. This analyzer was therefore used to accurately track the CO/CO₂ ratio during testing. Conventional heating did not require the higher range of CO measurement. Therefore this device was used specifically for SFH testing and data collection.

Sample Handling & Processing

The equipment outline below was used specifically in the handling, monitoring, or processing of the actual test samples.

- *Ceramic-Beaded Type-K Thermocouple* – During testing, the samples were hung from a piece of scrap steel which was welded to a thermocouple. This setup allowed for an accurate measurement of sample temperature in °F.

Exhibit 14: Ceramic-beaded type-K thermocouple for samples

- *Ohaus Scout Pro Digital Scale* – This scale provided for accurate measurement of sample mass during all phases of testing. The device was set to the unit of grams with a maximum capability of 400 grams. Measurements were displayed to the hundredths of a gram.
- *Mitutoyo 6” Calipers* – These calipers were used to measure each sample during the various phases. Data was displayed up to thousandths of an inch.
- *Central Pneumatic Double Door Blast Cabinet* – This unit was used to sand-blast as-cast scale as well as scale formed during testing depending upon the phase of testing.
- *Sony Cyber-shot Model DSC-P71* – This camera was used for all photographic data during testing.

3 DESCRIPTION OF SAMPLE TEST DATA

The following is provided as a brief overview of the recorded data for all conventional heating tests conducted. Further detailed analysis can be found in subsequent sections specifically covering the results of CH heating and holding testing.

3.1 Sample Test Results

The following ledger displays the results of all CH sample testing performed in sequential order and provides a quick reference for data comparison between samples.

General										Pre Test Data				Sample In										Test Data										Sample Out									
Test No.	Date	Made	Simulated Capacity	ID No.	Grade	Product	Height	Length	Width	Thick	Surface Condition	Partial Corrosion	Pictures Film	Height	Length	Width	Thick	Pictures Film	Temperature Profile Film		Atmosphere Profile Film		Link to Flow Data	Weight	Length	Width	Thick	Weight After Shot Blast	Length	Width	Thick	Weight Loss	% Scale of Surface	% Grade of Product	Partial Decarb	Pictures Film							
Type	File	Ign %											In Phase 1	In Phase 2	Required	Actual	Required	Actual	Required	Actual	Required	Actual	Unit	In	In	In	In	Unit	In	In	In	In	In	In	Phase 3	Phase 4	Decarb						
1	17/10/2008	CH	Test 1 Interact data	100	100%	1A	Standard ASTM	BEO	38.28	1.487	0.24	0.23	Saved	0.00%	-	38.28	1.487	0.24	0.23	Sample 1A Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	1A	40.46	1.507	0.251	0.264	30.47	1.454	0.864	0.25	7.75	30.3%	0.8	0.008	-	Sample 1A Interact (Saved)	Sample 1A Film (Saved)	Sample 1A Decarb.jpg		
1	17/10/2008	CH	Test 1 Interact data	200	100%	1B	Standard ASTM	BEO	50.85	1.476	0.297	0.26	Saved	0.00%	-	50.85	1.476	0.297	0.26	Sample 1B Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	1B	53.04	1.518	0.297	0.342	42.81	1.450	0.943	0.273	8.24	36.23%	0.84	0.010	-	Sample 1B Interact (Saved)	Sample 1B Film (Saved)	Sample 1B Decarb.jpg		
2	18/10/2008	CH	Test 2 Interact data	150	75%	2A	Standard ASTM	BSO	46.70	1.508	0.322	0.23	Saved	0.00%	-	46.70	1.508	0.322	0.23	Sample 2A Pre-Test Data	Conventional Filing 75 pct.ols	01208L Profile Data	Conventional Filing 75 pct.ols	01208R Profile Data	2A	52.70	1.383	0.3	0.308	39.32	1.483	0.893	0.29	10.38	20.85%	1.1	0.071	-	Sample 2A Interact (Saved)	Sample 2A Film (Saved)	Sample 2A Decarb.jpg		
2	18/10/2008	CH	Test 2 Interact data	150	75%	2B	Standard ASTM	BSO	36.53	1.522	0.305	0.26	Saved	0.00%	-	36.53	1.522	0.305	0.26	Sample 2B Pre-Test Data	Conventional Filing 75 pct.ols	01208L Profile Data	Conventional Filing 75 pct.ols	01208R Profile Data	2B	39.1	1.584	0.304	0.321	28.17	1.493	0.763	0.29	8.36	22.39%	1.05	0.010	-	Sample 2B Interact (Saved)	Sample 2B Film (Saved)	Sample 2B Decarb.jpg		
3	19/10/2008	CH	Test 3 Interact data	100	50%	3A	Standard ASTM	BSO	42.59	1.484	0.367	0.24	Saved	0.00%	-	42.59	1.484	0.367	0.24	Sample 3A Pre-Test Data	Conventional Filing 50 pct.ols	01148L Profile Data	Conventional Filing 50 pct.ols	01148R Profile Data	3A	42.59	1.484	0.365	0.321	26.46	1.447	0.853	0.324	10.58	27.05%	0.1	0.012	-	Sample 3A Interact (Saved)	Sample 3A Film (Saved)	Sample 3A Decarb.jpg		
3	19/10/2008	CH	Test 3 Interact data	100	50%	3B	Standard ASTM	BSO	37.37	1.528	0.316	0.241	Saved	0.00%	-	37.37	1.528	0.316	0.241	Sample 3B Pre-Test Data	Conventional Filing 50 pct.ols	01148L Profile Data	Conventional Filing 50 pct.ols	01148R Profile Data	3B	39.76	1.602	0.306	0.32	27.08	1.422	0.794	0.31	10.28	27.54%	0.2	0.008	-	Sample 3B Interact (Saved)	Sample 3B Film (Saved)	Sample 3B Decarb.jpg		
4	19/10/2008	CH	Test 4 Interact data	50	25%	4A	Standard ASTM	BSO	37.09	1.454	0.548	0.252	Saved	0.00%	-	37.09	1.454	0.548	0.252	Sample 4A Pre-Test Data	Conventional Filing 25 pct.ols	01268L Profile Data	Conventional Filing 25 pct.ols	01268R Profile Data	4A	42.05	1.389	0.539	0.319	22.33	1.427	0.762	0.54	14.78	39.83%	1.84	0.009	-	Sample 4A Interact (Saved)	Sample 4A Film (Saved)	Sample 4A Decarb.jpg		
4	19/10/2008	CH	Test 4 Interact data	50	25%	4B	Standard ASTM	BSO	47.77	1.497	0.552	0.271	Saved	0.00%	-	47.77	1.497	0.552	0.271	Sample 4B Pre-Test Data	Conventional Filing 25 pct.ols	01268L Profile Data	Conventional Filing 25 pct.ols	01268R Profile Data	4B	46.15	1.537	0.559	0.357	26.4	1.388	0.793	0.529	15.12	37.58%	1.88	0.008	-	Sample 4B Interact (Saved)	Sample 4B Film (Saved)	Sample 4B Decarb.jpg		
5	19/10/2008	CH	Test 5 Interact data	SA	Standard ASTM	BEO	31.46	1.444	0.763	0.231	Saved	0.00%	-	31.46	1.444	0.763	0.231	Sample 5A Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	5A	31.58	1.473	0.762	0.225	31.08	1.448	0.763	0.23	0.37	1.18%	0.8	0.010	-	Sample 5A Interact (Saved)	Sample 5A Film (Saved)	Sample 5A Decarb.jpg				
6	19/10/2008	CH	Test 6 Interact data	SA	Standard ASTM	BEO	31.46	1.444	0.763	0.231	Saved	0.00%	-	31.46	1.444	0.763	0.231	Sample 6A Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	6A	31.58	1.473	0.762	0.225	31.08	1.448	0.763	0.23	0.37	1.18%	0.8	0.010	-	Sample 6A Interact (Saved)	Sample 6A Film (Saved)	Sample 6A Decarb.jpg				
6	19/10/2008	CH	Test 6 Interact data	SA	Standard ASTM	BEO	31.46	1.444	0.763	0.231	Saved	0.00%	-	31.46	1.444	0.763	0.231	Sample 7A Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	7A	31.58	1.473	0.762	0.225	31.08	1.448	0.763	0.23	0.37	1.18%	0.8	0.010	-	Sample 7A Interact (Saved)	Sample 7A Film (Saved)	Sample 7A Decarb.jpg				
6	19/10/2008	CH	Test 6 Interact data	SA	Standard ASTM	BEO	31.46	1.444	0.763	0.231	Saved	0.00%	-	31.46	1.444	0.763	0.231	Sample 8A Pre-Test Data	Conventional Filing 100 pct.ols	01208L Profile Data	Conventional Filing 100 pct.ols	01208R Profile Data	8A	31.58	1.473	0.762	0.225	31.08	1.448	0.763	0.23	0.37	1.18%	0.8	0.010	-	Sample 8A Interact (Saved)	Sample 8A Film (Saved)	Sample 8A Decarb.jpg				
 																																								

Exhibit 15: CH sample test results.

3.2 Sample Test Results Legend

The table below is a complement to the Sample Test Results table and provides for a brief explanation of each data point category and its relevance.

General	Test No.		Sequential test number
	Date		Date of the test
	Mode	Type	Mode of operation of the test. CH for conventional heating, SFH for scale free heating, HOLD for a hold simulation, INFILL for an infiltration test
	Simulated Capacity	File	The doc file name where a detailed description of the intent of the test can be found.
Pre-Test	tph		The simulated tph heating rate of the test. All simulations are relative to a 200 tph, top and bottom fired, walking beam furnace.
	%		The % of rated capacity of the test. That is, a 100 tph would be 50% capacity.
	ID No.		SDI sample identification number
	Grade		The ASTM or other grade of the sample
	Product		The product the sample grade represents, that is, structural, rail, SBQ, bar, HSM, etc.
	Weight	gm	Weight of the sample prior to initial shot blasting in grams.
	Length	in	Length of the sample in inches
	Width	in	Width of the sample in inches
	Thick	in	Thickness of the sample in inches
	Surface Condition		Surface condition of the side to be analyzed for decarb. That is, as cast, sawed, shot blasted, etc.
Sample In	Partial Decarb	in	The partial decarb depth in inches of the side that has been selected for decarb analysis
	Picture Files	Phase 1	The file name of a digital picture of the sample before initial shot blasting
	Weight	gm	Weight of the sample prior to heating in grams.
	Length	in	Length of the sample in inches
	Width	in	Width of the sample in inches
Test Data	Thick	in	Thickness of the sample in inches
	Picture Files	Phase 2	The file name of a digital picture of the sample after initial shot blasting and before heating
	Temperature Profile File	Required	The excel file name of the spread sheet provided by ACL of the Required Time/Temperature Profile
	Atmosphere Profile File	Actual	The excel file name of the spread sheet provided by Bloom of the Actual Time/Temperature Profile maintained during the test.
	Atmosphere Profile File	Required	The excel file name of the spread sheet provided by ACL of the Required Time/Atmosphere Profile.
Sample Out	Picture Files	Actual	The excel file names of the spread sheets provided by Bloom of the Actual Time/Atmosphere Profile maintained during the test.
	Link to Flow Data		Hyperlink to flow data for sample during process run
	Weight Out	gm	Weight of the sample after heating in grams.
	Length Out	in	Length of the sample in inches after heating
	Width Out	in	Width of the sample in inches after heating
	Thick Out	in	Thickness of the sample in inches after heating
	Weight After Shot Blast	gm	Weight of the sample after shot blasting in grams.
	Length Final	in	Length of the sample in inches after shot blast
	Width Final	in	Width of the sample in inches after shot blast
	Thick Final	in	Thickness of the sample in inches after shot blast
	Weight Loss	gm	Weight in minus the weight of the sample after shot blasting
	% Scale of Sample	%	The calculated percent of scale that was formed on the piece = (Weight Loss)/(Weight In)
	% Scale of BB3	%	The percent scale extrapolated to the shape of a BB3.
	Partial Decarb	in	The partial decarb depth in inches of the side that has been selected for decarb analysis
	Picture Files	Phase 3	The file name of a digital picture of the sample after heating
	Phase 4		The file name of a digital picture of the sample after final shot blasting
	Decarb		The file name of a digital picture of the sample during Decarb analysis

Exhibit 16: Complement to the Sample Test Results table.

3.3 Sample Tests Flow Results

The subsequent ledger below presents the various flow data recorded during each test run and provides for quick evaluation of actual flow rates in comparison to desired values.

Test No.	Date	AFR	Pilot						Hydrogen					Carbon Monoxide					Nitrogen Quench					Additional Air			
			PDM	Temp. @ PDM	Pressure @ PDM	Gas Flow	Static Pressure	%O2	Pressure	Temp.	Flow Reading	Corrected Flow	Desired Flow	Pressure	Temp.	Flow Reading	Corrected Flow	Desired Flow	Pressure	Temp.	Flow Reading	Corrected Flow	Desired Flow	Pressure	Temp.	Flow Reading	Corrected Flow
#	-	#	sec	°F	psig	SCFH	"W.C.	%	psig	°F	LPM	SCFH	SCFH	psig	°F	SCFH	SCFH	SCFH	psig	°F	SCFH	SCFH	SCFH	psig	°F	SCFH	SCFH
1	1/7/2008	10.5	17.01	61	5.0	27.9	5.2	19.1	0	0	0	0.0	0	0	0	0	0.0	0	30.0	61	1.5	160.2	160	-	-	-	-
2	1/9/2008	10.5	18.65	66	5.0	25.2	5.3	19.2	0	0	0	0.0	0	0	0	0	0.0	0	40.0	66	3.0	354.4	350	-	-	-	-
3	1/14/2008	10.5	16.97	58	5.0	28.1	5.4	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	58	3.0	354.4	350	-	-	-	-
4	1/24/2008	10.5	16.09	57	5.0	29.7	5.5	19.2	0	0	0	0.0	0	0	0	0	0.0	0	40.0	57	3.0	354.4	350	-	-	-	-
5	1/25/2008	10.5	17.79	58	5.0	26.8	5.3	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	58	3.0	354.4	350	-	-	-	-
6	2/8/2008	10.5	16.99	62	5.0	27.8	5.3	19.2	0	0	0	0.0	0	0	0	0	0.0	0	40.0	62	3.0	354.4	350	-	-	-	-
7	2/11/2008	10.5	16.90	44	5.0	29.0	5.4	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	44	3.0	354.4	350	-	-	-	-
8	2/12/2008	10.5	18.25	56	5.0	26.2	4.9	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	56	3.0	354.4	350	-	-	-	-
9	2/13/2008	10.5	20.13	56	5.0	23.8	3.9	19.4	0	0	0	0.0	0	0	0	0	0.0	0	40.0	56	3.0	354.4	350	-	-	-	-
10	2/13/2008	10.5	18.48	61	5.0	25.6	4.7	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	61	3.0	354.4	350	-	-	-	-
11	2/22/2008	10.5	17.75	56	5.0	26.9	5.5	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	56	3.0	354.4	350	-	-	-	-
12	2/22/2008	10.5	17.32	55	5.0	27.7	5.4	19.2	0	0	0	0.0	0	0	0	0	0.0	0	40.0	55	3.0	354.4	350	-	-	-	-
13	2/28/2008	10.5	18.36	52	5.1	26.4	5.3	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	52	3.0	354.4	350	-	-	-	-
14	2/29/2008	10.5	16.64	50	5.0	29.1	5.3	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	50	3.0	354.4	350	-	-	-	-
15	3/3/2008	10.5	17.92	63	5.0	26.3	5.4	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	63	3.0	354.4	350	-	-	-	-
16	3/10/2008	12.8	18.68	60	5.0	25.4	5.4	19.2	0	0	0	0.0	0	0	0	0	0.0	0	40.0	60	3.0	354.4	350	20.0	60	0.55	48.9
17	3/11/2008	12.8	17.69	60	5.0	26.8	5.3	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	60	3.0	354.4	350	20.0	60	0.69	64.9
18	3/12/2008	12.8	17.55	62	5.4	27.5	5.4	19.1	0	0	0	0.0	0	0	0	0	0.0	0	40.0	62	3.0	354.4	350	20.0	62	0.65	61.2
22	6/25/2008	10.86	17.66	76	5.0	26.1	5.7	19.3	0	0	0	0.0	0	0	0	0	0.0	0	40.0	76	3.0	354.4	350	-	-	-	-

Exhibit 17: CH sample test data.

3.4 Sample Flow Results Legend

The table below is a complement to the Sample Test Flow Results table and provides for a brief explanation of each data point category and its relevance.

Test No.		#	Sequential test number
Date		-	Date of the test
AFR		#	Equivalent air to fuel ratio beign simulated
Pilot	PDM	sec	Seconds per rotation of PDM indicator (1 rev = 0.1 cubic ft.)
	Temp. @ PDM	°F	Temperature of incoming natural gas flow at PDM
	Pressure @ PDM	psig	Static pressure of incoming natural gas flow at PDM
	Gas Flow	SCFH	Corrected flow of natural gas
	Static Pressure	"W.C.	Static pressure of air/gas mixture at pilot measured in inches of water column
	%O2	%	%O2 content of air/gas mixture at pilot
Hydrogen	Pressure	psig	Static pressure of incoming hydrogen flow at rotameter
	Temperature	°F	Temperature of hydrogen flow at rotameter
	Flow Reading	LPM	Indicated flow reading on hydrogen rotameter
	Corrected Flow	SCFH	Corrected flow of hydrogen
	Desired Flow	SCFH	Desired flow of hydrogen from calculated atmosphere profile
Carbon Monoxide	Pressure	psig	Static pressure of incoming carbon monoxide flow at rotameter
	Temperature	°F	Temperature of incoming carbon monoxide at rotameter
	Flow Reading	SCFH	Indicated flow reading on carbon monoxide rotameter
	Corrected Flow	SCFH	Corrected flow of carbon monoxide
	Desired Flow	SCFH	Desired flow of carbon monoxide from calculated atmosphere profile
Nitrogen Quench	Pressure	psig	Static pressure of incoming nitrogen flow at rotameter
	Temperature	°F	Temperature of incoming nitrogen flow at rotameter
	Flow Reading	SCFM	Indicated flow reading on nitrogen rotameter
	Corrected Flow	SCFH	Corrected flow of nitrogen
	Desired Flow	SCFH	Desired flow of nitrogen developed from various scrap sample practice runs
Additional Air	Pressure	psig	Static pressure of compressed air at rotameter
	Temperature	°F	Temperature of compressed air at rotameter
	Flow Reading	SCFM	Indicated flow reading on compressed air rotameter
	Corrected Flow	SCFH	Corrected flow of compressed air

Exhibit 18: Sample test results legend.

4 BB3 HEATING TESTS

The following sections provide detailed information on the description, data results, and conclusions of tests that were conducted to simulate actual heating of BB3 products. All data for these tests is listed in the DESCRIPTION OF SAMPLE TEST DATA section above and should be reviewed closely to appreciate the complete set of data gathered in each test. The following sections will discuss only particular data and conclusions related to the scaling rate of samples and how they are affected by the furnace capacity.

4.1 Description of 200 tph (100% Capacity) Tests

Test #1 and Test #6 were conducted at the 100% furnace capacity conditions for a BB3 Product. The test samples for Test #1 were not shot blasted to clean off scale formed after the caster but before the reheat furnace at SDI. Therefore the samples that were tested had some pre-scale on them prior to being heated in the lab simulation. When this oversight was discovered a later 100% capacity test (Test #6) was conducted with samples that were shot blasted and weighed

prior to the heating simulation. Therefore the amount of scale formed on these samples was definitely all due to the furnace heating simulation only.

4.2 Results of 100% Capacity Tests

The actual and the desired surface temperature profile for Test #6 is shown in the graph below.

Exhibit 19: Temperature profile for Test #6, samples 6A and 6B.

The desired profile is the time temperature profile of the surface of a BB3 product being heated in the conventional furnace. The sample time temperature profile is the actual surface temperature profile of the test samples being heated in the lab simulation. Since these profiles are nearly the same, the test samples are experiencing production like scale conditions and the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surfaces.

The following table provides a summary of the scale rate results for these two tests.

Test No.	Simulated Capacity		Pre-Test Weight	Sample In Weight	Weight Out	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of BB3	Comments
	tph	%	gm	gm	gm	gm	gm	%	%	
1	200	100%	NA	38.26	40.46	30.47	7.79	20.36%	0.89	Samples were not shot blasted before test heating and therefore had casting scale on them
1	200	100%	NA	50.85	53.04	42.61	8.24	16.20%	0.84	
6	200	100%	32.24	32.04	33.19	27.31	4.73	14.76%	0.75	Samples were shot blasted before test heating and therefore were scale free going into test heating
6	200	100%	45.91	45.22	46.33	38.76	6.46	14.29%	0.69	

Exhibit 20: Summary of the scale rate results for Test #6 and Test #1

The average equivalent BB3 scale for the samples in Test #1 is 0.865% versus 0.72% scale from Test #6. The difference represents the scale that was created in the cooling of the original BB3 product after leaving the caster and cooling to room temperature. This scale was on the Test #1 samples that were cut from the BB3 and not removed prior to heating simulations. This scale was removed from the samples of Test #6 by shot blasting. The scale rate of 0.72% is therefore representative of the actual scale formed on a BB3 product when it is heated at a 200 tph (100% capacity) rate in a conventional heating furnace.

4.3 Conclusions from 100% Capacity Tests

The scale rate of 0.72% is considerably below the anticipated scale rate of 1.5% in the SDI conventional heating furnace. ACL has conducted numerous Quarterly Reports on the performance of this reference furnace over the past 8 years. It had generally been concluded by ACL and SDI that the typical scale generated in the reheat process is 1.5%. This conclusion is based on studies and observations made in the Quarterly Reports. Of course, this 1.5% scale rate is based on data and observations related to turn, weekly, monthly and annual results and represents the entire range of furnace operation between 200 tph (100% capacity) and holding for various amounts of times and at various temperatures. And, of course, the ACL/SDI observations and conclusions do not distinguish scale generated between the caster and the furnace which is probably in the range of 0.15% from the results of Test #1 versus Test #6.

It is expected that results from other tests at lower % capacity levels and results of scale formed during Holding Tests would increase the predicted scaling rate and bring it closer to the ACL/SDI experienced scaling rate.

4.4 Description of 150 tph (75% Capacity) Tests

Test #2 and Test #7 were conducted at the 75% furnace capacity conditions. The test samples for Test #2 were not shot blasted to clean off scale formed after the caster but before the reheat furnace at SDI. Therefore the samples that were tested had some pre-scale on them prior to being heated in the lab simulation. When this oversight was discovered a later 75% capacity test (Test #7) was conducted with samples that were shot blasted and weighed prior to the heating simulation. Therefore the amount of scale formed on these samples was definitely all due to the furnace heating simulation only.

4.5 Results of 75% Capacity Tests

The actual and the desired surface temperature profile for Test #7 is shown in the graph below.

Exhibit 21: Temperature profile for Test #7; Samples 7A and 7B.

The desired profile is the time temperature profile of the surface of a BB3 product being heated in the conventional furnace. The sample time temperature profile is the actual surface temperature profile of the test samples being heated in the lab simulation. Since these profiles are nearly the same, the test samples are experiencing production like scale conditions and the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surfaces.

The following table provides a summary of the scale rate results for these two tests.

Test No.	Simulated Capacity		Pre-Test Weight	Sample In Weight	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of BB3	Comments
	tph	%	gm	gm	gm	gm	%	%	
2	150	75%	NA	49.70	39.32	10.38	20.89%	1.11%	Samples were not shot blasted before test heating and therefore had casting scale on them
2	150	75%	NA	36.53	28.17	8.36	22.89%	1.05%	
7	150	75%	31.17	30.72	25.30	5.42	17.64%	0.86%	Samples were shot blasted before test heating and therefore were scale free going into test heating
7	150	75%	62.61	61.78	52.98	8.80	14.24%	0.74%	

Exhibit 22: Summary of the scale rate results for Test #2 and Test #7.

The average equivalent BB3 scale for the samples in Test #2 is 1.08% versus 0.80% scale from Test #7. The difference represents the scale that was created in the cooling of the original BB3 product after leaving the caster and cooling to room temperature. This scale was on the Test #2 samples that were cut from the BB3 and not removed prior to heating simulations. This scale was removed from the samples of Test #7 by shot blasting. The scale rate of 0.80% is therefore

representative of the actual scale formed on a BB3 product when it is heated at a 150 tph (75% capacity) rate in a conventional heating furnace.

4.6

conclusions from 75% Capacity Tests

The scale rate of 0.80% is considerably below the anticipated scale rate of 1.5% in the SDI conventional heating furnace but about 10% higher than the 0.72% scale rate observed on the 100% capacity simulation from Test #6. This is to be expected since the product is in the furnace longer when the furnace is running at 75% capacity, that is, about 116 minutes as opposed to about 90 minutes at 100% capacity. Also, as noted above the 1.5% scale rate is based on data and observations related to turn, weekly, monthly and annual results and represents the entire range of furnace operation between 200 tph (100% capacity) and holding for various amounts of times and at various temperatures. And, of course, the ACL/SDI observations and conclusions do not distinguish scale generated between the caster and the furnace which is probably in the range of 0.15% from the results of Test #1 versus Test #6 to 0.28% from the results of Test #2 versus Test #7.

As expected, the results at 75% capacity shows more scale than at 100% capacity (0.80% versus 0.72%). It is expected that results of scale formed during Holding Tests would increase the predicted scaling rate and bring it closer to the ACL/SDI experienced annual, average scaling rate.

4.7 Description of 100 tph (50% Capacity) Tests

Test #3 and Test #12 were conducted at the 50% furnace capacity conditions. The test samples for Test #3 were not shot blasted to clean off scale formed after the caster but before the reheat furnace at SDI. Therefore the samples that were tested had some pre-scale on them prior to being heated in the lab simulation. When this oversight was discovered a later 50% capacity test (Test #12) was conducted with samples that were shot blasted and weighed prior to the heating simulation. Therefore the amount of scale formed on these samples was definitely all due to the furnace heating simulation only.

4.8 Results of 50% Capacity Tests

The actual and the desired surface temperature profile for Test #12 is shown in the graph below.

Exhibit 23: Temperature profile for Test #12; samples 12A and 12B.

The desired profile is the time temperature profile of the surface of a BB3 product being heated in the conventional furnace. The sample time temperature profile is the actual surface temperature profile of the test samples being heated in the lab simulation. Since these profiles are nearly the same, the test samples are experiencing production like scale conditions and the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surfaces.

The following table provides a summary of the scale rate results for these two tests.

Test No.	Simulated Capacity		Pre-Test Weight	Sample In Weight	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of BB3	Comments
	tph	%	gm	gm	gm	gm	%	%	
3	100	50%	NA	40.39	29.46	10.93	27.06%	1.31%	Samples were not shot blasted before test heating and therefore had casting scale on them. Temperature profile was cooler.
3	100	50%	NA	37.37	27.08	10.29	27.54%	1.28%	
12	100	50%	25.79	25.18	14.46	10.72	42.57%	1.39%	Samples were shot blasted before test heating and therefore were scale free going into test heating. Temperature profile was hotter.
12	100	50%	74.12	73.33	55.9	17.43	23.77%	1.36%	

Exhibit 24: Summary of the scale rate results for Test #3 and Test #12.

The average equivalent BB3 scale for the samples in Test #3 is 1.29% versus 1.37% scale from Test #12. Based on previous results at 100% and 75% of rated capacity, one would have expected the scale rate in Test #3 to be higher than that of Test #12 since some scale was carried in on the sample for Test #3. However, this was not the case, and in fact slightly higher scale was recorded on Test #12.

A closer inspection of the time/temperature curves of tests #3 and #12 shows that the sample surface temperature history was actually a little higher in Test #12 as shown in the following graph.

Exhibit 25: Time vs. temperature curves of tests #3 and #12.

The surface temperature of the sample of Test #12 is higher than that of Test #3 throughout the heating cycle of approximately 180 minutes. This could very well explain why the scale formation for Test #12 was higher than that of Test #3 which did have some amount of scale carried in the sample that was not shot blasted prior to the test.

4.9 Conclusions from 50% Capacity Tests

The scale rate for Test #12 (1.37% average) was higher than that observed at 100% capacity (0.72% average) and 75% (0.80% average). This is to be expected since the product is in the furnace longer (180 minutes) as opposed to when the furnace is running at 100% capacity (90 minutes) and at 75% capacity (116 minutes).

4.10 Description of 50 tph (25% Capacity) Tests

Test #4 was conducted at the 25% furnace capacity conditions. The test samples for Test #4 were not shot blasted to clean off scale formed after the caster but before the reheat furnace at SDI. Therefore the samples that were tested had some pre-scale on them prior to being heated in the lab simulation.

When this oversight was discovered in earlier heating tests at 100%, 75% and 50% of rated capacity replacement tests were conducted with the samples being shot blasted prior to heating. It was decided to not do a replacement test for the 25% capacity test since it was later determined that scale free heating conditions could not be economically achieved at capacities near or below 25% of rated capacity as further detailed below under “Conclusions from 25% Capacity Tests.”

4.11 Results of 25% Capacity Tests

The actual and the desired surface temperature profile for Test #4 is shown in the graph below.

Exhibit 26: Temperature profile for Test #4; Samples 4A and 4B.

The desired profile is the time temperature profile of the surface of a BB3 product being heated in the conventional furnace. The sample time temperature profile is the actual surface temperature profile of the test samples being heated in the lab simulation. The sample temperature is significantly above the desired temperature in the first part of the test cycle, up to about 1200°F. This is not considered to be a problem since the scaling rate in this lower temperature range is very slow and it is expected that little or no scale is formed in this temperature range.

The following table provides a summary of the scale rate results of Test #4.

Test No.	Simulated Capacity		Pre-Test Weight	Sample In Weight	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of BB3	Comments
	tph	%	gm	gm	gm	gm	%	%	
4	50	25%	NA	37.09	22.33	14.76	39.80%	1.84%	Samples were not shot blasted before test heating and therefore had casting scale on them.
4	50	25%	NA	40.77	25.45	15.32	37.58%	1.89%	

Exhibit 27: Summarized scale rate results of Test #4.

The average scale generated in the two samples heated in Test #4 (25% of rated furnace capacity) was 1.87%. This is considerably higher than scale generated at 100%, 75% and 50% of furnace capacity but is understandable when one compares the time/temperature curves of the various tests. Test #4 (25% capacity) has a time temperature profile that lasts for 6 hours. That is 4 times that of the 1.5 hours needed for a 100% capacity time/temperature profile.

4.12 Conclusions from 25% Capacity Tests

The scale rate for the 25% capacity test was extremely high at 1.87% as compared to 0.72% at 100% capacity. This is not surprising in that excessive scale is observed after a furnace is held for a long time at temperature or while a furnace is running at very low production rates. The products are in the furnace for a much longer time and excessive scale is developed.

Even though Test #4 was done with samples that were not shot blasted prior to heating it was decided not to reproduce the test with pre shot blasted samples. That is due to the fact that ongoing work related to CH and SFH heat balances had indicated that SFH conditions could not be economically achieved in a reheat furnace when it was operated at very low production rates or during long holds.

The ongoing work indicated that in order to even come close to achieving SFH conditions at low furnace capacity one had to fire the furnace at very high combustible levels over the entire furnace length. This resulted in rich flue gasses being exhausted from the furnace and therefore resulted in extremely high MMBtu/ton levels. In fact, any cost savings realized by scale reduction were more than offset by the higher fuel cost needed for SFH as opposed to CH. Therefore, it had already been decided that SFH conditions would not be recommended for furnace capacities at or below about 25% of rated capacity.

The relatively high scaling rates observed in the 50% and 25% capacity tests (about 1.3% and 1.8% respectively) help justify the lab test results as compared to the observed and expected scaling rate of about 1.5% on an annual, average basis. As noted earlier, SDI/ACL had concluded that the annual scale formation rate of the Medium Section Mill furnace was about 1.5%. This was substantially higher than the 0.72% and 0.80% scaling rate concluded from the 100% and 75% furnace capacity tests. But it was also noted that the estimated 1.5% annual scaling rate was based on annual operation which included holds, delays, low furnace production runs and even the scale carried into the furnace that was formed at the caster. The 1.3% scale measured at the 50% capacity test and the 1.8% scale measured at the 25% capacity test dramatically shows how reduced capacity incurred during annual production can significantly contribute to the estimated annual, average scaling rate.

5 DISCUSSION AND RECOMMENDATIONS OF BB3 HEATING TESTS

The following table summarizes all of the heating tests conducted for a furnace heating BB3's in a conventional heating (CH) time/temperature profile.

SUMMARY OF HEATING TESTS			
% CAPACITY	SAMPLE PREPARATION	BB3 % SCALE	% SCALE AVERAGE
100%	NO PRE BLAST	0.89%	0.87%
		0.84%	
	PREBLAST	0.75%	0.72%
		0.69%	
75%	NO PRE BLAST	1.11%	1.08%
		1.05%	
	PREBLAST	0.86%	0.80%
		0.74%	
50%	NO PRE BLAST	1.31%	1.30%
		1.28%	
	PREBLAST *	1.39%	1.38%
		1.36%	
25%	NO PRE BLAST	1.84%	1.87%
		1.89%	

* This test had a higher temperature profile than the NO PRE BLAST test

Exhibit 28: Summary of heating tests.

Generally, samples that were not pre shot blasted had more scale than samples that were pre shot blasted. The only exception being for the 50% capacity comparison but it is noted here and in the previous section of this report that pre shot blasted samples did experience a considerably higher time/temperature profile which would explain why the amount of scale generated was slightly higher.

The increase in scaling rate as the operating capacity of the furnace is reduced is also obvious in this table with the scaling rate ranging from 0.72% at 100% capacity to 1.87% at 25% capacity.

The following graph presents the same data in graphical form for both samples that were not pre shot blasted as well as samples that were pre shot blasted.

Exhibit 29: BB3 % scale vs. % capacity (all data).

One can see the drastic increase in % scale as the furnace capacity is reduced and it is no wonder that the SDI/ACL observed annual scale on the Medium Section Mill furnace that these tests are related to was about 1.5%.

The curve fit shown on this graph is a power expression with the equation of $y = 0.0079x^{-0.6533}$.

The following graph presents the data in graphical form for only those samples that were pre shot blasted.

Exhibit 30: BB3 % scale vs. capacity (preblast only)

The curve fit shown on this graph is a power expression with the equation of $y = 0.0067x^{-0.9613}$.

It is recommended that these results be used to predict the scaling rate of products that have a time temperature profile similar to that of the BB3 product heated in the reference SDI Medium Section Mill furnace and also have a surface area to volume ratio similar to the BB3 product.

Note that this restriction ("and also have a surface area to volume ratio similar to the BB3 product) is an important restriction in the use of this data to predict scaling rates in other furnace and for other products since it could lead to erroneous results. The time temperature history of a product and its size will dictate how much scale is formed during its heating. All test results were based on the time temperature history of a BB3 product heating in the reference SDI furnace. The BB3 product has a distinct shape resulting in a distinct surface area to volume ratio. The surface area to volume ratio of the samples heated in the lab test facility are significantly different from that of a BB3 but if the time temperature history of the lab sample is the same as that of BB3 than the scaling rate of a BB3 product can correctly be extrapolated from the lab test results. This had been discussed in a previous section of this report titled "**Test Sample Size**" and it is recommended that one reviews this section again. In fact, a portion of this section is repeated here for convenience.

"Due to the obvious variance in shape and size of industrial products, a method of scaling the results for comparison was created. Since the formation process of scale is largely based upon

surface area and heating curve, a rather simple mathematical conversion was able to be used assuming similar heating curves were followed. For each test run conducted, a ratio of weight loss due to scale versus sample surface area was developed. Then this calculated ratio was used to project weight losses associated with scale formation for a common industry product “dogbone” known as a BB3, given the known surface area. The BB3 was used since this product was chosen as the benchmark for heating curve simulation by the project group and provided for a common product reference point. The table below illustrates the conversion application for percentage of scale formed on a test sample.”

Scale Formation Conversion					
Steel Description	Initial Weight	Surface Area	Metal Loss	% Weight Loss	Metal Loss V.S. SA
	Lbs.	ft ²	Lbs.	%	Lbs./ft. ²
Test Sample	0.0706	0.020	0.0104	14.76%	0.5285
Industry Product	Initial Weight	Surface Area	Metal Loss V.S. SA	Projected Metal Loss	Projected % Weight Loss
	Lbs./ft. Length	ft ² /ft. Length	Lbs./ft. ²	Lbs./ft. Length	%
BB3	598.73	8.51	0.5285	4.50	0.75%

Exhibit 31: Scale formation conversion.

The “Test Sample” data in the above table is that of sample 6A which was a 200 tph (100% capacity) simulation of heating a BB3 in the SDI furnace. Note that the scale weight loss on the sample was 14.76% due to a scale loss of 0.5285 pounds per square foot of sample surface. When this same 0.5285 lbs/ft² scale rate is applied to the surface area of an actual BB3 dogbone shape, the actual % scale formed on the BB3 is only 0.75%. But this is a good prediction of the scale formed on the BB3 product since the test was simulating the actual time and surface temperature history of a BB3 product heated in the SDI furnace.

What one cannot do is use the 0.5285 lbs/ft² scaling rate to extrapolate scale formed on other products that have a different time temperature history from that of a BB3 product. This error is demonstrated in the following table where the scaling rate of 0.5285 lbs/ft² is applied to many different sizes and shapes of products. Notice the wide range in surface area and weight to foot length of the various products as compared to the Heavy Dogbone (actually the BB3). Using the common 0.5285 lbs/ft² scaling rate for all the products results in a Projected % Weight Loss or % scale that is not correct since many of these products would have a substantially different time temperature heating profile and therefore a different scaling rate than 0.5285 lbs/ft².

Industry Product	Initial Weight	Surface Area	Metal Loss V.S. SA	Projected Metal Loss	Projected % Weight Loss
	Lbs/ft Length	ft ² /ft Length	Lbs/ft ²	Lbs/ft Length	%
4" x 4" Billet	54.44	1.33	0.5285	0.70	1.29%
7" x 7" Billet	166.74	2.33	0.5285	1.23	0.74%
8" x 10" Bloom	272.22	3.00	0.5285	1.59	0.58%
Light Dogbone	315.83	5.35	0.5285	2.83	0.90%
Heavy Dogbone *	598.73	8.51	0.5285	4.50	0.75%
6" x 48" Slab	980.00	9.00	0.5285	4.76	0.49%
8" x 80" Slab	2,177.78	14.67	0.5285	7.75	0.36%

* Reference Product

Exhibit 32: Calculations for projected metal and weight loss for different products

For example, the above table would indicate that an 8" thick by 80" wide slab would have only 0.36% scale if it were to be heated in the SDI furnace at a rate of 200 tph. Based on experience this was way too low of a scaling rate for a slab and based on experience it was well know that an

8" x 80" slab would have a much longer and therefore a much different time temperature profile while being heated in the reference furnace.

To substantiate this and to add additional reference data on conventional scaling rates of various products it was decided to simulate the heating of a heavy slab in the lab test facility to determine what the resulting scaling rate was.

The results of slab heating simulations are covered in the following section.

6 SLAB HEATING TESTS

The following sections provide detailed information on the description, data results and conclusions of tests that were conducted to simulate actual heating of heavy slab products. The entire data for these tests is listed in the DESCRIPTION OF SAMPLE TEST DATA section above and should be reviewed closely to appreciate the complete set of data gathered in each test.

It was decided to use a reference slab that was 8" thick and 84" wide for the lab heating simulations. The following sections will discuss the particular data and conclusions related to the scaling rate of samples used to simulate the heating of heavy slab in the SDI reference furnace

6.1 Description of 200 tph (100% Capacity) Slab Heating Test

Test #22 was conducted at the 100% furnace capacity conditions for a 8" x 84" Slab Product. The test samples for Test #22 were shot blasted to clean off scale formed after the caster but before the reheat furnace at SDI. Therefore the amount of scale formed on these samples was definitely all due to the furnace heating simulation only.

6.2 Results of 100% Capacity Slab Heating Test

The actual and the desired surface temperature profile for Test #22 is shown in the graph below.

Exhibit 33: Temperature profile for test #22; samples 22A and 22B.

The desired profile is the time temperature profile of the surface of the slab product being heated in the conventional SDI furnace. The sample profile is the actual surface temperature profile of the test samples being heated in the lab simulation. The actual surface temperature is a little higher in the initial part of the tests but comes on track at about 1200°F. Scaling rates are very low below 1200°F and therefore this test should provide accurate data on the scaling rate of a heavy slab.

Note the major difference in the time temperature profile of the heavy slab as opposed to the BB3 product even though both are heated at a rate of 200 tph in the same, simulated reheat furnace. The heating time of the thick slab is about 175 minutes as opposed to only about 90 minutes for the BB3. This is why the scale rate of the BB3 cannot be applied to extrapolating the expected scale on a heavy slab product. The surface temperature profile of each product is substantially different. The following table provides a summary of the scale rate results for this test.

Test No.	Simulated Capacity		Pre-Test Weight	Sample In Weight	Weight Out	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of Slab	Comments
	tph	%	gm	gm	gm	gm	gm	%	%	
22	200	100%	12.22	12.00	13.65	6.85	5.15	42.92%	0.63	Samples were shot blasted before test heating and therefore were scale free going into test heating
22	200	100%	14.33	14.01	14.57	9.14	4.87	34.76%	0.57	

Exhibit 34: Summarized scale rate results for test #22.

The average equivalent slab scale for the samples in Test #22 is 0.60% for an 8" x 84" slab being heated at a rate of 200 tph in the reference SDI furnace. Remember that from the above section, a scale formation of 0.36% was extrapolated for a heavy slab when the scale rate of BB3 product was used for the extrapolation.

This is a valid example of why scale rate data from one particular product has to be carefully applied to other product shapes and time temperature histories.

6.3 Conclusions from 100% Capacity Slab Test

The scale rate of 0.60% for a heavy slab is consistent with the experience of both Bloom and ACL. Typically the annual scale rate of a HSM furnace is less than that of SBQ or Structural Mill furnace. Even though the heating time of a heavy slab is significantly longer than a SBQ mill billet or a Structural Mill dogbone type product there is a much higher weight to surface area ratio for the heavy slab. The lbs/ft² surface for the heavy slab is 149.1 lbs/ft² as opposed to 70.4 lbs/ft² for a BB3 dogbone. Therefore, even though the slab spends a much longer time in the furnace as opposed to a BB3 and even though the resulting scale thickness on the slab is actually thicker than that on the BB3, the % scale generated on the slab is less due to the slab being much heavier in terms of pounds per foot of surface area.

7 DISCUSSION AND RECOMMENDATIONS OF SLAB HEATING TEST

The single CH test of a heavy slab conducted in Test #22 demonstrates the importance of correctly simulating the actual time temperature profile of a given product in a given furnace. Extrapolation of BB3 product's scaling rate to predict the scale formation in heating a heavy slab yields incorrect results. That is, a prediction of only 0.36% scale when and if the slab was heated at 200 tph in an SDI type reheat furnace.

Test #22 was conducted with the actual expected time temperature profile of a heavy slab in the reference furnace and the result was scale formation of 0.60% at 200 tph which is in line with experience from HSM type furnaces.

Therefore, in future SFH considerations it is important to carefully analyze the specific time temperature history that a particular product experiences in a particular furnace before extrapolating scaling rates from data generated in this work.

It is recommended that SFH simulations be done of a heavy slab as well as BB3 products in future SFH lab tests in order to generate SFH data on a heavy slab as well as BB3 products.

8 HOLDING TESTS

The following sections provide detailed information on the description and results of tests that were conducted to simulate holding of products at various temperatures, for various times and in various atmospheres. All data for these tests is listed in the DESCRIPTION OF SAMPLE TEST DATA section above and should be reviewed closely to appreciate the complete set of data gathered in each test. The following sections will discuss only particular data and conclusions related to the scaling rate of samples and how they are affected by the holding conditions of the furnace.

8.1 Description of Holding Tests

Test #5 and Test #8 through #11 and Test #13 through #17 were conducted to generate scaling rate information as a function of samples held at varying temperatures for varying times and with varying % oxygen in the flue products. Test #5 was conducted without shot blasting the sample prior to heating and the results were therefore contaminated with scale generated when the BB3 from which the sample was cut from cooled to room temperature after the caster. Therefore, Test #5 results will not be analyzed. All other holding tests were done with samples that were shot blasted before holding simulations. Test #12 was a redo of a Heating Test at 50% capacity.

Three basic series of tests were conducted with specific parameters fixed or varying. The following tables summarize the test series and the parameter fixed or varied.

FIRST SERIES	
Tests #	8, 9, 10, 11
Purpose	Effect of scaling rate with varying Temperature and fixed Time and % Oxygen in the flue products
Temperature	Varied: 1200°F, 1400°F, 1600°F, 1800°F
Time	Fixed at 2 Hours
% Oxygen	Fixed at 1.7%

SECOND SERIES

Tests #	11, 13, 14
Purpose	Effect of scaling rate with varying Time and fixed Temperature and % Oxygen in the flue products
Temperature	Fixed at 1800°F
Time	Varied: 2 hrs, 1 hr, 0.5 hrs
% Oxygen	Fixed at 1.7%
THIRD SERIES	
Tests #	15, 16, 17
Purpose	Effect of scaling rate with varying Time and fixed Temperature and % Oxygen in the flue products
Temperature	Fixed at 1800°F
Time	Varied: 2 hrs, 1 hr, 0.5 hrs
% Oxygen	Fixed at 5.0%

Exhibit 35: Summary of test series and the parameters (fixed or variable).

8.2 Results of Holding Tests

The following table summarizes all of the Holding Test data relative to the scaling rate and how it was affected by the holding temperature and/or holding time and/or holding atmosphere.

Test No.	Holding Conditions			Pre-Test Weight	Sample In Weight	Weight Out	Weight After Shot Blast	Weight Loss	% Scale of Sample	% Scale of BB3	Average of Both Samples			
	°F	Hrs	O ₂ %	gm	gm	gm	gm	gm	%	%	% Scale of BB3	°F	Hrs	O ₂ %
8	1200°F	2.0	1.7%	34.48	33.99	34.08	33.70	0.29	0.85%	0.04	0.035	1200	2.0	1.7%
8	1200°F	2.0	1.7%	79.62	78.45	78.60	78.02	0.43	0.55%	0.03				
9	1400°F	2.0	1.7%	33.66	33.19	33.41	32.54	0.65	1.96%	0.10	0.095	1400	2.0	1.7%
9	1400°F	2.0	1.7%	54.46	53.70	54.01	52.69	1.01	1.88%	0.09				
10	1600°F	2.0	1.7%	36.71	36.12	36.65	34.48	1.64	4.54%	0.24	0.230	1600	2.0	1.7%
10	1600°F	2.0	1.7%	79.67	78.54	79.47	75.54	3.00	3.82%	0.22				
11	1800°F	2.0	1.7%	31.81	31.58	30.52	27.95	3.63	11.49%	0.56	0.550	1800	2.0	1.7%
11	1800°F	2.0	1.7%	69.74	68.80	69.05	62.07	6.73	9.78%	0.54				
13	1800°F	1.0	1.7%	35.36	35.26	35.84	32.89	2.37	6.72%	0.36	0.350	1800	1.0	1.7%
13	1800°F	1.0	1.7%	81.39	80.36	81.32	75.93	4.43	5.51%	0.34				
14	1800°F	0.5	1.7%	22.80	22.20	22.78	20.40	1.80	8.11%	0.23	0.240	1800	0.5	1.7%
14	1800°F	0.5	1.7%	69.32	68.38	69.30	65.12	3.26	4.77%	0.25				
15	1800°F	2.0	5.0%	43.69	42.29	43.66	37.90	4.39	10.38%	0.51	0.520	1800	2.0	5%
15	1800°F	2.0	5.0%	32.28	31.24	32.85	25.27	5.97	19.11%	0.53				
16	1800°F	1.0	5.0%	33.71	33.57	34.24	31.60	1.97	5.87%	0.30	0.295	1800	1.0	5%
16	1800°F	1.0	5.0%	28.06	27.86	28.58	25.61	2.25	8.08%	0.29				
17	1800°F	0.5	5.0%	31.55	31.37	31.81	30.03	1.34	4.27%	0.22	0.220	1800	0.5	5%
17	1800°F	0.5	5.0%	35.47	35.43	35.91	33.96	1.47	4.15%	0.22				

Exhibit 36: Results of Holding Tests data

Data review and analysis is simplified by considering the specific series of tests and the summarized results individually.

8.3 Results of the First Series of Holding Tests

The First Series varied the temperature from 1200°F to 1400°F to 1600°F to 1800°F while fixing the holding time at 2 hours and % oxygen in the flue products to 1.7%. This summarized data is presented in the following table.

FIRST SERIES			
% Scale of BB3	°F	Hrs	O ₂ %
0.035%	1200	2.0	1.7%
0.095%	1400	2.0	1.7%
0.230%	1600	2.0	1.7%
0.550%	1800	2.0	1.7%

Exhibit 37: Results of the first series of holding tests.

These results are shown graphically below.

Exhibit 38: % scale vs. temperature at fixed 2 hours & 1.7% oxygen.

8.4 Conclusions from First Series of Holding Tests

As would be expected, the scaling rate increases significantly with temperature when the holding time and the holding atmosphere is held constant. After 2 hours at 1400°F about 0.1% scale is generated on a BB3 product and this increases to about 0.55% scale if the BB3 is held at 1800°F for 2 hours. Remember that about 0.72% scale was created on the product when it was heated to rolling temperatures at a rate of 200 tph. Therefore, holding at any temperature is detrimental to scale formation and holding at high temperatures for long times will significantly add to the total scale on a product.

8.5 Results of the Second Series of Holding Tests

The Second Series varied the Time from 2 hours to 1 hour to 0.5 hours while fixing the holding Temperature at 1800°F and % oxygen in the flue products to 1.7%. This summarized data is presented in the following table.

SECOND SERIES			
<u>% Scale of BB3</u>	°F	Hrs	O ₂ %
0.550	1800	2.0	1.7%
0.350	1800	1.0	1.7%
0.240	1800	0.5	1.7%

Exhibit 39: Results of the second series of holding tests.

These results are shown graphically below.

Exhibit 40: % scale vs. time at fixed 1800F & 1.7% oxygen.

8.6 Conclusions from Second Series of Holding Tests

As would be expected the % scale increases significantly with increasing time if the sample is held at a constant temperature of 1800°F in an atmosphere with 1.7% oxygen. Remember that 1.7% oxygen in flue gases is equivalent to a furnace being operated at 110% of stoichiometric ratio. In only a half hour nearly 0.25% is created. In 30 minutes at 1800°F the amount of scale generated is nearly one third of the scale that was generated in heating the product to rolling temperature in 90 minutes which was about 0.72% scale.

8.7 Results of the Third Series of Holding Tests

The Third Series varied the Time from 2 hours to 1 hour to 0.5 hours while fixing the holding Temperature at 1800°F and increased the % oxygen in the flue products to 5.0%. This summarized data is presented in the following table.

THIRD SERIES			
<u>% Scale of BB3</u>	°F	Hrs	O ₂ %
0.520	1800	2.0	5.0%
0.295	1800	1.0	5.0%
0.220	1800	0.5	5.0%

Exhibit 41: Results of the third series of holding tests.

These results are combined with the results of the 1.7% oxygen in flue gas data and shown graphically below.

Exhibit 42: % scale vs. time at fixed 1800F & 1.7% - 5% oxygen.

8.8 Conclusions from Third Series of Holding Tests

These results are disturbing in that they show slightly lower scale formation with higher oxygen in the flue products. One would expect that the scale formation at each time increment would have been higher for the tests with 5% oxygen in the flue gasses as opposed to 1.7% oxygen in the flue products.

One possible explanation is that the kinetics of scale formation is governed more by time and temperature and that the level of oxygen in the flue gasses is not so important. Actually, similar results have been reported in a paper presented in the IFRF Combustion Journal Article Number 200602, September 2006, ISN 1562-497X. The paper was titled 'High Temperature Oxidation of Steel in an Oxygen-enriched Low NO_x Furnace Environment.' Figure 14 of this paper shows very little increase in scale formation for samples held for 30 minutes at 2012°F in either 1.7% or 4.3% oxygen in the flue gasses. Figure 14 of this paper also shows virtually no difference in the scale formation for samples held for 4 hours in either 1.7% or 4.3% oxygen in the flue gasses.

9 DISCUSSION AND RECOMMENDATIONS OF HOLDING TESTS

The Holding Tests results show considerable scale formed when steel is above about 1400°F. The amount of the scale formed is dependent on how long the steel is exposed to the oxidizing conditions but in as short of a time as only 30 minutes at 1800°F the amount of scale formed is about one third of the scale formed when steel is heated to 2250°F in 90 minutes.

Therefore scale formation during holding conditions needs to be carefully considered in determining the effect of annual average scale formed. Refer back to the section

Conclusions from 100% Capacity Tests presented earlier in this report. It is noted there that the scale rate of 0.72% determined when heating a BB3 in a CH furnace was significantly below the annual, average scale rate of 1.5% that was concluded by SDI on this same CH furnace in its day in and day out operation. It was suggested that the annual, average scale rate observed by SDI was probably higher due to the fact that its observations included a significant amount of scale formed while the furnace was either holding product at high temperatures or the while the furnace was operating at production levels well below the 100% capacity level.

The results of the Holding Tests substantiate this expectation. A considerable amount of scale can and will be formed when the product is held at temperature above about 1400°F for times longer than 30 minutes.

The amount of scale formed during holding conditions will need to be carefully evaluated in any operating cost comparison of CH to SFH since additional work now completed in this project has determined that SFH cannot be accomplished in holding conditions. This consideration and concern are addressed in more detail in the SFH section of the report.

Appendix B: Scale Free Heating Sample Report

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1 INTRODUCTION

This Report describes the testing and results of a series of sample heating tests that were conducted to determine the amount of scale that can be saved by operating a furnace in a scale free time, temperature and atmosphere mode. Determining what the time, temperature, atmosphere (t/t/a) profiles were for a furnace operating in the Scale Free Heating (SFH) mode was the first order of business for this sample heating test series. The INTRODUCTION Section of the Conventional Heating Report has already discussed how a Heating Model was used to determine the time/temperature profile of a BB3 bloom product being heated in the SDI Medium Section Mill furnace. This product and this furnace was used for the simulation of all sample heating test runs performed in the Conventional Heating sample testing phase of this Project. The same product and the same furnace was used for the simulation of all sample tests conducted in the Scale Free Heating sample testing phase of this Project which is the subject of this Report. Before presenting the data and results of the SFH Sample Heating Tests it is necessary to describe how the t/t/a profiles for the SFH tests were determined.

A basic premise adopted by the Project Team throughout the burner and sample testing phases of this Project has always been that a new furnace capable of SFH heating had to be also capable of Conventional Heating (CH) over its entire range of operation. This would provide the end user with the flexibility to operate in either the CH or SFH mode with the same furnace. Of course the same requirements would be inherent in an existing CH furnace that was converted or retrofitted to SFH capabilities, that is, the furnace had to retain its CH capabilities. This premise resulted in the three burner development phases of this Project being defined by a Burner Specification that covered a burner's required performance as both a CH and SFH burner. For example, burners in the soak zone of the furnace had to be capable of providing the required heat load while firing at stoichiometric conditions when the furnace was operating in the CH mode as well as firing at approximately 50% stoichiometric conditions when the furnace was operated in the SFH mode.

Because of the basic premise that the furnace had to be capable of both CH and SFH it was necessary to deduce the t/t/a profiles of the SFH heating mode from t/t/a profiles that were dictated by the furnace when it was operated in the CH mode. In other words, a new furnace capable of CH and SFH would be initially sized and designed based on the CH mode of operation just like any potential retrofit furnace was designed originally. The size and the design of the CH furnace would result in particular t/t/a profiles that were generated by the furnace while heating various products at various production rates and those time/temperature (t/t) profiles would be assigned to the SFH mode. The unique aspect of CH mode t/t/a profiles would be that the atmosphere would always be an atmosphere equivalent to stoichiometric or slightly greater than stoichiometric combustion of all burners in all zones. But while the same t/t profiles would be used for the SFH mode the atmosphere profile superimposed with the t/t profiles would provide scale free conditions in the discharge zones of the furnace and gradually burn down the atmosphere toward the charge end of the furnace while maintaining scale free or near scale free condition on the product being heated.

This is graphically demonstrated below.

Exhibit 1: conventional heating time-temperature-atmosphere (t/t/a) profile.

A heating model is used to determine the time/temperature profile of a particular furnace heating a particular product. The graph shows the FURNACE TEMPERATURE profile from the charge end to the discharge end that the heating model used in calculating the resultant WORK TEMPERATURE profile. The ATMOSPHERE profile does not affect the heating of the product but it is added to the graph to show that atmosphere within the furnace would be equivalent to that of 100% stoichiometric combustion from the charge end to the discharge end of the furnace in the CH mode t/t/a.

The same t/t profile would be used for the same furnace if it was to be operated as a SFH furnace as shown below.

Exhibit 2: scale free heating time-temperature-atmosphere (t/t/a) profile.

The difference in the SFH t/t/a profile is the atmosphere profile. The t/t profile for the furnace and work is exactly the same as that of the CH t/t/a but as the work temperature increases in the SFH heating mode the atmosphere profile is made reducing by lowering the % stoichiometric. In practice it will be seen that this is achieved by firing the burners in the discharge zone (soak zone) at about 50% stoichiometric and then gradually increasing the % stoichiometric toward the charge end of the furnace by injecting burn down air into the furnace and/or by firing burners at a higher % stoichiometric ratio.

It is important to emphasize that the very same t/t is used for both the CH and SFH mode. In effect, this assures that the furnace is basically designed as a CH furnace since the CH t/t profile is imposed on the SFH t/t/a. As long as the burners can achieve the required CH and SFH firing conditions throughout the furnace and as long as the combustion control systems can provide either the CH or the SFH modes of operation than the furnace is essentially transparent to CH or SFH and will operate and perform in both modes.

The remaining challenges are to determine what is the SFH atmosphere profile that is generated by the CH t/t profile and once this SFH atmosphere profile is defined, does it indeed result in scale free or low scale heating? The SFH atmosphere profiles were able to be defined as described in the following Section. Than SFH sample testing was done to determine what level of scale would be developed by the SFH t/t/a. This work is described in later Sections of this Report.

2 CONVENTIONAL AND SCALE FREE HEATING HEAT BALANCES

Heat balances are key to developing the parameters of time, temperature and atmosphere profiles that are needed to simulate heating of products in either a conventional or a scale free environment. The process of determining a SFH t/t/a starts with a heat balance generated from a CH t/t. A typical CH heat balance for the reference SDI furnace is shown below.

Structural Dynamics Inc. 200 tph Walking Beam FURNACE CAPACITY 200 TPH PIECE THICKNESS BB3 IN PIECE WIDTH 28.75 IN PIECE LENGTH 47.5 FT PIECE SPACING 45.3 IN PREHEAT TEMP 1000 °F EXCESS AIR 10 % % TOP HEATING 55 % % INSULATION 100											
HEATING CURVE INFORMATION											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
SET POINT °F		2250	2250	2225	2225	1950	1950	OFF	OFF		
WALL TEMP °F		2250	2250	2225	2225	1950	1950	1755	1755		
FG TEMP °F		2350	2350	2325	2325	2050	2050	1560	1560		
TIME IN ZONE (MIN)		26.25	26.25	31.5	31.5	22.5	22.5	8.75	8.75	89	
HEAT TO WORK BTU/H		5.8	N/A	98.8	N/A	185.7	N/A	73.8	N/A		
Q TOTAL MMBTU/HR		3.52	N/A	35.52	N/A	66.28	N/A	28.32	N/A	137.64	
FURNACE NET HEAT BALANCE CALCULATIONS											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
WORK MMBTU/HR		1.94	1.58	21.74	17.78	36.45	29.83	15.58	12.74	137.64	86.43%
WALLS MMBTU/HR		0.502	0.496	0.565	0.408	0.361	0.342	0.153	0.116	2.94	1.85%
RAILS MMBTU/HR		0.00	2.624	0.000	3.054	0.000	1.503	0.000	0.431	7.61	4.78%
POSTS MMBTU/HR		0.00	1.083	0.000	1.043	0.000	1.160	0.000	0.293	3.58	2.25%
SLOTS MMBTU/HR		0.00	1.845	0.000	1.776	0.000	1.729	0.000	0.411	5.76	3.62%
MISC MMBTU/HR		0.653	0.654	0.000	0.000	0.000	0.000	0.201	0.201	1.71	1.07%
NET-TOT MMBTU/HR		3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20	159.25	100%
AVAILABLE HEAT CALCULATIONS											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
AH-TOTAL %		0.500	0.500	0.507	0.507	0.579	0.579	0.708	0.708		
CARRYOVER CALCULATIONS											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
TOTAL MMBTU/HR		0.00	0.00	0.04	0.12	3.94	5.92	14.56	15.65		
SUMMARY OF FURNACE HEAT BALANCE											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
NET TOT		3.09	8.29	22.26	23.95	32.88	29.54	1.37	-1.45	120.00	
AH-TOTAL %		0.500	0.500	0.507	0.507	0.579	0.579	0.708	0.708		
GROSS TOT		6.18	16.57	43.93	47.27	56.78	51.92	0.00	0.00	221.76	
SUMMARY OF REQUIRED INPUT											
		SOAK		HEAT		PREHEAT		UFFH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
REQUIRED/CHAMBER		22.76		91.21		107.80		48.6%		221.76	
% TOTAL/CHAMBER		10.3%		41.1%				100.0%			
MMBTU/TON BY FURNACE = 1.109											

Exhibit 3: Conventional heating (CH) heat balance.

The upper left corner identifies basic information about the heat balance in that it represents the SDI Structural Mill furnace operating at 200 tph while heating a BB3 dog bone product.

Structural Dynamics Inc. 200 tph Walking Beam		
FURNACE CAPACITY	200 TPH	
PIECE THICKNESS	BB3	IN
PIECE WIDTH	28.75 IN	
PIECE LENGTH	47.5 FT	
PIECE SPACING	45.3 IN	
PREHEAT TEMP	1000 °F	
EXCESS AIR	10 %	
% TOP HEATING	55 %	
% INSULATION	100	

Exhibit 4: Structural Dynamics Inc. walking furnace information

It notes that the basis of the heat balance is preheated air at 1000°F with a combustion ratio based on 10% excess air. The heat to the work is distributed at 55% from the top and 45% from the bottom due to shielding of walking beam rails and posts. Finally, it indicates that this particular heat balance is based on the assumption that the rail and post insulation is 100% intact.

The next section lists the output from the Heating Model such as the zone temperature set points as well as the flue gas temperature that the available heat for the various zones will be based upon.

HEATING CURVE INFORMATION										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
SET POINT	°F	2250	2250	2225	2225	1950	1950	OFF	OFF	
WALL TEMP	°F	2250	2250	2225	2225	1950	1950	1755	1755	
FG TEMP	°F	2350	2350	2325	2325	2050	2050	1560	1560	
TIME IN ZONE (MIN)		26.25	26.25	31.5	31.5	22.5	22.5	8.75	8.75	89
HEAT TO WORK BTU/#		8.8	N/A	98.8	N/A	165.7	N/A	70.8	N/A	
Q TOTAL	MMBTU/HR	3.52	N/A	39.52	NA	66.28	N/A	28.32	NA	137.64

Exhibit 5: Summary of output from the Heating Model.

The Heating Model is used to determine the heating rate of the specified product per the zone set points and the time in each zone. The output of the Heating Model is a time/temperature array of the product along with the heat absorbed by the product. This heat absorbed in each zone is shown in the above table in Btu/# as well as in net MMBtu/hr. Eventually, the flue gas temperature listed for each zone along with the already identified preheat air temperature (1000°F) and the combustion ratio (10% excess air) will be used to calculate the available heat in each furnace zone.

The next section of the heat balance lists the net heat input to the work, walls, rails and posts, slots and miscellaneous (doors and other openings) in each zone.

FURNACE NET HEAT BALANCE CALCULATIONS											
		SOAK		HEAT		PREHEAT		UFPH		TOTAL	
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM		
WORK	MMBTU/HR	1.94	1.58	21.74	17.78	36.45	29.83	15.58	12.74	137.64	86.43%
WALLS	MMBTU/HR	0.502	0.496	0.565	0.408	0.361	0.342	0.153	0.116	2.94	1.85%
RAILS	MMBTU/HR	0.00	2.624	0.000	3.054	0.000	1.503	0.000	0.431	7.61	4.78%
POSTS	MMBTU/HR	0.00	1.083	0.000	1.043	0.000	1.160	0.000	0.293	3.58	2.25%
SLOTS	MMBTU/HR	0.00	1.845	0.000	1.778	0.000	1.729	0.000	0.411	5.76	3.62%
MISC	MMBTU/HR	0.653	0.654	0.000	0.000	0.000	0.000	0.201	0.201	1.71	1.07%
NET-TOT	MMBTU/HR	3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20	159.25	100%

Exhibit 6:Furnace net heat balance calculations.

The heat to the work is simply the MMBtu/hr already defined by the Heating Model and distributed 55% to the top zones and 45% to the bottom zones. The heat balance program relies on other sub-routines to calculate the losses based on size, insulation value, number, shape, etc. of the other items listed above.

The next sections summarize the available heat, carryover and gross input to each zone.

AVAILABLE HEAT CALCULATIONS										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
AH-TOTAL	%	0.500	0.500	0.507	0.507	0.579	0.579	0.708	0.708	
CARRYOVER CALCULATIONS										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
TOTAL	MMBTU/HR	0.00	0.00	0.04	0.12	3.94	5.02	14.56	15.65	
SUMMARY OF FURNACE HEAT BALANCE										
		SOAK		HEAT		PREHEAT		UFPH		TOTAL
		TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
NET TOT		3.09	8.29	22.26	23.95	32.88	29.54	1.37	-1.45	120.00
AH-TOTAL	%	0.500	0.500	0.507	0.507	0.579	0.579			
GROSS TOT		6.18	16.57	43.93	47.27	56.78	51.02	0.00	0.00	221.76

Exhibit 7: Summary of calculations of available heat, carryover, and gross input to each zone.

As discussed above, the available heat of each zone is calculated based on the flue gas temperature, % excess air and preheat air used for combustion in each zone. Carryover calculations from zone to zone account for the gain in useful heat of a zone operating at lower temperature than the upstream zone and therefore gains heat from the cooling of the flue gasses flowing into the zone.

The SUMMARY OF FURNACE HEAT BALANCE section shows the total net heat, available heat and GROSS TOT input required in each zone.

The final section summarizes the gross input in terms of furnace soak, heat and preheat chambers for later comparison of a SFH heat balance to this CH heat balance.

SUMMARY OF REQUIRED INPUT									
	SOAK		HEAT		PREHEAT		UFPH		
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
REQUIRED/CHAMBER	22.76		91.21			107.80			221.76
% TOTAL/CHAMBER	10.3%		41.1%			48.6%			100.0%
MMBTU/TON BY FURNACE = 1.109									

Exhibit 8: Summary of required input.

As can be seen, about 10% of the total gross input is fired into the soak chamber, (the top and bottom soak zones), while 41% is fired into the heat chamber and 49% fired into the preheat chamber for this CH heat balance based on the reference furnace heating the reference product at a rate of 200 tph. The resulting input per ton is $221.76/200 = 1.109$ MMBtu/ton.

The CH heat balance as described above will be used as the input for the SFH heat balance that needs to now be developed for the same furnace operating under the same conditions. The only difference is that the chambers will now be fired in a SFH mode such that the available heat in each chamber will be substantially different than that used in the CH mode and the CH heat balance discussed above. Of course the SFH atmosphere profile will also be substantially different from that of the CH atmosphere profile which was constant at 110% stoichiometric in the CH mode.

The important criteria is that the exact same time/temperature profile and the exact same net demands that were used for the CH heat balance will now be used for the SFH heat balance. In effect, this is saying that the same furnace can operate in either the CH or SFH mode without any change in its heating abilities since both heating modes will be addressing the same time/temperature curves.

The following page provides the SFH Heat Balance extrapolated from the above CH Heat Balance. The extrapolation is done on a chamber basis as opposed to individual zones since zone details are not required at this stage of the evaluation. What is required at this stage is what is the SFH atmosphere profile that is generated in a SFH heat balance so that this profile can be used in a Sample Heating Test and the level of scale formation can be measured in that test.

Structural Dynamics Inc 200 tph Walking Beam									
FURNACE CAPACITY		200 TPH							
PIECE THICKNESS		BB3		IN					
PIECE WIDTH		28.75		IN		REFERENCE IS bb3 200 tph conventional(1)			
PIECE LENGTH		47.5		FT					
PIECE SPACING		45.3		IN					
PREHEAT TEMP		1000		°F					
EXCESS AIR		As Noted		%					
% TOP HEATING		55		%					
% INSULATION		100							
HEATING CURVE INFORMATION									
SET POINT °F WALL TEMP °F FG TEMP °F TIME IN ZONE (MIN) HEAT TO WORK BTU/HR Q TOTAL MMBTU/HR	SOAK		HEAT		PREHEAT		UFPH		TOTAL
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
	2250	2250	2225	2225	1950	1950	OFF	OFF	
	2250	2250	2225	2225	1950	1950	1755	1755	
	2350	2350	2325	2325	2050	2050	1560	1560	
	26.25	26.25	31.5	31.5	22.5	22.5	8.75	8.75	
	8.8	N/A	98.8	N/A	165.7	N/A	70.8	N/A	
	3.52	N/A	39.52	N/A	66.28	N/A	28.32	N/A	
	137.64								
	FURNACE NET HEAT BALANCE CALCULATIONS								
WORK MMBTU/HR WALLS MMBTU/HR RAILS MMBTU/HR POSTS MMBTU/HR SLOTS MMBTU/HR MISC MMBTU/HR NET-TOT MMBTU/HR	SOAK		HEAT		PREHEAT		UFPH		TOTAL
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
	1.94	1.58	21.74	17.78	36.45	29.83	15.58	12.74	
	0.502	0.496	0.565	0.408	0.361	0.342	0.153	0.116	
	0.00	2.624	0.000	3.054	0.000	1.503	0.000	0.431	
	0.00	1.083	0.000	1.043	0.000	1.160	0.000	0.293	
	0.00	1.845	0.000	1.778	0.000	1.729	0.000	0.411	
	0.653	0.654	0.000	0.000	0.000	0.000	0.201	0.201	
	3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20	
	159.25	100%							
TOTAL									
Net Heat Required @ Zone Exit = 138.65 MMBtu/hr AH @ 50% = 8.21% Firing Rate Required = 138.65 MMBtu/hr Total Net Heat Required @ Zone Exit = 57.75 MMBtu/hr which included Soak and Heat Zones AH @ 80% = 35.14% Firing Rate Required = 164.34 MMBtu/hr Firing Rate from Previous Zones = 138.65 MMBtu/hr Firing Rate Required = 25.69 MMBtu/hr Furnace Total Net Heat Required @ Furnace Exit = 159.25 MMBtu/hr which includes total Furnace AH @ 110% = 70.81% Firing Rate Required = 224.88 MMBtu/hr Firing Rate from Previous Zones = 164.34 MMBtu/hr Firing Rate Required = 60.54 MMBtu/hr Total Furnace Input = 224.88 MMBtu/hr SFH MMBtu/ton = 1.1244 MMBtu/ton CH MMBtu/ton = 1.1088 MMBtu/ton									
<pre>graph LR; A[138 MMBtu/hr @ 50%] --> B[26 MMBtu/hr @ 80%]; B --> C[138 MMBtu/hr B/D from 50% to 80%]; C --> D[61 MMBtu/hr @ 110%]; D --> E[164 MMBtu/hr B/D from 80% to 110%]; E --> F[224.88 MMBtu/hr Total Furnace Input];</pre>									
SUMMARY OF REQUIRED INPUT									
REQUIRED/CHAMBER	SOAK		HEAT		PREHEAT		UFPH		TOTAL
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	
	138.65		25.69		60.54		26.9%		224.88
% TOTAL/CHAMBER	61.7%		11.4%						100.0%
MMBTU/TON BY FURNACE = 1.124									

Exhibit 9: Scale Free Heating (SFH) heat balance

It can be seen that SFH Heat Balance has the exact same heating conditions as the CH Heat Balance presented above. The upper left corner denotes the same information as that of the CH Heat Balance except to note that to the CH Heat Balance is the reference source and also to note that the % Excess Air is not 10% but rather as noted per chamber.

The HEATING CURVE INFORMATION and the FURNACE NET HEAT BALANCE CALCULATIONS are exactly the same as CH Heat Balance since we want to compare the SFH mode to that of exactly the same CH mode. In so doing it is assured that the furnace will be transparent to the CH or SFH mode of operation since the heat demand used is that of the CH mode.

The resulting new SFH Heat Balance starts at the NET-TOT MMBTU/HR row of the CH Heat Balance as shown below.

NET-TOT	MMBTU/HR	3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20	159.25	100%
		SOAK		HEAT		PREHEAT		UFPH		TOTAL	
Net Heat Required @ Zone Exit =		11.38	MMBTu/hr								
AH @ 50% =		8.21%	%								
Firing Rate Required =		138.65	MMBTu/hr								
Furnace Total Net Heat Required @ Zone Exit =				57.75	MMBTu/hr						
AH @ 80% =				35.14%							
Firing Rate Required =				164.34	MMBTu/hr						
Firing Rate from Previous Zones =				138.65	MMBTu/hr						
Firing Rate Required =				25.69	MMBTu/hr						
Furnace Total Net Heat Required @ Zone Exit =						159.25	MMBTu/hr				
AH @ 110% =						70.81%					
Firing Rate Required =						224.88	MMBTu/hr				
Firing Rate from Previous Zones =						164.34	MMBTu/hr				
Firing Rate Required =						60.54	MMBTu/hr				
Total Furnace Input =						224.88	MMBTu/hr				
SFH MMBtu/ton =						1.1244	MMBTu/ton				
CH MMBtu/ton =						1.1088	MMBTu/ton				

Exhibit 10: New scale free heating (SFH) heat balance.

From this point forward the SFH Heat Balance involves the calculation of chamber inputs on the basis of firing the chambers at or near SFH conditions for the product that is in the chamber. The net top and bottom soak zone inputs are combined into the soak zone chamber net input of 11.38 MMBtu/hr. For this particular heat balance it had been decided to fire the soak zone chamber at 50% stoichiometric. The preheat air temperature to the burners in the soak chamber has already been defined as 1000°F in the CH Heat Balance and the flue gas temperature leaving the soak chamber has already been defined as 2350°F. With these input conditions; 50% stoichiometric, 1000°F preheat air and 2350°F flue gas temperature, the available heat is calculated to be 0.082058 or about 8.21%. Therefore, the burners in the soak chamber will need to fire at a total of 138MMBTu/hr (at 50% stoichiometric) in order to satisfy the 11.38 MMBtu/hr net demand of this chamber.

The SFH Heat Balance extrapolation then moves to the heat chamber and treats both the soak and heat chamber as one entity in order to determine the firing conditions of the heat chamber as shown below.

The total net demand at the end of the heat chamber is 57.75 MMBtu/hr. For this particular heat balance it has been decided that the heat zone chamber would be fired at 80% stoichiometric

NET-TOT	MMBTU/HR	3.09	8.29	22.30	24.07	36.82
		SOAK		HEAT		PRE
Net Heat Required @ Zone Exit =		11.38	MMBTu/hr			
AH @ 50% =		8.21%	%			
Firing Rate Required =		138.65	MMBTu/hr			
Furnace Total Net Heat Required @ Zone Exit =				57.75	MMBTu/hr	
AH @ 80% =				35.14%		
Firing Rate Required =				164.34	MMBTu/hr	
Firing Rate from Previous Zones =				138.65	MMBTu/hr	
Firing Rate Required =				25.69	MMBTu/hr	

Exhibit 11: Calculations for the required firing rate for scale free heating (SFH) furnace

and/or the 50% stoichiometric flue gasses carried over from the soak chamber would be burned

down to 80% stoichiometric by the injection of burn down air. The available heat for 80% stoichiometric combustion in the heat zone chamber is calculated to be 35.14%. Therefore, the total firing rate required to meet this total net demand is 164.34 MMBtu/hr fired at 80% stoichiometric. But by burning down the carryover flue gasses from the soak chamber to the heat chamber to 80% combustibles a total of 138.65 MMBtu/hr are already provided. Therefore, the burners in the heat chamber only have to add an additional 25.69 MMBtu/hr at 80% stoichiometric in order to achieve a heat balance addressing the needs of both the soak and heat zone chambers.

The same procedure is done for the entire furnace (the soak, heat and preheat chambers) by addressing the net demands at the charge end of the unfired preheat chamber.

The total net demand for the entire furnace is 159.25 MMBtu/hr. The preheat zone is to be fired at 110% stoichiometric and all carryover flue gasses from the upstream zone are to be burned

TU/HR	3.09	8.29	22.30	24.07	36.82	34.56	15.93	14.20
	SOAK		HEAT		PREHEAT		UFPH	
red @ Zone Exit =	11.38		MMBtu/hr					
AH @ 50% =	8.21%							
g Rate Required =	138.65		MMBtu/hr					
e Total Net Heat Required @ Zone Exit =			57.75		MMBtu/hr			
AH @ 80% =	35.14%							
Firing Rate Required =	164.34		MMBtu/hr					
Firing Rate from Previous Zones =	138.65		MMBtu/hr					
Firing Rate Required =	25.69		MMBtu/hr					
Furnace Total Net Heat Required @ Zone Exit =	159.25		MMBtu/hr					
AH @ 110% =	70.81%							
Firing Rate Required =	224.88		MMBtu/hr					
Firing Rate from Previous Zones =	164.34		MMBtu/hr					
Firing Rate Required =	60.54		MMBtu/hr					
Total Furnace Input =	224.88		MMBtu/hr					
SFH MMBtu/ton =	1.1244		MMBtu/ton					
CH MMBtu/ton =	1.1088		MMBtu/ton					

Exhibit 12: Calculations for heat requiremntn scale free and conventional heating

down to 110% stoichiometric. Therefore the available heat at this point is calculated to be 70.81%. The total firing rate required to meet this total net demand is 224.88 MMBtu/hr fired at 110% stoichiometric. By burning down the carryover flue gasses from the heat chamber to the preheat chamber to 110% stoichiometric a total of 164.34 MMBtu/hr are already provided. Therefore, the burners in the preheat chamber only have to add an additional 60.54 MMBtu/hr at 110% stoichiometric in order to achieve a heat balance. The total furnace input of 224 MMBtu/hr yields a heating efficiency of 1.1244 MMBtu/hr, slightly higher than the CH Heat Balance result of 1.1088 MMBtu/hr.

The chamber burn down and burner firing process is summarized with a sketch at the bottom of the SFH Heat Balance.

Exhibit 13: Summary of the burn down and burner firing requirement

The soak chamber burners fire a total of 138 MMBtu/hr at 50% stoichiometric. The heat chamber burners fire a total of 26 MMBtu/hr at 80% stoichiometric and burn down air is added in the heat chamber to burn the 50% stoichiometric gasses from the soak chamber down to 80% stoichiometric. The preheat chamber burners fire a total of 61 MMBtu/hr at 110% stoichiometric and burn down air is added in the preheat chamber to burn the 80% stoichiometric flue gasses from the heat chamber down to 110% stoichiometric.

The summary of the chamber conditions are shown at the bottom of the SFH Heat Balance.

SUMMARY OF REQUIRED INPUT								
	SOAK		HEAT		PREHEAT		UFPH	
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
REQUIRED/CHAMBER	138.65		25.69				60.54	
% TOTAL/CHAMBER	61.7%		11.4%				26.9%	
MMBTU/TON BY FURNACE =								1.124

Exhibit 14: Summary of the heat requirement in different zones of a scale free furnace

Note the marked differences from the chamber firing conditions of the CH Heat Balance repeated below.

SUMMARY OF REQUIRED INPUT								
	SOAK		HEAT		PREHEAT		UFPH	
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
REQUIRED/CHAMBER	22.76		91.21				107.80	
% TOTAL/CHAMBER	10.3%		41.1%				48.6%	
MMBTU/TON BY FURNACE =								1.109

Exhibit 15: Summary of the heat requirement in different zones of a conventional furnace.

If the furnace was to be operated in the CH mode the soak chamber would be inputting 10.3% of the total heat required to heat the reference product at 200 tph. If the same furnace is operated in the SFH mode the soak chamber would be inputting 61.7% of the total heat required to heat the reference product at 200 tph. The burners in the soak chamber fire about 6 times more gas in the SFH mode as compared to the CH mode. This demonstrates the extreme ranges of firing rates required between CH and SFH modes and demonstrates why it was necessary to develop specialized burners to obtain these ranges. As noted earlier, these same heat balance

comparisons were used to develop the Burner Specifications for the Burner Development Phases of this Project.

3 ATMOSPHERE GUIDE

The primary goal of the SFH Heat Balance extrapolation is to end up exhausting the furnace at 110% stoichiometric conditions so that it becomes equivalent to the final combustion conditions as that of the CH Heat Balance. A secondary goal was to heat the product to final temperatures with an atmosphere that was at or near scale free conditions so that minimum scale would be generated.

Often two or more extrapolations that vary the % stoichiometric in the soak and/or heat chambers are needed in order to optimize the SFH Heat Balance and arrive at 110% stoichiometric conditions at charge end of the furnace with minimum scale. The Project Team developed an Atmosphere Guide as a tool to assist in selecting and optimizing a SFH atmosphere profile.

The Atmosphere Guide was based on published CO_2/CO ratio versus temperature profiles that defined the limits of reducing to oxidizing conditions on steel. A typical profile is presented in the following graph.

Exhibit 16: CO_2/CO ratio versus temperature profile.

Heating in a flue gas atmosphere generated by a CO_2/CO to the right of the line would result in the steel oxidizing or scaling with time. Heating in a flue gas atmosphere generated by a CO_2/CO

to the left of the line would result in the steel remaining scale free since the atmosphere is essentially reducing to steel at the respective temperatures.

The above graph can be translated to a more practical use when it is expressed as the CO/CO₂ ratio for reducing/oxidizing conditions as compared to the surface temperature profile of a BB3 product being heated in the reference SDI furnace as shown in the following graph.

Exhibit 17: the surface temperature profile of a BB3 product being heated in the reference SDI furnace. X

Finally, the above graph can be translated to the more familiar graph relating % stoichiometric to reducing/oxidizing conditions as presented below.

Exhibit 18: scale free heating time-temperature-atmosphere (t/t/a) profile.

As noted above, the "Atmosphere Guide" became an important resource in determining the SFH t/t/a profile that needed to be tested in a Sample Heating Test. The SFH heat balance was

tweaked by adjusting the % stoichiometric combustion in the soak and heat chambers until the optimum atmosphere profile could be achieved while still maintaining complete 110% stoichiometric combustion within the furnace. An example of the application of the Atmosphere Guide is provided in the following graph.

Exhibit 19: 150 TPH BB3 testing

This particular graph provides data for the reference SDI furnace heating the reference product (BB3) at a rate of 150 tph. The top surface temperature of the BB3 as it is heated in the furnace is shown in red. The “Atmosphere Guide” is the blue line denoted as “Required Stoichiometric Path”. This is what the stoichiometric ratio needs to be based on the surface temperature of the billet in order to be sure that the entire heating cycle is achieved in a reducing (scale free) atmosphere.

The green stepped line “Test #19 Stoichiometric Path” is the actual stoichiometric ratio per zone that was dictated by the SFH heat balance and would therefore be the atmosphere profile used in the Sample Heating Test in the lab furnace where a test sample would be heated to simulate a BB3 being heated at the rate of 150 tph.

The actual stoichiometric profile versus the required is obviously not reducing to the BB3 in the heat and preheat zones that are being fired at the above defined stoichiometric ratios of 50% in the soak chamber, 80% in the heat chamber and 110% in the preheat chamber. (Note that “steps” are used to simulate some sort of burn down as the flue gasses pass through the chambers). One can therefore see why it was necessary to do two or more extrapolations of the SFH Heat Balance and t/t/a in order to optimize the results and dictate the test parameters for the Sample Heating Tests. The remaining Sections of this report address these Sample Heating Tests.

4 DESCRIPTION OF TEST FACILITY

As this report is in many ways a continuation of the previously filed "Conventional Heating Report", it was determined that by and large the focus of this section would cover any modifications or additions to the test facility that occurred during scale free testing. For further information of the facility in question, a review of the aforementioned report is highly recommended as the facility was documented in great detail therein.

4.1 Test Sample Size

The test sample size remained virtually the same as for previous testing due to the purposeful selection of the outlined dimensions found in the "Conventional Heating Report". The only note of interest is that a second selection of samples was obtained in order to appropriately complete SFH testing and these samples were generally smaller in dimension than those already tested. It is felt, however, that the integrity of the sample results is absolutely maintained as the general size remained similar enough to preserve the larger surface area to weight ratio desired while still allowing for multiple test samples to be heated at the same time.

In addition, the process of scaling the sample results remained the same. As a reminder, a rather simple mathematical conversion was able to be used assuming similar heating curves were followed. For each test run conducted, a ratio of weight loss due to scale versus sample surface area was developed. Then this calculated ratio was used to project weight losses associated with scale formation for either a common industry product "dogbone" known as a BB3, or a HSM 8" x 84" production slab depending upon the test parameters and given the known surface area. The BB3 remained the major focus of testing, however, as this product was chosen as the benchmark for heating curve simulation by the project group.

As an illustration, the table below demonstrates the conversion application for percentage of scale formed on a test sample.

Scale Formation Conversion					
Steel Description	Initial Weight	Surface Area	Metal Loss	% Weight Loss	Metal Loss V.S. SA
	Lbs.	ft ²	Lbs.	%	Lbs./ft. ²
Test Sample	0.0196	0.012	0.0017	8.89%	0.1459
Industry Product	Initial Weight	Surface Area	Metal Loss V.S. SA	Projected Metal Loss	Projected % Weight Loss
	Lbs./ft. Length	ft ² /ft. Length	Lbs./ft. ²	Lbs./ft. Length	%
BB3	598.73	8.51	0.1459	1.24	0.21%

Exhibit 20: Scale formation conversion.

4.2 Furnace Facility

As with the above sections, due to the similar testing parameters of previously documented work, the electric furnace and various facilities remained largely unchanged from the detailed layout provided in the "Conventional Heating Report." Again, a review of this document is strongly

recommended in conjunction with this report. With that being said, there was one important addition to the overall test set up; the installation of a gas preheater.

As the following sections are studied, it is important at this point to briefly discuss the chosen method of monitoring stoichiometric conditions as it plays a role in the aforementioned facility addition. After reviewing empirical data and sub-stoichiometric combustion theory, it became obvious that two markers were capable of defining an atmosphere as either reducing or oxidizing for a given sample temperature during sub-stoichiometric combustion. These two values were dimensionless volumetric ratios of hydrogen to water vapor (H_2/H_2O) and carbon monoxide to carbon dioxide (CO/CO_2). Suitably, both of these ratios correspond to specific sub-stoichiometric values as seen in the table below and therefore either could be chosen to serve as an accurate depiction of atmospheric conditions during actual sub-stoichiometric combustion. Since sample testing actually involved sub-stoichiometric simulation through the manipulation of both carbon monoxide and hydrogen in conjunction with 110% stoichiometric products, the ideal scenario would have been to monitor both ratios throughout testing. The project team determined, however, such a scenario was simply not cost-effective and it was thus decided that a careful monitoring of only the CO/CO_2 ratio would suffice during testing, given that careful control of hydrogen flow was maintained throughout testing conditions to match theoretical values. As a result, the CO/CO_2 ratio became the primary method of monitoring stoichiometric conditions throughout testing.

Composition of Flue Products by Volume - Wet Basis (1250 °C Equilibrium Temp)								
% Stoich	CO	CO₂	H₂	H₂O	O₂	N₂	H₂/H₂O	CO/CO₂
50%	12.11%	3.01%	17.28%	11.50%	0.00%	56.10%	1.50	4.03
55%	10.72%	3.60%	14.33%	12.93%	0.00%	58.42%	1.11	2.97
60%	9.39%	4.21%	11.75%	14.14%	0.00%	60.50%	0.83	2.23
65%	8.12%	4.83%	9.50%	15.16%	0.00%	62.39%	0.63	1.68
70%	6.89%	5.47%	7.52%	16.02%	0.00%	64.10%	0.47	1.26
75%	5.69%	6.13%	5.79%	16.73%	0.00%	65.67%	0.35	0.93
80%	4.52%	6.81%	4.27%	17.30%	0.00%	67.10%	0.25	0.66
85%	3.36%	7.51%	2.96%	17.75%	0.00%	68.42%	0.17	0.45
90%	2.22%	8.24%	1.82%	18.09%	0.00%	69.63%	0.10	0.27
95%	1.10%	8.97%	0.83%	18.34%	0.00%	70.76%	0.05	0.12
100%	0.00%	9.70%	0.00%	18.48%	0.00%	71.82%	0.00	0.00
110%	0.00%	8.90%	0.00%	16.95%	1.75%	72.40%	0.00	0.00

Exhibit 21: Composition of flue products by volume – wet basis (1250 C equilibrium temp.)

During the early stages of Scale Free Heating testing attempts, a point of carbon monoxide and hydrogen injection was installed downstream of the products of combustion pilot along the vertical internally insulated section of 309 stainless steel. While performing mock test runs, two major issues arose.

First, it rapidly became apparent that the injection of these gases at ambient temperatures created an overwhelming load on the electric furnace, particularly during higher capacity trials. The project team met and reviewed various possible solutions before settling on an external method of pre-heating the injected gases which would serve to greatly reduce the heating load on the electric furnace. As a result, a relatively small rectangular furnace of fire brick in an angle-iron

frame was therefore assembled and lined with fiber blanket for further insulation. The preheater furnace made use of a Bloom standard 030 pilot (30,000 Btu/Hr) as the heat source. In order to enhance the preheater efficiency, a section of stainless steel tubing was coiled concentrically along the longitudinal firing pilot while also extending through the brick walls of the preheater. Consequently, hydrogen and carbon monoxide were piped together into a single, ambient temperature inlet line that was connected into the stainless steel coils. On the outlet side of the preheater, fiber insulation was carefully wrapped along the stainless steel extension that connected downstream of the products of combustion pilot via a stainless steel tee. A rectangular section of fiber board provided for the preheater's removable roof, which allowed for observation during furnace light off.

Secondly, the original specifications of the *California Analytical NDIR Analyzer* were quoted based upon the theoretical percentage values of carbon monoxide and carbon dioxide during 50% stoichiometric firing conditions on Bloom Pittsburgh natural gas. During sample testing, however, 50% stoichiometric conditions were merely simulated through the addition of carbon monoxide and hydrogen flow based upon known theoretical ratios. Since the products of combustion pilot was actually firing at near stoichiometric values, a larger percentage of carbon dioxide was inherently present than actual 50% stoichiometric firing would have produced. This scenario resulted in the necessity of a higher percentage reading of carbon monoxide in order to obtain the desired CO/CO₂ ratios for SFH. As a consequence, the percentage of CO required was notably above the range of the analyzer's carbon monoxide sensor. In the interest of avoiding further increases in project expenditures, the project team determined that an overall dilution via nitrogen flow would serve to bring the carbon monoxide percentage within the analyzer's range while not influencing the atmospheric reactions in any way due to nitrogen's inert nature. Further review even indicated that the additional nitrogen flow would more realistically simulate actual 50% stoichiometric firing conditions in general. Additionally, it was realized that the preheater furnace would require some gas flow during warm-up and any stoichiometric conditions during SFH testing in order to prevent damage to the internal stainless steel coils while still having no effect on the overall scale formation. It was with all this in mind, that an orifice run for nitrogen injection was installed in parallel to the carbon monoxide and hydrogen supply lines. The nitrogen was also accordingly piped into the single ambient temperature preheater inlet line.

As a closing note on the furnace facility, a schematic detailing the overall furnace layout can be found on the following page.

Exhibit 22: The test hot gas atmosphere generator arrangement

Exhibit 23: Schematic furnace layout

Instrumentation

As in previous work, the test furnace instrumentation covers a large array of devices used to accurately monitor testing conditions. Again, however, much of the apparatus is identical to that

already detailed in the “Conventional Heating Report”. Therefore, the following breakdown of the test setup will only present those items that were changed or implemented specifically for SFH testing while covering all areas of interest.

Products of Combustion Pilot

All instrumentation remained unchanged for the products of combustion pilot.

Furnace Monitoring and Compressed Gas Injection

While the majority of equipment remained from previous work, several items were additionally installed due to the required carbon monoxide, hydrogen, and nitrogen flow injection. Manipulation of certain devices was also necessary.

- *Omega Type-K Sheathed Thermocouples* – These devices remained in use on the furnace setup in order to provide real-time temperature data in unites of °F. Due to the nature of SFH testing, the thermocouple previously used for monitoring POC pilot gas temperature was re-installed to measure the injection temperature of carbon monoxide, hydrogen, and nitrogen flow.
- *King Rotameter* – Regulated flow control of carbon monoxide through the stainless steel preheated injection line during sub-stoichiometric firing simulation. This rotameter was designed for 0-65 SCFH of air scaled in 5 SCFH increments and was re-rated for carbon monoxide flow.
- *Dwyer Rotameter* – Regulated flow control of hydrogen through the stainless steel preheated injection line during sub-stoichiometric firing simulation. This rotameter was designed for 0-10 LPM of air scaled in 0.5 LPM increments and was re-rated for hydrogen flow.
- *Bloom R&D #5004 Orifice Run* – Used in conjunction with standard brass ball valves in order to regulate flow control of nitrogen through the stainless steel preheated injection line during sub-stoichiometric firing simulation. The orifice was originally rated for a natural gas flow of 550 SCFH at a differential pressure of 16” W.C. and was re-rated for nitrogen flow.
- *Meriam Instruments U-Tube Water Manometer* – This manometer measured the differential pressure across the *Bloom R&D #5004 Orifice Run* scaled in 0.1” W.C. increments.
- *Fischer & Porter Rotameter* – Removed from test setup since this device was originally used to regulate flow control of compressed air during oxygen manipulation required in convention heating hold tests.

Emissions

All instrumentation remained unchanged for emissions collection in reference to the previously detailed conventional heating testing.

Sample Handling & Processing

Due to the planned comparison evaluation of SFH sample testing to CH sample testing, special care was taken to ensure that sample handling, monitoring, and processing was performed with the identical equipment and techniques. This was done in order to ensure the validity of all future test comparisons.

5 DESCRIPTION OF SAMPLE TEST DATA

The following is provided as a brief overview of the recorded data for all scale-free heating tests conducted. Further detailed analysis can be found in subsequent sections specifically covering the results of SFH heating testing.

Sample Test Results

The following ledger displays the results of all SFH sample testing performed in sequential order and provides a quick reference for data comparison between samples.

General				Pre-Test										Sample In				Test Data		Sample Out																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
Test No.	Date	Mode	Simulated Capacity	D.No.	Grade	Product	Weight	Length	Width	Thick	Surface Condition	Picture Files	Weight	Length	Width	Thick	Picture Files	Temperature Profile File		Atmosphere Profile File		Link to Flow Data	Height Out		Length Out		Width Out		Thick Out		Height After Shot Blast		Length Final		Width Final		Thick Final		% Scale of Sample	% Scale of Product	Period Ducts	Picture Files																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
																		Required	Actual	Required	Actual		gm	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in				in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in	in

Exhibit 24: SFH sample test results data log

5.1 Sample Test Results Legend

The table below is a complement to the Sample Test Results table and provides for a brief explanation of each data point category and its relevance.

General	Test No.		Sequential test number
	Date		Date of the test
	Mode	Type	Mode of operation of the test. CH for conventional heating, SFH for scale free heating, HOLD for a hold simulation, INFILL for an infiltration test
		File	The doc file name where a detailed description of the intent of the test can be found.
	Simulated Capacity	tph	The simulated tph heating rate of the test. All simulations are relative to a 200 tph, top and bottom fired, walking beam furnace.
%		The % of rated capacity of the test. That is, a 100 tph would be 50% capacity.	
Pre-Test	ID No.	SDI sample identification number	
	Grade	The ASTM or other grade of the sample	
	Product	The product the sample grade represents, that is, structural, rail, SBQ, bar, HSM, etc.	
	Weight	gm	Weight of the sample prior to initial shot blasting in grams.
	Length	in	Length of the sample in inches
	Width	in	Width of the sample in inches
	Thick	in	Thickness of the sample in inches
	Surface Condition	Surface condition of the side to be analyzed for decarb. That is, as cast, sawed, shot blasted, etc.	
	Partial Decarb	in	The partial decarb depth in inches of the side that has been selected for decarb analysis
	Picture Files	Phase 1	The file name of a digital picture of the sample before initial shot blasting
	Sample In	Weight	gm
Length		in	Length of the sample in inches
Width		in	Width of the sample in inches
Thick		in	Thickness of the sample in inches
Picture Files		Phase 2	The file name of a digital picture of the sample after initial shot blasting and before heating
Test Data		Temperature Profile File	Required
		Actual	The excel file name of the spread sheet provided by Bloom of the Actual Time/Temperature Profile maintained during the test.
	Atmosphere Profile File	Required	The excel file name of the spread sheet provided by ACL of the Required Time/Atmosphere Profile.
		Actual	The excel file names of the spread sheets provided by Bloom of the Actual Time/Atmosphere Profile maintained during the test.
Sample Out	Link to Flow Data		Hyperlink to flow data for sample during process run
	Weight Out	gm	Weight of the sample after heating in grams.
	Length Out	in	Length of the sample in inches after heating
	Width Out	in	Width of the sample in inches after heating
	Thick Out	in	Thickness of the sample in inches after heating
	Weight After Shot Blast	gm	Weight of the sample after shot blasting in grams.
	Length Final	in	Length of the sample in inches after shot blast
	Width Final	in	Width of the sample in inches after shot blast
	Thick Final	in	Thickness of the sample in inches after shot blast
	Weight Loss	gm	Weight in minus the weight of the sample after shot blasting
	% Scale of Sample	%	The calculated percent of scale that was formed on the piece = (Weight Loss)/(Weight In)
	% Scale of Product	%	The percent scale extrapolated to the shape of the product associated with the test run
	Partial Decarb	in	The partial decarb depth in inches of the side that has been selected for decarb analysis
	Picture Files	Phase 3	The file name of a digital picture of the sample after heating
		Phase 4	The file name of a digital picture of the sample after final shot blasting
		Decarb	The file name of a digital picture of the sample during Decarb analysis

Exhibit 25: Complement to the Sample Test Results table.

5.2 Sample Test Flow Results

The subsequent ledge below presents the various flow data recorded during each test run and provides for quick evaluation of actual flow rates in comparison to desired values.

Test No.	Date	AFR	Pilot					Nitrogen					Carbon Monoxide					Nitrogen					Nitrogen Quench				
			PDM	Temp	Pressure	Static	%O2	Pressure	Temp.	Flow	Corrected	Desired	Pressure	Temp.	Flow	Corrected	Desired	Pressure	Temp.	D.P.	Corrected	Desired	Pressure	Temp.	Flow	Corrected	Desired
#	-	#	sec	°F	psig	SCFH	W.C.	%	psig	°F	SCFH	SCFH	psig	°F	SCFH	SCFH	SCFH	psig	°F	W.C.	SCFH	SCFH	psig	°F	SCFH	SCFH	SCFH
18	5/7/2008	10.86	17.38	80	5.0	26.3	5.9	19.2	0.0	0	0	0.0	0.0	0	0.0	0.0	0.0	10.00	80	1.0	125.8	-	0.0	0	0.0	0.0	0
		9.38	17.38	80	5.0	26.3	5.9	19.2	11.0	88	0.4	4.2	2.9	10.5	90	4	5.3	3.5	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		7.90	17.38	80	5.0	26.3	5.9	19.2	9.5	89	1.4	14.4	14.7	10.0	91	16	21.2	15.1	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		6.42	17.38	80	5.0	26.3	5.9	19.2	10.0	94	3.6	37.5	36.9	10.0	94	39	51.6	50.7	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		4.94	17.38	80	5.0	26.3	5.9	19.2	27.0	85	6.3	85.2	87.9	55.0	80	65	144.5	121.7	29.00	80	2.3	253.7	157	0.0	0	0.0	0
19	5/20/2008	Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0	12.50	80	4.2	270.5	-	40.0	80	3.0	354.4	350
		10.86	16.84	67	5.0	27.8	5.9	19.2	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0	10.0	67	1.0	127.3	-	0.0	0	0.0	0.0	0
		9.38	16.84	67	5.0	27.8	5.9	19.2	9.0	75	0.3	3.1	2.9	10.5	75	4	5.3	3.6	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		7.9	16.84	67	5.0	27.8	5.9	19.2	9.75	78	1.4	14.5	14.7	10.25	78	16	21.3	15.1	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		6.42	16.84	67	5.0	27.8	5.9	19.2	10.0	85	3.5	36.4	36.9	11.0	82	45	60.7	50.7	0.00	0	0.0	0.0	0	0	0.0	0.0	0
20	6/4/2008	4.94	16.84	67	5.0	27.8	5.9	19.2	26.5	84	5.9	92.8	87.9	41.0	81	65	128.1	121.7	24.00	67	1.3	181.7	157	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0	11.0	67	2.5	205.3	-	40.0	67	3.0	354.4	350
		6.80	16.98	77	5.0	27.1	5.9	19.1	10.5	82	3.1	32.6	34.0	10	83	34	45.0	44.1	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		5.95	16.98	77	5.0	27.1	5.9	19.1	8.0	84	4.5	44.9	46.9	8.75	84	48	61.9	65.8	52.00	77	0.05	46.3	-	0.0	0	0.0	0
		5.40	16.98	77	5.0	27.1	5.9	19.1	11.0	86	6.4	69.0	70.3	19.75	84	80	93.8	92.1	46.00	77	0.1	62.5	-	0.0	0	0.0	0
21	6/16/2008	5.35	16.98	77	5.0	27.1	5.9	19.1	12.75	88	7.0	78.8	73.3	20.0	84	62	97.2	97.2	42.00	77	0.2	85.5	-	0.0	0	0.0	0
		5.25	16.98	77	5.0	27.1	5.9	19.1	18.5	89	6.3	77.2	76.2	23.5	86	62	102.0	100.0	20.00	77	1.2	163.7	157	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0	8.0	77	2.1	175.2	-	40.0	77	3.0	354.4	350
		10.86	16.47	75	5.25	28.4	6.2	19.1	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	10.0	75	1.0	126.3	-	0.0	0	0.0	0.0	0
		8.89	16.47	75	5.25	28.4	6.2	19.1	9.0	81	0.5	5.1	5.9	10.0	81	5	6.6	8.2	0.00	0	0	0.0	0	0	0.0	0.0	0
23	7/7/2008	6.91	16.47	75	5.25	28.4	6.2	19.1	10.5	84	2.5	26.3	27.5	10.0	83	29	38.4	38.1	0.00	0	0.0	0.0	0	0	0.0	0.0	0
		5.93	16.47	75	5.25	28.4	6.2	19.1	10.5	87	4.5	47.3	48.6	10.5	84	50	66.8	67.3	14.50	75	0.25	68.7	-	0.0	0	0.0	0
		4.94	16.47	75	5.25	28.4	6.2	19.1	25.0	87	5.8	76.6	87.9	41.0	83	58	115.2	121.7	26.00	75	1.7	211.5	157	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	12.0	75	3.0	227.5	-	40.0	75	3.0	354.4	350
		10.86	17.67	78	5.0	26.0	5.8	19.2	0	0	0.0	0.0	0.0	0	0	0.0	0.0	10.0	78	1.0	126.0	-	0.0	0	0.0	0.0	0
24	9/10/2008	9.04	17.67	78	5.0	26.0	5.8	19.2	9.5	88	0.4	4.1	4.1	11.0	86	8	10.8	6.0	0.00	0	0	0.0	0	0	0.0	0.0	0
		7.21	17.67	78	5.0	26.0	5.8	19.2	10.5	91	2.1	22.1	22.3	10.0	89	26	34.4	31.1	0.00	0	0	0.0	0	0	0.0	0.0	0
		6.22	17.67	78	5.0	26.0	5.8	19.2	10.0	93	3.8	39.6	39.9	10.0	91	40	52.9	55.6	0.00	0	0	0.0	0	0	0.0	0.0	0
		5.23	17.67	78	5.0	26.0	5.8	19.2	28.5	94	4.3	59.2	73.8	29.0	91	51	89.8	104.2	29.50	90	0.95	162.5	157	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	16.0	90	1.9	191.5	-	40.0	78	3.0	354.4	350
25	9/12/2008	10.86	13.63	72	5.0	34.0	6.0	19.0	0.0	0	0	0.0	0.0	0	0	0.0	0.0	10.5	75	1.0	127.6	-	0.0	0	0.0	0.0	0
		9.04	13.63	72	5.0	34.0	6.0	19.0	10.0	76	0.4	4.2	4.1	10.0	76	8	10.6	6.0	0.00	0	0	0.0	0	0	0.0	0.0	0
		7.21	13.63	72	5.0	34.0	6.0	19.0	10.0	78	2.1	21.9	22.3	10.0	78	34	46.0	31.1	0.00	0	0	0.0	0	0	0.0	0.0	0
		6.22	13.63	72	5.0	34.0	6.0	19.0	35.0	80	2.1	31.0	39.9	37.2	80	51	97.8	55.6	39.00	80	0.2	82.9	-	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	15.0	80	0.7	115.4	-	40.0	80	3	354.4	350
26	10/2/2008	10.86	13.67	73	5.0	33.9	5.8	19.0	0	0	0.0	0.0	0.0	0	0	0.0	0.0	10.0	73	1	126.0	-	0.0	0	0.0	0.0	0
		9.04	13.67	73	5.0	33.9	5.8	19.0	10	79	0.4	4.2	4.1	10	79	8	10.6	6.0	10.00	73	1	125.9	-	0.0	0	0.0	0
		7.21	13.67	73	5.0	33.9	5.8	19.0	10	80	2.3	23.9	22.3	12	80	35	48.1	31.1	11.00	80	1	126.3	-	0.0	0	0.0	0
		6.22	13.67	73	5.0	33.9	5.8	19.0	10	80	4.3	44.8	39.9	10	80	57	75.4	55.6	11.00	80	0.1	40.6	-	0.0	0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0	0	0.0	0.0	0.0	0	0	0.0	0.0	20.0	81	4.4	312.4	-	40.0	81	3.0	354.4	350
27	12/10/2008	10.86	14.61	68	5.0	32.0	5.1	19.1	0	0	0.0	0.0	0.0	0	0	0.0	0.0	10.0	73	0.9	120.1	-	0.0	0	0.0	0.0	0
		9.04	14.61	68	5.0	32.0	5.1	19.1	10.25	75	0.4	4.2	4.1	10.0	75	4	5.3	6.0	10.00	75	0.9	119.9	-	0.0	0	0.0	0
		7.21	14.61	68	5.0	32.0	5.1	19.1	10.0	77	2.2	22.9	22.3	10.25	77	19	25.3	31.1	10.00	77	0.9	119.6	-	0.0	0	0.0	0
		6.22	14.61	68	5.0	32.0	5.1	19.1	10.25	78	3.9	40.8	39.9	10.0	78	45	59.5	55.6	0.00	0	0	0.0	0	0	0.0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	12.0	79	3.3	237.7	-	40.0	79	3.0	354.4	350
28	12/29/2008	10.86	15.13	60	5.0	31.4	5.5	19.3	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	10.0	65	0.9	121.0	-	0.0	0	0.0	0.0	0
		8.79	15.13	60	5.0	31.4	5.5	19.3	10.0	66	0.5	5.2	6.5	10.0	66	7	9.3	9.1	10.00	66	0.8	114.0	-	0.0	0	0.0	0
		6.72	15.13	60	5.0	31.4	5.5	19.3	10.0	66	2.9	30.2	31.1	10.25	66	31	41.2	41.7	10.00	66	0.3	89.8	-	0.0	0	0.0	0
		6.32	15.13	60	5.0	31.4	5.5	19.3	9.5	66	4.5	46.4	39.3	10.0	66	45	58.5	53.8	0.00	0	0	0.0	0	0	0.0	0.0	0
		Quench	0	0	0.0	0.0	-	-	0.0	0	0.0	0.0	0.0	0	0	0.0	0.0	16.0	66	0.4	89.8	-	40.0	79	3.0	354.4	350

5.3 Sample Test Flow Results Legend

The table below is a complement to the Sample Test Flow Results table and provides for a brief explanation of each data point category and its relevance.

Test No.		#	Sequential test number
Date		-	Date of the test
AFR		#	Equivalent air to fuel ratio being simulated
Pilot	PDM	sec	Seconds per rotation of PDM indicator (1 rev = 0.1 cubic ft.)
	Temp. @ PDM	°F	Temperature of incoming natural gas flow at PDM
	Pressure @ PDM	psig	Static pressure of incoming natural gas flow at PDM
	Gas Flow	SCFH	Corrected flow of natural gas
	Static Pressure	"W.C.	Static pressure of air/gas mixture at pilot measured in inches of water column
	%O2	%	%O2 content of air/gas mixture at pilot
Hydrogen	Pressure	psig	Static pressure of incoming hydrogen flow at rotameter
	Temperature	°F	Temperature of hydrogen flow at rotameter
	Flow Reading	LPM	Indicated flow reading on hydrogen rotameter
	Corrected Flow	SCFH	Corrected flow of hydrogen
	Desired Flow	SCFH	Desired flow of hydrogen from calculated atmosphere profile
Carbon Monoxide	Pressure	psig	Static pressure of incoming carbon monoxide flow at rotameter
	Temperature	°F	Temperature of incoming carbon monoxide at rotameter
	Flow Reading	SCFH	Indicated flow reading on carbon monoxide rotameter
	Corrected Flow	SCFH	Corrected flow of carbon monoxide
	Desired Flow	SCFH	Desired flow of carbon monoxide from calculated atmosphere profile
Nitrogen	Pressure	psig	Static pressure of incoming nitrogen flow at orifice plate
	Temperature	°F	Temperature of incoming nitrogen flow at orifice plate
	D.P.	"W.C.	Differential pressure of nitrogen flow measured across the orifice plate
	Corrected Flow	SCFH	Calculated flow of nitrogen
	Desired Flow	SCFH	Desired flow of nitrogen from dilution calculation
Nitrogen Quench	Pressure	psig	Static pressure of incoming nitrogen flow at rotameter
	Temperature	°F	Temperature of incoming nitrogen flow at rotameter
	Flow Reading	SCFM	Indicated flow reading on nitrogen rotameter
	Corrected Flow	SCFH	Corrected flow of nitrogen
	Desired Flow	SCFH	Desired flow of nitrogen developed from various scrap sample practice runs

Exhibit 27: Sample test flow results legend.

6 BB3 SFH TESTS

The following sections provide detailed information on the description, data results, and conclusions of tests that were conducted to simulate proposed scale-free sub-stoichiometric paths based upon actual heating requirements of BB3 products. The entire data set for these tests is listed in the DESCRIPTION OF SAMPLE TEST DATA section above and should be reviewed closely to appreciate the complete scope of data gathered in each test. The following sections will discuss only particular data and conclusions related to the scaling rate of samples and how they are affected by stoichiometric path and furnace capacity.

6.1 Description of 200 tph (100% Capacity Tests)

Test #18, Test #20, Test #21, Test #27, and Test #28 were all conducted at the defined temperature profile associated with the calculated SFH 100% furnace capacity conditions for a BB3 Product. It is important to note that all test samples received by Bloom Engineering from SDI already carried a layer of scale formation from the casting process. Therefore all samples were purposely shot blasted and weighed prior to the heating simulation in order to remove any scale that would be present after the caster but before the reheat furnace. As a result, the amount of scale formed on these samples was strictly due to the furnace heating simulation alone.

Test #18 was performed upon the basis of stoichiometric atmospheres of 110%, 80%, and 50% in the charge zone, heat zone, and soak zone respectively. In the interest of realistically approximating the stoichiometric stages of the combustion gases throughout the proposed furnace process, testing utilized five stoichiometric 'steps': 110%, 95%, 80%, 65%, and 50%.

Test #20 was performed specifically to observe the results of a truly reducing atmosphere throughout the entire reheating process. In order to accomplish this, the stoichiometric atmospheres were stepped through 67%, 60%, 55%, 54%, and 53% with 67%, 55%, and 53% representing the charge zone, heating zone, and soak zone respectively. Of note, this scenario resulted in a theoretically unacceptable value of heat input per ton of product when forced onto the SDI furnace layout.

Test #21 was one of three attempts at optimizing 100% capacity atmospheric conditions with the charge zone, heating zone, and soak zone tuned to 110%, 70%, and 50% stoichiometric values respectively. Testing simulation accordingly used the additional stoichiometric steps of 90% and 60% conditions.

Test #27 was the second of three attempts at optimizing 100% capacity atmospheric conditions with the charge zone, heating zone, and soak zone designated at 110%, 68%, and 60% stoichiometric values respectively. Additional stoichiometric steps of 89% and 64% were utilized in simulation testing.

Test #28 was the third and final attempt at optimizing 100% capacity reducing conditions. The charge zone, heating zone, and soak zone were set at 92%, 65%, and 55% stoichiometric conditions respectively with the additional stoichiometric steps of 88% and 60% added during simulation testing.

The following graph provides a visual comparison of the variations in stoichiometric paths for each of the five 200 tph SFH BB3 tests conducted. The Required Stoichiometric Path profile has

been overlaid in order to display the theoretical stoichiometric values that would be required to produce a truly reducing atmosphere throughout the entirety of the heating process.

Exhibit 28: 200 TPH BB3 testing.

6.2 Results of 100% Capacity Tests

As a demonstration of the data collected for each test, the actual and desired profiles regarding sample surface temperature and atmospheric conditions for Test #27 can be seen in the graphs below.

Exhibit 29: Temperature profile for test #27; samples 27A and 27B.

The Desired Heating Curve displayed in the Temperature Profile graph above is representative of the theoretical time temperature profile of a BB3 product undergoing actual scale-free heating as defined in the SDI furnace. The Sample TC profile is the actual surface temperature of the samples as they underwent the heating process. Since these profiles are nearly identical, it is therefore valid to assert that the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surface when processed under the same atmospheric conditions. While only the profile of Test #27 is displayed above, it is worthwhile to state that all reported tests were conducted under the strict guideline that the heating curves very closely emulate those of the theoretical BB3 heating process.

Exhibit 30: Atmosphere profile for test #27; samples 27A and 27B.

The Desired CO/CO₂ profile displayed in the above chart is indicative of the chosen stoichiometric 'steps' previously mentioned. As a reminder, the CO/CO₂ ratio was chosen by the project team as the primary marker used in monitoring simulated sub-stoichiometric values as described under the Furnace Facility report section. The CO/CO₂ profile subsequently depicts the actual atmospheric conditions experienced by the test samples being heated in the lab simulation. As a result of these profiles being nearly the same, the test samples therefore accurately depict the scale formation improvement for the given stoichiometric test path.

The following table provides a summary of the scale rate results for these 5 tests.

200 TPH (100% Capacity) BB3 Testing								
Test #	Sample #	Simulated Capacity		% Scale of Sample	% Scale of BB3	Average % Scale of BB3	Stoichiometric Path	Net Heat Input
#	#	TPH	%	%	%	%	-	MMBtu / Ton of Product
18	18A	200	100	8.89%	0.21%	0.21%	110% → 95% → 80% → 65% → 50%	1.1244
	18B	200	100	8.16%	0.21%			
20	20A	200	100	0.88%	0.033%	0.036%	67% → 60% → 55% → 54% → 53%	VERY HIGH
	20B	200	100	1.00%	0.038%			
21	21A	200	100	3.83%	0.14%	0.14%	110% → 90% → 70% → 60% → 50%	1.0643
	21B	200	100	3.54%	0.14%			
27	27A	200	100	10.30%	0.27%	0.28%	110% → 89% → 68% → 64% → 60%	1.0693
	27B	200	100	10.77%	0.28%			
28	28A	200	100	10.23%	0.14%	0.14%	92% → 88% → 65% → 60% → 55%	1.1926
	28B	200	100	4.79%	0.14%			

Exhibit 31: 200 TPH (100% capacity) BB3 testing.

Again, it is important to note that each official test run reported was found to closely simulate both the 100% capacity temperature profile as well as each test-specific designed stoichiometric path based upon the SDI reheat furnace. Consequently all results are therefore accurate projections of BB3 scale formation that would result if the SDI reheat furnace were run at identical atmospheric and heating parameters.

6.3 Conclusions from 100% Capacity Tests

When considering the 100% capacity BB3 test data, it is easily observed that the scaling rate of 0.036% from Test #20 was the lowest rate recorded. This data fits nicely with expectations as

Test #20 was designed as an exploration of scale formation given a reducing atmosphere throughout the entire heating process. As seen above in the graph *200 TPH BB3 Testing*, the stoichiometric path of Test #20 does, in fact, remain true to the ideal reducing profile represented by the Required Stoichiometric Path curve. The scaling rate of 0.036% therefore represents the actual optimum scale-free performance possible for a BB3 product when heated in a truly scale-free process on SDI's furnace. While true scale free results of 0.000% were obviously not realized, 0.036% is remarkably close and represents a significant reduction over conventional heating methods, a comparison that is covered in great detail under CH VERSUS SFH COMPARISONS.

While these results are quite compelling, it is important to understand the context of the testing scenario. As a result of using SDI's actual furnace layout, which was not originally intended for SFH heating, the heat balance for Test #20 was actually quite unacceptable. This means that, if SDI's furnace were converted to run SFH production based upon Test #20's parameters, scale formation would be vastly reduced. Any cost savings, however, would easily be outweighed by the additional expenditure regarding natural gas consumption. The key thing to keep in mind, though, is that while true scale free performance is not economically feasible on the SDI reheat furnace that does not necessary exclude all furnace arrangements. It is important to emphasize that the balance of optimum scale formation and economic feasibility should only be considered on a case-by-case basis. While SDI's layout would certainly eliminate true scale-free performance, it is quite possible that a new furnace arrangement, designed with SFH in mind, could conceivably achieve true scale-free production.

Comparatively, while not as successful as Test #20, the remaining data warrants a careful review. As discussed in SCALE FREE HEATING HEAT BALANCES, Test #18 was representative of the "best-case scenario" possible for conversion of SDI's reheat furnace to SFH when considering the described difficulties associated with burner control and SFH turndown heat balances. The scaling rate of 0.21% therefore represents a realistic representation of scale formation for a BB3 product heated at 100% furnace capacity if SDI were to actually consider SFH conversion with the existing furnace structure. Again, while a detailed comparison to conventional heating is forthcoming, it is important to note that 0.21% represents a significant reduction in overall scale formation by comparison. Test #18, however, also plainly demonstrates the penalty taken when considering the inability of burner controls to extrapolate stoichiometric zone conditions as well as turndown versus furnace capacity. Test #18 is clearly one of the less successful 100% capacity SFH test run in terms of scale formation. This was to be expected when viewing the tests stoichiometric path in comparison to the Required Stoichiometric Path, as well as the other testing curves displayed in the above graph *200 TPH BB3 Testing*.

Furthermore, a careful look at the three tests aimed at 100% capacity optimization is required. Test #21 data represents the optimal balance of heat input (natural gas usage) and scale formation improvement when strictly considering 100% capacity only on SDI's reheat furnace. The scaling rate of 0.14% is essentially the realistic maximum reduction in scale formation possible on SDI's reheat furnace. Notably, this represents a 33% improvement over Test #18. This fact highlights the effect of burner control limitations on the SFH process in general. If a control program were able to extrapolate through both stoichiometric conditions and turndown versus furnace capacity, 0.14% scale formation would in fact be the resulting scale formation for an SDI BB3 under 100% furnace capacity. In reality, however, it would be nearly impossible to implement such a controlling mechanism. Even if such a unit were theoretically possible, the capital expenses would likely prohibit installation altogether. As a result, Test #18 is actually the

more realistic representation of possible scale reduction on SDI's furnace while Test #21 provides a look at the cost of lost scale performance due to controller simplification.

Test #27 represented a different approach to economically approximating the Required Stoichiometric Path. This test explored the concept of attempting to better emulate a reducing atmosphere during the furnace heat zone with the resulting penalty of remaining slightly oxidizing during the soak zone in order to maintain a practical net heat input. The visualization of this can be seen above in the graph *200 TPH BB3 Testing*. Unfortunately, the scaling rate of 0.28% clearly demonstrates that despite the improved atmosphere throughout the heating zone, the oxidizing soak zone conditions serve to outweigh the improvement. Additionally, this curve suffers from similar controller and lower capacity heat balance issues discussed in regards to Test #21 results. Essentially, this means that given a conversion of SDI's furnace and the capability of an affordable complex controller, the process parameters of Test #21 would still result in slightly less heat input per ton of product while providing even greater reduction in scale formation at 100% furnace capacity. Even Test #18 provided for slightly better scale performance at only a 0.0551 MMBtu/Ton of product penalty. Combined with the heating balance concerns of reduced capacity and the corresponding lack of a suitable controller, the parameters of Test #27 are best avoided in the scenario of an SDI reheat furnace conversion. Despite this, Test #27 still served to provide an important lesson in SFH stoichiometric path development.

The third and final optimization attempt was bore out in Test #28, where a better overall approximation of the ideal reducing curve was created, specifically regarding the charge and heat zones. As a penalty for this improvement, it should be observed that the soak zone is essentially forced to run just on the oxidizing side of the required stoichiometric curve while the charge zone is actually exhausting sub-stoichiometric combustion flue products. As a corollary to this exhaust gas condition, the process resulted in a slight increase in the total net heat input per ton of product versus the other tested SFH profiles. Despite all the tradeoffs, however, the scaling rate of 0.14% only managed to match that of Test #21. This means that given a direct comparison, Test #21 manages to perform at the same level of scale reduction while requiring less net heat input, which leaves no justification for Test #28 parameters to be chosen over those in Test #21. Aside from these issues, Test #28 parameters also suffered from the same issues of lower capacity heat balancing and burner control complexity without even taking into account the problems generated by the concept of exhausting sub-stoichiometric flue gas. None-the-less Test #28 provides yet another lesson in the development of SFH profiles.

In summary, 100% capacity SFH BB3 testing accomplished several important benchmarks. First, the realization and verification of a truly scale-free heating process was achieved with an actual scaling rate of 0.036% recorded, a value far and away below that of common conventional heating. Secondly, an economically feasible and optimized scale performance rate of 0.14% was developed in Test #21 when considering 100% furnace capacity alone. This provided a realistic "peak" performance for scale formation on a BB3 product heating in a theoretically converted SDI reheat furnace. Thirdly, Test #18 highlights a more tempered view of possible scale reduction when considering the overall conversion process of the SDI furnace, taking into account items such as burner control, lower furnace capacities, and burner turndown. While it is clear controller limitations caused a level of scale reduction to be left "on the table" so to speak, a very palpable and significant reduction in BB3 product scale formation is still obtainable in the conversion of the SDI reheat furnace. Moreover, remember that the heat balance limitations described above are specific to the SDI furnace only and that even greater scale performance may in fact be achievable on a different furnace layout.

6.4 Description of 150 tph (75% Capacity Tests)

Test #19 was conducted at the defined temperature profile associated with the calculated SFH 75% furnace capacity conditions for a BB3 Product. Simultaneously Test #19 was performed upon the basis of stoichiometric atmospheres of 110%, 80%, and 50% in the charge zone, heat zone, and soak zone respectively. In the interest of realistically approximating the stoichiometric stages of the combustion gases throughout the proposed furnace process, testing utilized five stoichiometric 'steps': 110%, 95%, 80%, 65%, and 50%.

It is important to note that all test samples received by Bloom Engineering from SDI already carried a layer of scale formation from the casting process. Therefore all samples were purposely shot blasted and weighed prior to the heating simulation in order to remove any scale that would be present after the caster but before the reheat furnace. As a result, the amount of scale formed on these samples was strictly due to the furnace heating simulation alone.

The following graph provides an illustration of the stoichiometric path of Test #19. The Required Stoichiometric Path profile has been overlaid in order to display the theoretical stoichiometric values that would be required to produce a truly reducing atmosphere throughout the entirety of the heating process.

Exhibit 32: 150 TPH BB3 testing.

6.5 Results of 75% Capacity Tests

As a demonstration of the data collected for each test, the actual and desired profiles regarding sample surface temperature and atmospheric conditions for Test #19 can be seen in the graphs below.

Exhibit 33: Temperature profile for test #19; samples 19A, 19B, and 19C.

The Desired Heating Curve displayed in the Temperature Profile graph above is representative of the theoretical time temperature profile of a BB3 product undergoing actual scale-free heating as defined in the SDI furnace. The Sample TC profile is the actual surface temperature of the samples as they underwent the heating process. Since these profiles are nearly identical, it is therefore valid to assert that the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surface when processed under the same atmospheric conditions.

Exhibit 34: Temperature profile for test #19; samples 19A, 19B, and 19C.

The Desired CO/CO₂ profile displayed in the above chart is indicative of the chosen stoichiometric 'steps' previously mentioned. As a reminder, the CO/CO₂ ratio was chosen by the

project team as the primary marker used in monitoring simulated sub-stoichiometric values as described under the Furnace Facility report section. The CO/CO₂ profile subsequently depicts the actual atmospheric conditions experienced by the test samples being heated in the lab simulation. As a result of these profiles being nearly the same, the test samples therefore accurately depict the scale formation improvement for the given stoichiometric test path.

The following table provides a summary of the scale rate results for the 75% capacity SFH BB3 testing.

150 TPH (75% Capacity) BB3 Testing								
Test #	Sample #	Simulated Capacity		% Scale of Sample	% Scale of BB3	Average % Scale of BB3	Stoichiometric Path	Net Heat Input
#	#	TPH	%	%	%	%	-	MMBtu / Ton of Product
19	19A	150	75	4.33%	0.18%	0.17%	110% → 95% → 80% → 65% → 50%	1.0790
	19B	150	75	4.35%	0.15%			

Exhibit 35: 150 TPH (75% capacity) BB3 testing.

Again, it is important to note that the official test run reported was found to closely simulate both the 75% capacity temperature profile as well as the test-specific designed stoichiometric path based upon the SDI reheat furnace. Consequently all results are therefore accurate projections of BB3 scale formation that would result if the SDI reheat furnace were run at identical atmospheric and heating parameters.

6.6 Conclusions from 75% Capacity Tests

When considering the 150 TPH test data, it is perhaps best to keep the analysis within a set context. While it is possible to draw comparisons against all the 100% capacity testing, it has already been established that at this time the combination of heat balance concerns in conjunction with the lack of a suitable burner controller leave all but Test #18 from the realm of real-world application regarding a retro-fit of the SDI reheat furnace. Further supporting this direction of study is the fact that the stoichiometric path explored in Test #19 is actually identical to that of Test #18 discussed prior.

Interestingly enough, the scale rate of 0.17% resulted in a surprising improvement over the 0.21% scale formation observed in Test #18, a 19% reduction. This was unexpected as the 75% capacity mimics the atmospheric conditions of the 100% capacity scenario while actually residing in the furnace for a longer period of time, that is, about 116 minutes as opposed to about 90 minutes at 200 TPH. While multiple attempts were made to explain this result, including a wide range of analysis techniques, it remains slightly unclear as to the cause for scale formation improvement. Regardless, Test #19 data represents a realistic representation of scale formation for a BB3 product heated at 75% furnace capacity if SDI were to actually consider SFH conversion with the existing furnace structure.

6.7 Description of 100 tph (50% Capacity) Tests

Test #29 was conducted at the defined temperature profile associated with the calculated SFH 50% furnace capacity conditions for a BB3 Product. Simultaneously Test #29 was performed upon the basis of stoichiometric atmospheres of 110%, 80%, and 50% in the charge zone, heat zone, and soak zone respectively. In the interest of realistically approximating the stoichiometric

stages of the combustion gases throughout the proposed furnace process, testing utilized five stoichiometric 'steps': 110%, 95%, 80%, 65%, and 50%.

It is important to note that all test samples received by Bloom Engineering from SDI already carried a layer of scale formation from the casting process. Therefore all samples were purposely shot blasted and weighed prior to the heating simulation in order to remove any scale that would be present after the caster but before the reheat furnace. As a result, the amount of scale formed on these samples was strictly due to the furnace heating simulation alone.

The following graph provides an illustration of the stoichiometric path of Test #29. The Required Stoichiometric Path profile has been overlaid in order to display the theoretical stoichiometric values that would be required to produce a truly reducing atmosphere throughout the entirety of the heating process.

Exhibit 36: BB3 shape steel reheating at 100 tons/hour (TPH) caapcity.

6.8 Results of 50% Capacity Tests

As a demonstration of the data collected for each test, the actual and desired profiles regarding sample surface temperature and atmospheric conditions for Test #19 can be seen in the graphs below.

Exhibit 37: Temperature profile for test #29; samples 29A and 29B.

The Desired Heating Curve displayed in the Temperature Profile graph above is representative of the theoretical time temperature profile of a BB3 product undergoing actual scale-free heating as defined in the SDI furnace. The Sample TC profile is the actual surface temperature of the samples as they underwent the heating process. Since these profiles are nearly identical, it is therefore valid to assert that the amount of scale formed on the sample surfaces is proportional to the scale formed on a BB3 surface when processed under the same atmospheric conditions.

Exhibit 38: Atmosphere profile for test #29; samples 29A and 29B.

The Desired CO/CO₂ profile displayed in the above chart is indicative of the chosen stoichiometric 'steps' previously mentioned. As a reminder, the CO/CO₂ ratio was chosen by the

project team as the primary marker used in monitoring simulated sub-stoichiometric values as described under the Furnace Facility report section. The CO/CO₂ profile subsequently depicts the actual atmospheric conditions experienced by the test samples being heated in the lab simulation. As a result of these profiles being nearly the same, the test samples therefore accurately depict the scale formation improvement for the given stoichiometric test path.

The following table provides a summary of the scale rate results for the 50% capacity SFH BB3 testing.

100 TPH (50% Capacity) BB3 Testing								
Test #	Sample #	Simulated Capacity		% Scale of Sample	% Scale of BB3	Average % Scale of BB3	Stoichiometric Path	Net Heat Input
#	#	TPH	%	%	%	%	-	MMBtu / Ton of Product
29	29A	100	50	25.31%	0.39%	0.39%	110% ? 95% ? 80% ? 65% ? 50%	1.0782
	29B	100	50	10.71%	0.39%			

Exhibit 39: 100 TPH (50% capacity) BB3 testing.

Again, it is important to note that the official test run reported was found to closely simulate both the 50% capacity temperature profile as well as the test-specific designed stoichiometric path based upon the SDI reheat furnace. Consequently all results are therefore accurate projections of BB3 scale formation that would result if the SDI reheat furnace were run at identical atmospheric and heating parameters.

6.9 Conclusions from 50% Capacity Tests

As with the 150 TPH testing, it is perhaps best to keep the analysis within the set context of Test #18 and Test #19. While it is possible to draw comparisons against all the 100% capacity testing as well as 75% capacity testing, it has already been established that at this time the combination of heat balance concerns in conjunction with the lack of a suitable burner controller leave all but Test #18 from the realm of real-world application regarding a retro-fit of the SDI reheat furnace. Further supporting this direction of study is the fact that the stoichiometric path explored in Test #29 is actually identical to that of Test #18 and Test #19 discussed prior.

The scale rate of 0.39% for Test #29 was notably higher than the observed 0.21% in Test #18 (100% capacity) as well as the 0.17% in Test #19 (75% capacity). This was to be expected, however, since the product experienced the identical atmospheric path while remaining in the furnace longer than in the higher capacity scenarios, about 180 minutes by comparison to 90 minutes for 100% capacity and 116 minutes for 75% capacity. As a result of the close simulation of the proposed temperature and atmospheric profiles, Test #29 represents a realistic representation of scale formation for a BB3 product heated at 50% furnace capacity if SDI were to consider SFH conversion with the existing furnace structure. Additionally, Test #29 served to round out the full data set for scale formation given a proposed SFH conversion of the SDI reheat furnace. This means that a detailed economic analysis regarding actual projected scale savings for the SDI reheat furnace is possible, given that SDI could accurately present the projected amount of time the furnace is to be used at each capacity.

7 RECOMMENDATIONS OF BB3 SFH TESTS

While it should be regarded that all BB3 SFH testing has proven valuable for scale reduction analysis, a particular focus on Test #18, Test #19, and Test #29 should be held. As outlined in

the previous sections, as a group these tests represent the accurate expectations of realistic scale reduction that could be obtained through a SFH conversion of the SDI reheat furnace. The adjacent table summarizes the data for the common stoichiometric path testing.

Summary of SFH BB3 Capacity Tests			
% Capacity	% Scale of BB3	Average % Scale of BB3	Net Heat Input
%	%	%	MMBtu/Ton of Product
100%	0.21%	0.21%	1.1244
	0.21%		
75%	0.18%	0.17%	1.0790
	0.15%		
50%	0.39%	0.39%	1.0782
	0.39%		

Exhibit 40: Summary of SFH capacity tests.

Overall, the increase in scaling rate as the operating capacity of the furnace is reduced should be observed in this table with the scaling rate ranging from 0.21% at 100% capacity to 0.39% at 50% capacity. As discussed previously, it is unclear as to why the 75% capacity data provided for a slight improvement over 100% capacity, but it should be kept in mind that the 50% capacity scale formation increased as expected. The following graph presents the same data in graphical format with the curve showing a polynomial expression of $y = 0.0216x^2 - 0.036x + 0.0165$.

Exhibit 41: SFH heating of BB3: % scale vs. % capacity.

It is recommended that these test results be used specifically to predict the scaling rate of products that have similar time temperature and proposed stoichiometric conditions as well as a congruent surface area to volume ratio to that of the BB3 product only.

Special note should be taken regarding to the above mentioned restrictions though. First, the topic of similar surface area to volume ratio is a key requirement of the possible projection of this data for another product. This subject was covered in great detail in the CH Sample Report and a review of the "Discussion and Recommendations of BB3 Heating Tests" is suggested in order to better understand the implications of data extrapolation. As a brief summary, the following excerpt asserts the topics main points.

"The time temperature history of a product and its size will dictate how much scale is formed during its heating. All test results were based on the time temperature history of a BB3 product heating in the reference SDI furnace. The BB3 product has a distinct shape resulting in a distinct surface area to volume ratio. The surface area to volume ratios of the samples heated in the lab test facility are significantly different from that of a BB3 but if the time temperature history of the lab sample is the same as that of BB3 than the scaling rate of a BB3 product can correctly be extrapolated from the lab test results"

The additional requirement of similar stoichiometric conditions, however, adds another important dimension to data projection. As 100% capacity testing performed in Test #18, Test #20, Test #21, Test #27, and Test #28 clearly indicates, samples with identical heating profiles and surface area/volume ratios, but with different stoichiometric pathways will result in varying scale formation. Just as a reminder, projected BB3 scale formation ranged from 0.033% to 0.28% within the five completed 200 tph tests. This highlights the importance of correctly simulating the actual proposed sub-stoichiometric conditions while following a given heating profile for a specific product and furnace. Therefore, in order to properly use the specific scaling data from the testing completed to date, such as with an actual conversion of the SDI reheat furnace, the product must match the three process criteria; heating profile, atmosphere profile, and surface area/volume ratio.

With that being said, given that similar heating and atmospheric conditions are maintained, but the surface area to volume ratio of a product is different than that of the BB3, it is possible to use the raw test data and extrapolate the expected product scale formation, as briefly described in the CH Sample Report excerpt above. Recall, as discussed in this report under the section Test Sample Size, a simple mathematical conversion may be utilized for projecting scale formation, provided that the time temperature profile and stoichiometric pathways are nearly identical. The following table is provided as an illustration of such a conversion when going from test sample data to a BB3 extrapolation.

Scale Formation Conversion					
Steel Description	Initial Weight	Surface Area	Metal Loss	% Weight Loss	Metal Loss V.S. SA
	Lbs.	ft ²	Lbs.	%	Lbs./ft. ²
Test Sample	0.0196	0.012	0.0017	8.89%	0.1459
Industry Product	Initial Weight	Surface Area	Metal Loss V.S. SA	Projected Metal Loss	Projected % Weight Loss
	Lbs./ft. Length	ft ² /ft. Length	Lbs./ft. ²	Lbs./ft. Length	%
BB3	598.73	8.51	0.1459	1.24	0.21%

Exhibit 42: Scale formation conversion.

The "Test Sample" data in the above table is that of sample 18A which was a 200 tph (100% capacity) SFH simulation of a proposed conversion of the SDI reheat furnace. As shown, the sample scale weight loss of 8.89% for the sample corresponded to a scale loss of 0.1459 pounds per square foot of sample surface. When this same scale loss ratio of 0.1459 Lbs/ft² is applied to the surface area of a BB3 dogbone shape, the % scale formed on the BB3 was only 0.21%. This is then a valid prediction of the reduced scale production for a BB3 product that is processed along the same heating and atmospheric profile followed in Test #18. If another product of a different surface area to volume ratio were to be processed under the same heating and atmospheric conditions, it would then be possible to use the 0.1459 Lbs/ft² to correct predict the scaling formation for that products surface area to volume ratio.

8 SLAB SFH TESTS

The following sections provide detailed information on the description, data results, and conclusions of tests that were conducted to simulate proposed scale-free sub-stoichiometric paths based upon actual heating requirements of heavy slab products. The entire data set for these tests is listed in the DESCRIPTION OF SAMPLE TEST DATA section above and should be reviewed closely to appreciate the complete scope of data gathered in each test.

In continuance of previous testing, the reference slab investigated via lab simulation was an 8" x 84" slab. The following sections will discuss only particular data and conclusions related to the scaling rate of samples used to simulate the SFH heating of such a slab in the SDI reference furnace.

8.1 Description of 200 tph (100% Capacity) Slab Heating Test

Test #26 was conducted at the defined temperature profile associated with the calculated SFH 100% furnace capacity conditions for an 8" x 84" Slab Product. Simultaneously Test #26 was performed upon the basis of stoichiometric atmospheres of 110%, 73%, and 53% in the charge zone, heat zone, and soak zone respectively. In the interest of realistically approximating the stoichiometric stages of the combustion gases throughout the proposed furnace process, testing utilized five stoichiometric 'steps': 110%, 91.5%, 73%, 63%, and 53%.

It is important to note that all test samples received by Bloom Engineering from SDI already carried a layer of scale formation from the casting process. Therefore all samples were purposely shot blasted and weighed prior to the heating simulation in order to remove any scale that would be present after the caster but before the reheat furnace. As a result, the amount of scale formed on these samples was strictly due to the furnace heating simulation alone.

The following graph provides an illustration of the stoichiometric path of Test #26. The Required Stoichiometric Path profile has been overlaid in order to display the theoretical stoichiometric values that would be required to produce a truly reducing atmosphere throughout the entirety of the heating process.

Exhibit 43: 200 TPH slab material testing.

8.2 Results of 100% Capacity Slab Heating Test

As a demonstration of the data collected for each test, the actual and desired profiles regarding sample surface temperature and atmospheric conditions for Test #26 can be seen in the graphs below.

Exhibit 44: Temperature profile for test # 26; sample 26A and 26B.

The Desired Heating Curve displayed in the Temperature Profile graph above is representative of the theoretical time temperature profile of an 8" x 84" slab product undergoing actual scale-free

heating as defined in the SDI furnace. The Sample TC profile is the actual surface temperature of the samples as they underwent the heating process. Since these profiles are nearly identical, it is therefore valid to assert that the amount of scale formed on the sample surfaces is proportional to the scale formed on an 8" x 84" slab surface when processed under the same atmospheric conditions.

Exhibit 45: Atmosphere profile for test #26; samples 26A and 26B.

The Desired CO/CO₂ profile displayed in the above chart is indicative of the chosen stoichiometric 'steps' previously mentioned. As a reminder, the CO/CO₂ ratio was chosen by the project team as the primary marker used in monitoring simulated sub-stoichiometric values as described under the Furnace Facility report section. The CO/CO₂ profile subsequently depicts the actual atmospheric conditions experienced by the test samples being heated in the lab simulation. As a result of these profiles being nearly the same, the test samples therefore accurately depict the scale formation improvement for the given stoichiometric test path.

The following table provides a summary of the scale rate results for the 100% capacity SFH Slab testing.

200 TPH (100% Capacity) Slab Testing								
Test #	Sample #	Simulated Capacity		% Scale of Sample	% Scale of BB3	Average % Scale of BB3	Stoichiometric Path	Net Heat Input
#	#	TPH	%	%	%	%	-	MMBtu / Ton of Product
26	26A	200	100	3.70%	0.05%	0.06%	110% ? 91.5% ? 73% ? 63% ? 53%	1.0508
	26B	200	100	3.43%	0.07%			

Exhibit 46: 200TPH (100% capacity) slab testing.

Again, it is important to note that the official test run reported was found to closely simulate both the 100% capacity temperature profile as well as the test-specific designed stoichiometric path based upon the SDI reheat furnace parameters. Consequently all results are therefore accurate

projections of scale formation that would result if the SDI reheat furnace were run at identical atmospheric and heating parameters while heating an 8" x 84" heavy slab.

8.3 Conclusions from 100% Capacity Slab Test

While a direct comparison to conventional heating is to be discussed in greater detail under the heading CH VERSUS SFH COMPARISONS, the scale rate of 0.06% marks a 90% reduction in scale over the 100% capacity CH slab testing completed based upon the SDI reheat furnace. This means, that if SDI were to heat 8" x 84" heavy slab product using a SFH conversion of the reheat furnace, it would be possible to recover 90% of the material lost during a production rate of 200 TPH compared to traditional conventional heating methods.

Moreover, the stoichiometric path proposed for the Test #26 simulation represents the importance of product shape and corresponding heating and atmospheric profiles resulting from a given furnace layout. As discussed above, the realistic implementation for SFH of BB3 product on the SDI reheat furnace examined in Test #18 at 200 TPH involved the stoichiometric conditions of 110%, 80%, and 50% for the charge zone, heat zone, and soak zone respectively over the course of approximately 90 minutes. These conditions were a direct result of the heat balance work as discussed in the section SCALE FREE HEATING (SFH) HEAT BALANCES. By comparison, simply by reworking the heat balance data with the alternative 8" x 84" slab product while remaining on the same furnace, very different heating and atmospheric profiles were found to be required. For instance, the heating time of the thick slab is roughly 175 minutes while the charge zone, heat zone, and soak zone calculate out to 110%, 73%, and 53% stoichiometric set-points respectively. Interestingly enough, the minimum required reducing stoichiometric value for both products in the soak zone is 53%, meaning that both products were protected by reducing atmospheric conditions in the respective soak zones which, in theory, ceased any further scale formation under those conditions. However, the heat balance for the heavy slab product allowed for a heat zone stoichiometric value of 73% versus the resulting 80% for BB3 product calculations. Essentially, this highlights the concept that the SDI reheat furnace would actually be slightly "friendlier" to SFH conversion for a slab product versus a BB3 product since overall lower stoichiometric conditions are possible despite the identical furnace layout. This serves to emphasize the important role that product shape plays in the implementation of the SFH process. In short, in the evaluation of any proposed SFH conversion, it is extremely important that factors such as product shape as well as any furnace layout restrictions are taken into account via a detailed heat balance analysis in order to develop the appropriate heating and atmospheric curves.

9 RECOMMENDATIONS OF SLAB SFH TEST

The single SFH test of a heavy slab conducted in Test #26 demonstrates the high level of material savings possible with the scale-free heating process during 100% furnace capacity on the SDI reheat furnace for an 8" x 84" slab. It should be noted that additional testing at reduced capacities, as feasibly allowed for by the furnace heat balance, could be conducted in order to provide a full set of SFH 8" x 84" slab scale projections. Such testing would invariably lead to the possibility of a detailed economic evaluation specifically for the SDI furnace if slab production were to be desired. However, at this time, such testing is not recommended.

The SFH slab test conducted also served to illustrate the impact that product shape can have on the overall scale-free performance possible on a given furnace layout as discussed above. Therefore, in future SFH considerations, it is important to carefully analyze the resulting heat

balances for a given product shape and furnace layout in order to define the stoichiometric capabilities of each furnace zone.

As a reminder, any extrapolation of collected slab SFH testing should also be completed with great care. As discussed at length in RECOMMENDATIONS OF BB3 SFH TESTS, specific scale data as reported for an 8" x 84" slab may only be used for other products if the three SFH criteria of heating profile, atmosphere profile, and surface area/volume ratio are held to be identical. However, given a product of similar heating and atmospheric profiles, yet differing surface area to volume ratio, it remains possible to use the raw test data and extrapolate the expected product scale formation. Consequently, it is important to prudently consider the heat balance based time temperature history and stoichiometric path a particular product would experience in a particular furnace before extrapolating scaling rates from data generated in this work.

10 INTEGRAL ANALYSIS

As scale-free testing entered the SFH BB3 100% furnace capacity optimization phase, a method of predicting possible scale reduction before collection of empirical data became highly desirable. With Test #20 verifying the possibility of actual scale-free performance, it was fairly obvious that the closer the stoichiometric paths approached true reducing atmospheric conditions, the better the scale performance. However, after tempering this approach with heat balance calculations, it became increasingly difficult to simply visually judge a proposed atmospheric profile. For instance, as heating zone conditions were manipulated towards ideal reducing conditions, soak zone inputs were obviously forced away from the ideal reducing atmosphere in order to allow for total fuel burndown while maintaining a reasonable net heat input per ton of material. As an illustration of this, graph *200 TPH BB3 Testing* is shown below with the addition of actual scale results.

Exhibit 47: 200 TPH BB3 testing.

At a casual glance, it is clearly observed that Test #18 appears to be the worst approximation of the ideal reducing atmosphere, particularly in the heating zone, yet test results revealed the more visually attractive Test #27 to in fact produce the highest level of scale for 200 tph testing. The argument could be made that this was simply due to the soak zone atmosphere being held at oxidizing conditions, but Test #28, refutes this notion. It is clear that Test #28 approached reducing conditions in an improved manner, regarding the soak zone conditions, but remained oxidizing while providing one of the lowest levels of scale formation by comparison.

As a result of the apparent conflicting visual results, significant effort was put into the development of an analysis method that could explain the observed data and thus provide a method of predicting scale formation for future considerations while not being limited to a set furnace capacity. Subsequently, Integral Analysis (IA) was created. Integral Analysis works with the team chosen stoichiometric marker, the CO/CO₂ ratio. As discussed in prior sections, it is possible to determine the specific ratio value associated with a specific stoichiometric value, including the theoretical fringe of a reducing atmosphere. Going further, it should also be stated that the temperature-driven atmospheric requirements for a reducing atmosphere are well known throughout the combustion industry as a result of accepted empirical evidence. IA utilizes these facts by mapping out the “required” CO/CO₂ values associated with the fringe of a reducing atmosphere based upon product surface temperature over the course of a proposed test. The actual sub-stoichiometric settings selected through heat balance computation are then imposed over the “required curve” as shown in the adjacent graph.

Exhibit 48: 200 TPH test #18.

Integral Analysis then calculates the mathematical variance between true reducing CO/CO₂ values and the proposed stoichiometric path. Of course, further calculations are then used to account for curve intersection and overlap, as well as lower temperature exclusion due to the lack

of scale formation that occurs below approximately 1300°F. IA was therefore exercised over the entire range of testing, including conventional heating tests previously conducted, the results of which are summarized in the following table.

Integral Analysis Calculations Summary									
Product	Test	Type	TPH	Integral Variance	MMBtu/Ton	% Scale	Soak Zone	Heat Zone	Charge Zone
BB3	6	CH	200	200.83	1.105	0.72	110%	110%	110%
BB3	18	SFH	200	81.38	1.124	0.21	50%	80%	110%
BB3	20	SFH	200	0.00	Very High	0.035	53%	54%	67%
BB3	21	SFH	200	60.91	1.064	0.14	50%	70%	110%
BB3	27	SFH	200	93.18	1.069	0.275	60%	68%	110%
BB3	28	SFH	200	61.21	1.193	0.14	55%	65%	92%
BB3	7	CH	150	257.48	1.0641	0.80	110%	110%	110%
BB3	19	SFH	150	94.19	1.0790	0.165	50%	80%	110%
BB3	12	CH	100	397.40	1.0717	1.375	110%	110%	110%
BB3	29	SFH	100	158.40	1.0782	0.39	50%	80%	110%
8" x 84" Slab	22	CH	200	353.56	0.938	0.60	110%	110%	110%
8" x 84" Slab	26	SFH	200	98.56	1.051	0.06	53%	73%	110%

Exhibit 49: Integral analysis calculations summary.

The reason Integral Analysis was created, however, was the high level of corroboration observed between the calculated variance and the resulting level of scale formation over the designed capacity range. Recall the high impact that product shape plays upon the extrapolation of scale data as discussed previously. Therefore it is extremely important to contain the IA comparison within a specific product. Since the BB3 product was selected as the project benchmark, the widest range of data is available for this product shape and is accordingly the focus of review.

The following graph depicts the Integral Analysis technique for the range of all BB3 heating tests conducted.

Exhibit 50: Integral analysis of BB3 heating tests.

As displayed, the curve fit overlaid on the data is a polynomial expression with the equation of $y = 2E-06x^2 + 0.0025x - 0.011$ with a fit coefficient of $R^2 = 0.9814$, representative of the high level of convergence the data presents.

The profound corollary of this agreement of data is that Integral Analysis, in effect, presents the necessary tools to predict actual % scale formed given a few empirical sample test points. For example, IA's inception occurred just prior to the performance of Test #28. At that point in time, several atmosphere profiles were being reviewed and IA was performed on each of the proposals. The profile that went on to be Test #28 projected an Integral Variance of 61.2. Test #21, having already been discovered as the optimal 100% capacity SFH BB3 scenario, projected an Integral Variance of 60.9 which corresponded to a scale rate of 0.14%. Test #28 parameters were therefore chosen as a result of the similar Integral Variance with the expectation that similar scale rate results would follow. As can clearly be observed, the scale rate for Test #28 actually matched that of Test #21, verifying the pre-test prediction.

The power to predict actual scale rates for a given product provides for two important ramifications of Integral Analysis. First and foremost involves the ability to perform data-less t/t/a profile optimization. This means that given a specific furnace and product, IA can be used in conjunction with heat balance calculations in order to develop the optimum atmospheric profile while maintaining a target heat input for a desired temperature schedule without ever having to actual perform a sample test. This greatly expedites the development stage by allowing various proposed furnace scenarios to be compared instantly to one another, thus reducing the time consuming required amount of actual sample testing. For instance, without ever actually performing 200 TPH SFH optimization testing, the comparable scale reduction could have been predicted as illustrated in the following table.

Integral Analysis 200 TPH BB3 Comparison				
Product	Test	TPH	Integral Variance	% Scale
BB3	18	200	81.38	0.21
BB3	20	200	0.00	0.035
BB3	21	200	60.91	0.14
BB3	27	200	93.18	0.28
BB3	28	200	61.21	0.14

Exhibit 51: Integral analysis 200 TPH BB3 comparison.

Based on Integral Variance alone, the tests would have ranked from best to worst scale rate as: Test #20, Test #21, Test #28, Test #18, and Test #27. The completed tests resulted in the identical ranking with 0.033%, 0.14%, 0.14%, 0.21%, and 0.28% scale rates respectively.

Secondly, Integral Analysis could be used in conjunction with limited sample testing in order to accurately determine the potential of SFH retrofits. Given a possible retrofit opportunity, the heating balance work and IA would initially define the optimum SFH curve to be inspected based upon the furnace and product specifics. This information would then be able to be transferred to a sample test setup. With only a few runs, perhaps covering each capacity, realistic scale projections could then be developed in correspondence with the Integral Variance values calculated. The benefits of this are two-fold. First, based upon the tested SFH atmosphere and heating profiles, a detailed report of potential economic savings is fairly easy to develop, based upon actual production the furnace has previously experienced. Secondly, it is possible to then predict a specific scale rate for capacity in question, particularly a capacity not actually tested.

This, in effect, allows for a projection of further possible savings or costs that running a furnace at or below 100% capacity would entail. This can also be said of any desired changes to the stoichiometric paths tested. If later consideration reveals that the various zone atmospheres would perhaps be better set to different conditions, Integral Analysis allows for scale projection simply based upon the previously existing data, provided that the product shape and material are maintained.

In summary, Integral Analysis provides a stunningly useful tool throughout the SFH process. During the initial development of heating and atmospheric profiles, IA furnishes a quick and easy method by which to compare and optimize suggested scenarios. As the proposed atmosphere and heating curves are certified, a limited number of sample tests can then be used in association with Integral Analysis in order to develop a coherent base of scale rate data. IA then allows for an accurate prediction of % scale over the range of capacities and atmospheric modifications. As a result, Integral Analysis should be considered a key tool to utilize in determining the potential of SFH retrofits. Scale reduction offers additional energy savings that would amount to approximately 0.195 MM Btu/ton of steel reheated. Hence accurate prediction of scale reduction is very important. The Integral Analysis method, discussed below, allows us to predict reduction in scale formation and hence the associated energy savings with use of scale free heating system. Approximately 76 MM tons/year steel being reheated can use scale free heating resulting in approximately 15 TBtu/year energy savings for the US steel industry. This is in addition to energy savings resulting from improved energy efficiency related to improved furnace design and heating system.

Appendix C: Preheated Air Burner Report

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1 INTRODUCTION

The range of sizes for burners that are to be used on a reheat furnace to achieve both Conventional Heating (CH) and Scale Free Heating (SFH) was based on the reheat furnace at SDI's Structural Mill Division in Columbia City, Indiana. Not only is this furnace operated by the Project Team's Industry Representative, SDI, but it also was designed and built by the Project Team's Furnace Representative, ACL, and it is fired by burners supplied by the Project Team's Burner Representative, Bloom. In an ongoing Project, ACL has provided SDI with Quarterly Reports of the furnace's operation and performance. This provides an extensive database to draw upon in order to study and evaluate typical furnace operation and utilization.

The furnace is a state of the art reheat furnace in that it is a walking beam type furnace with up to date combustion and control technology. Since it was installed in 2001 it is designed as an extremely efficient furnace with a substantial unfired preheat section at the furnace entry and very high preheat air temperature. The basic arrangement of the furnace is shown in the following sketch,

Exhibit 1: Furnace firing arrangement for a typical walking beam furnace

All zones are longitudinally fired with longitudinal burners featuring a mixture of Bloom's Low NO_x and Ultra Low NO_x burners. The specific size of the burners was dictated by many different and specific requirements that any Project has and are relative to that specific Project. Such things as cold and/or hot charge and size, shape and length of the various products can effect the specific burner sizing in any zone. This particular furnace was designed for a wide range of products from billets to blooms to large and small dog bones, (rough structural shapes).

The reference burner sizes for the CH/SFH Burner Specification were developed on a more generic production specification but the basic size and arrangement of the SDI furnace was used as the basis for burner location and number. This work was done in Phase I and the following table summarizes the range and size of burners required in the different zones for either CH or SFH.

CONVENTIONAL HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	187	84	41	312
% of total input =	60.0%	27.0%	13.0%	100%
Air/gas ratio =	10/1	10/1	10/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	10.4	4.7	1.9	
SCALE FREE HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	0	146	166	312
% of total input =	0.0%	46.7%	53.3%	100%
Air/gas ratio =		7/1	5/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	0.0	8.1	7.9	

Exhibit 2: Summary of the range and size of the burners.

The basis of the % total input in each zone for either CH or SFH and the Air/gas ratio in each zone is discussed in detail in the Phase I Final Report.

The above table was used to generate the detailed burner specification sent to Bloom Engineering for their evaluation of a burner series that could achieve the wide range operation required for CH and SFH. This specification is provided on the following page.

Burner Specification Submitted to Bloom Engineering

SCALE FREE HEATING BURNER SPECIFICATION: PREHEATED AIR												
ZONE	CONNECTED			DESIGN			TURNDOWN			ZONE	NUMBER OF BURNER	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G			
SOAK	39,619	7,924	5	30,476	6,095	5	5,079	1,016	5	SOAK	21	166
HEAT	56,622	8,089	7	43,556	6,222	7	7,259	1,037	7	HEAT	18	146
CHARGE	63,886	0	NA	49,143	0	NA	8,190	0	NA	CHARGE	0	0
										FURNACE	39	312

Fuel: Natural gas @ 1027 Btu/cf (East Ohio Natural Gas)

Burner Notes: No burners are required for Charge Zone. Number of burners shown for Soak and Heat Zones are for both top and bottom heating zones.

Preheat Air Temperature: Background suggests that the minimum preheat air temperature required for 5/1 combustion is 1000°F. Burner Supplier to note if higher preheat air temperature is required.

Air and Gas Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

CONVENTIONAL HEATING BURNER SPECIFICATION: PREHEATED AIR												
ZONE	CONNECTED			DESIGN			TURNDOWN			ZONE	NUMBER OF BURNER	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G			
SOAK	19,314	1,931	10	14,857	1,486	10	2,476	248	10	SOAK	21	41
HEAT	46,800	4,680	10	36,000	3,600	10	6,000	600	10	HEAT	18	84
CHARGE	104,000	10,400	10	80,000	8,000	10	13,333	1,333	10	CHARGE	18	187
										FURNACE	57	312

Fuel: Natural gas @ 1027 Btu/cf (East Ohio Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 1000°F

Air and Gas Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 3: Burner specifications for scale free and conventional heating

:Bloom submitted Proposal No. P-1205-202-C dated June 6, 2006 outlining the type, size and price of the burners that they believed could achieve the submitted Specification.

Phase II work involved demonstrating that the proposed burners could achieve the specified ranges for both CH and SFH and if necessary further developing the burner series in order to achieve the specified ranges.

2 DESCRIPTION OF TESTS

The Project Team met and reviewed the Burner Specification that was submitted as the basis for burner testing. The general burner type to be tested, test furnace, and instrumentation was agreed upon and described in detail in the following sections.

2.1 Test Burner

Based on the Burner Specification submitted, the Cyclops burner series was chosen as the prime candidate for implementation given the wide range of testing parameters. This burner series was originally created as an ultra low NO_x solution based on the concept of staged combustion. This concept is the scenario where total combustion is delayed through various methods such as air staging, which reduces NO_x as a result of the slow mixing and a natural internal furnace atmosphere re-circulation that tends to occur simultaneously. In order to achieve burner stability during furnace start-up and conditions below auto-ignition while balancing low emissions at higher furnace temperatures, the Cyclops burners are typically designed to vary air splits between primary and secondary airflows. A larger percentage of primary airflow during start-up and low temperature conditions provides for stronger flame anchoring and shape due to faster initial mixing. During high temperature conditions where flame stability is easier to maintain, the percentage of primary air can be reduced, thus delaying combustion and aiding in minimizing NO_x emissions.

These design characteristics aligned almost perfectly with the desired capabilities of the proposed SFH burner. During SFH mode, a large percentage of primary airflow provides for very rapid initial mixing of fuel and air, providing the best possible conditions for combustion to be completed while maintaining a satisfactory atmosphere without formation of soot. Due to absence of free oxygen in the SFH mode, NO_x formation was anticipated to be very low despite the increased primary airflow. During the proposed CH mode, the burner would then be able to switch over to the standard firing conditions with a much lower percentage of primary air, resulting in ultra low NO_x emissions. Additionally, the Cyclops burner has also been previously designed for stability down to 10:1 turndown with the addition of a turndown air lance. Given the need for extreme turndown, essentially down to 32:1 turndown from the noted Burner Specification, this burner series was put into favorable consideration and was ultimately chosen for testing.

At the project onset, however, it was quickly realized that testing the burner as designed would not be practical due to the high input of the capacities specified (≈ 8 MMBtu/hr) and the resulting size of the test furnace and equipment. This was not viewed with much concern, though, as Bloom Engineering often encounters this situation in the highly variable combustion product market. Burners are usually designed with the interest of maintaining the ability to scale up or down in capacity in order to allow for such cases and to reduce application limitations of burner designs. In fact, the practice of scaling burners down for lab testing and research is a common practice and has shown to provide reliable results in a plethora of cases. Confident in prior scaling results, a standard 1610-013 Cyclops burner already appropriately sized for lab furnaces

and located in the lab facilities was chosen as the test burner and is shown below. Also, the resulting capacity scaling can be seen in the provided table below.

Exhibit 4: Standard 1610-013 Cyclops Bloom burner.

SPECIFIED VERSUS TESTED BURNER SIZE			
ZONE	@	%	
STOICHIOMETRIC			
			SPECIFIED (MMBtu/hr)
			TESTED (MMBtu/hr)
SOAK	@	50%	
STOICHIOMETRIC			
			7.924
			4.400
HEAT	@	70%	
STOICHIOMETRIC			
			8.069
			4.492
SOAK	@	105%	
STOICHIOMETRIC			
			1.931
			1.073
HEAT	@	105%	
STOICHIOMETRIC			
			4.68
			2.599

Exhibit 5: Specified vs. tested burner size.

2.2 Furnace Facility

The test furnace chosen for this project was done so for a variety of reasons. First of all, there were two fairly large preheaters setup in the lab facility that were originally designed to provide hot combustion air to several furnaces for various testing needs. However, given the required 1000°F air pre-heat, it was realized that these two preheaters would need to be run in series in order to reach such a value. As a result, the designated furnace needed to be located in close proximity to these in order to reduce heat losses in the piping. Secondly, the furnace had to be large enough to accommodate a 4.492 MMBtu/Hr burner, yet small enough that the furnace could be heated to testing temperatures of 2200°F -2300°F in a reasonable amount of time as well as providing for positive furnace pressure. Thirdly, and perhaps most importantly, since the excess gas input during SFH had to be burned down outside the chamber, a refractory lined flue was desired to prevent excessive damage to the flue stack.

Given these parameters, the 4ft. Lab Furnace became the clear choice. This furnace is a cylindrical furnace 4' in diameter and 12' long internally, with external dimensions of 5.5' diameter

and 13.5' long. As stated, the furnace made use of a refractory lined flue stack that extended outside of the main lab enclosure.

Exhibit 6: The Bloom test furnace used for the burner testing

A port for the insertion of a water-cooled emissions probe was located on the flue just after the junction with the furnace. Additional ports were located on the side of the furnace facing the center of the lab and these were used to collect Bacharach smoke data during testing.

Exhibit 7: Ports used to collect Bacharach smoke data.

Air and gas flows were controlled manually through high temperature butterfly valves on the air lines and a ball valve on the gas line. Flows were accordingly manipulated by trimming each valve as necessary. Each trim valve was installed downstream of an orifice run, which was the chosen method of setting and measuring various flows via static and differential pressures. Additional shut-off valves were installed as a method to shut down flow if and when necessary.

Exhibit 8: Test furnace piping (hot air) arrangement

In order to measure furnace temperature accurately, eight ceramic-shielded Type K thermocouples were evenly spaced along the side of the furnace facing the lab wall. These not only provided local furnace temperatures, but also allowed for an average furnace temperature to be easily accessible. Additional unshielded Type K thermocouples were installed into the primary and secondary air lines to monitor air preheat accurately.

Exhibit 9: Temperature monitoring in the test furnace

Viewing windows were found on the lab-inward side of the furnace as well as the end of the furnace. These viewing ports allowed for visual observance of flame appearance as well as collection of video and photographic data.

Exhibit 10: Viewing ports for the test furnace

As mentioned previously, two preheaters were run in series to meet the 1000°F air preheat required for SFH testing. Pictures of each of these can be seen below.

Exhibit 11: Air preheaters used for the burner tests

In order to provide for the actual burn down of the excess fuel during SFH, a large pilot was installed at the top of the flue stack. When actually in SFH, this pilot was lit via spark igniter and provided a source of flame for the fuel and other products of combustion exiting the stack. Located opposite this pilot was the flue controller, which allowed the flue to be open or closed to create proper furnace pressure during testing. As a final note on the furnace equipment, a schematic detailing the arrangement of the preheaters, test furnace, burner, gas controls, and air controls can be found on the following page.

Exhibit 12: Pilot. Used for ignition of the furnace atmosphere (flue gases)

2.3 Instrumentation

The test furnace instrumentation includes a large variety of items and is perhaps best discussed via column-by-column review of the Test Data Sheet identified as Appendices 1, 2, 3, and 4 below. The primary, secondary, and lance (where applicable) air columns are identical in nature and will be discussed first.

Primary, Secondary, & Lance Air

- *Run* – This column serves a dual purpose in providing an identification number for each data point while also keeping the test date readily visible. The format was simply the date of testing followed by alphanumeric coding in chronological order regarding test points taken the same day.

- *S.P. @ Orifice; "Hg* – This column represents the upstream static pressure of the pre-heated air in inches of mercury. This data was collected at the upstream side of the corresponding (Primary/Secondary) orifice run by Meriam Instrument U-Tube Mercury Manometers scaled in 0.1" Hg.
- *Temp. @ Orifice; °F* – This column provides the preheated air temperature in degrees Fahrenheit. This data was collected just after the orifice runs and right before the burner via Omega Type-K Unshielded Thermocouples as mentioned previously.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the respective (Primary/Secondary) orifice plate in inches of water column. This data was recorded across the orifice by Meriam Instrument U-Tube Water and/or Oil Manometers scaled in 0.1" W.C. During CH testing, where turndown was much higher, a panel of inclined oil manometers was used in place of the U-Tube design as scaling resolution improved to 0.01" W.C. with the inclined design.

Exhibit 14: Meriam Instrument U-tube water and oil manometers.

- *Q; SCFH* – This column represents the real-time actual airflow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using orifice plates designed and calibrated at Bloom.
- *S.P. @ Burner; "W.C.* – Data in this column refers to the static pressure of the air right at the burner inlets and is given in inches of water column. These values represent the pressure drop across the burner. This data is provided by Meriam Instrument U-Tube Water Manometers.

Natural Gas

- *Run* – This column remains the same as previously discussed with Primary and Secondary Air.
- *S.P. @ Orifice; psig* – This column represents the upstream static pressure of the pre-heated air in pounds per in². This data was collected at the upstream side of the orifice run by a Reotemp 0-30 psig pressure gauge scaled in 0.5 psig increments.
- *Temp. @ Orifice; °F* – This column provides the gas temperature in degrees Fahrenheit. This data was collected just before the orifice run via a Weksler Instruments 20-240°F temperature gauge marked in 2°F increments.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the gas orifice plate in inches of water column. This data was recorded across the orifice by a Meriam Instrument U-Tube Water Manometer scaled in 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual gas flow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using orifice plates designed and calibrated at Bloom.
- *S.P. @ Burner; psig* – Values in this column refer to the static pressure of the gas right at the burner inlet and is given in pounds per in². These results indicate the pressure drop across the

gas nozzle. This data is provided by a US Gauge 0-30 psig pressure gauge scaled in 1.0 psig increments.

Emissions

All emissions samples were taken via a water-cooled stainless steel emissions probe connected to a pump station and water chiller regulated down to 12 psig output. Images of this setup can be seen below. The emission samples were then pumped into a control room where they were sent through a Drierite-filled canister before being sent to individual analyzers that are described in greater detail below. This setup allowed for all of the moisture to be removed from the flue gas before reaching the analyzers, resulting in all readings and measurements being taken on a “dry” basis. The analyzers themselves output analog signals, which are then picked up by Bloom’s computer software for visual display and trend recording.

Exhibit 15: Gas sampling probe arrangement

- *Run* – This column remains the same as previously discussed.
- *Furnace Temp.; °F* – This column expresses the average furnace temperature in °F for the specific test point. The average is taken from the eight-shielded thermocouples discussed under Furnace Facility.
- *NO_x; ppm* – Data in this column displays the Nitrous Oxide emissions in parts per million. This was provided by a Rosemount Analytical Model 951A NO/NO_x Analyzer set on 0-100 ppm range resulting in +/- 5.0 ppm error.
- *CO; ppm* – This column represents the Carbon Monoxide emissions in parts per million, which was the preferred scale for furnace warm-up and CH. This data was provided by a Rosemount Analytical Model 880A CO Analyzer with a 0-5000 ppm range resulting in +/- 20.5 ppm error.
- *% O₂* – Data in this column displays the Oxygen content of emissions based upon volumetric percentage, which was the preferred scale during furnace warm-up and CH. This data was provided by a Teledyne Brown Engineering Portable Oxygen Analyzer.
- *% CO* – This column presents the Carbon Monoxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.
- *% CO₂* – This column presents the Carbon Dioxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.
- *CO/CO₂ Ratio* – This column displays the ratio of the recorded Carbon Monoxide emissions to the corresponding data point’s Carbon Dioxide emissions.

- *Desired CO/CO₂ Ratio* – This column presents the corresponding desired emissions ratio for the particular test point being reviewed. Review of this number allows for a triple-check on the burner settings versus complete combustion during SFH testing.
- *Smoke #* – Data in this column displays the smoke number results of the Bacharach Smoke Test during SFH. This test was performed with a handheld pump used to draw flue emissions across special filter paper that left a darkened circle. This darkened circle was then measured against a Bacharach provided scaling to develop a smoke number. Smoke test results that were even darker than the highest scale value of 9 were rated a 9+ simply to provide a way to make note of such a scenario. This testing is a common method of checking the amount of soot produced during firing. However, if the emissions are drawn too close to flame, they often present higher scale readings than actually experienced. Photos of the Bacharach Smoke Testing equipment and scale can be seen below.

Exhibit 16: Bacharach smoke testing equipment.

- *Calculated TD* – Values displayed in this column display the data point's actual turndown. This is calculated from the burner's nominal gas flow rating and the actual gas flow recorded.
- *TD* – This column presents the data points desired turndown, which was used when setting in airflow and gas flow differential pressure values.
- *Calculated AFR* – Values in this column present the actual air to fuel ratio experienced based upon the flow results calculated from orifice data. This data served as a check against desired flow rates and settings.
- *Desired AFR* – This column displays the desired air to fuel ratio for a data point.
- *Chamber Appearance* – These values show the visual review of the furnace chamber appearance. Acceptable notes were given to points where the chamber remained relatively clear, allowing a view of burner components on the opposite chamber wall.
- *NO_x; Lbs/MMBtu* – This data column shows the NO_x emissions in pounds per million Btu. These values were corrected based upon the %O₂ and NO_x (ppm) results during CH and the Calculated AFR and NO_x (ppm) during SFH.

3 50% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted, the test results and conclusions for the test burner operated at the specified 50% stoichiometric conditions.

3.1 Description of Tests

The burner was operated at the specified 50% stoichiometric ratio, which would be the expected conditions for burners in the soak zone of a furnace that was operated under SFH conditions.

The specified versus the tested operating conditions for a burner in the soak zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: SOAK ZONE											
BURNER FOR	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A / G	AIR (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	GAS (scfh)	A / G	T / D
FURNACE	39,619	7,924	5	30,476	6,095	5	1.3	5,079	1,016	5	7.8
TESTED	22,000	4,400	5	16,923	3,385	5	1.3	2,821	564	5	7.8

Exhibit 17: Burner specification/testing: soak zone.

Each day, prior to actual recording of data, all emissions equipment was calibrated, the pre-heated air furnaces were brought up to proper temperature, and the test furnace was lit off and brought to the specified operating temperature. Initial furnace warm-up was achieved by firing the test burner at or near stoichiometric conditions.

For each test point in SFH, the burner was first adjusted to the corresponding turndown at stoichiometric conditions. This allowed for the desired airflow to be set in prior to venturing into SFH, as well as providing a check on emission oxygen content against the flow settings, ensuring air and fuel flows followed the developed settings. The gas flow was then increased to SFH values. A few examples of the stoichiometric to SFH transition can be seen in the following table.

STOICHIOMETRIC TO SFH TRANSITION						
(50% STOICHIOMETRIC VALUES)						
TD	STOICHIOMETRIC			SFH		
	PRIMARY AIR (scfh)	SECONDARY AIR (scfh)	NATURAL GAS (scfh)	PRIMARY AIR (scfh)	SECONDARY AIR (scfh)	NATURAL GAS (scfh)
1	20,900	1,100	2095	20,900	1,100	4,400
2	10,450	550	1048	10,450	550	2,200
3	6,967	367	698	6,967	367	1,467

Exhibit 18: Stoichiometric to SFH transition (50% stoichiometric values).

Once the flow settings were at 50% stoichiometric conditions, test point data was collected. Static pressures, temperatures, differential pressures, and emission values were recorded by hand, with emissions also being collected via tracking software. Video was also taken of the furnace chamber appearance along with handwritten notes. The Bacharach probe was inserted into a side port and pumped accordingly to develop a smoke number for the test point. With all data collected, the burner was then taken back to stoichiometric conditions in preparation of the next test point.

3.2 Results of Tests

As described, extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 50% stoichiometric tests is provided in Data Appendix Section 37. 1. The following table summarizes the performance of the test burner when firing at 50% stoichiometric conditions.

BURNER TEST DATA: 50% STOICHIOMETRIC										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO	CO ₂	CO/CO ₂	DESIRE D CO	DESIRE D CO/CO ₂	COMMENTS
120707a	22,544	4,305	5.24	1.02	12.41	4.45	2.79	12.6	3.2	Acceptable but CO/CO ₂ ratio is borderline.
120707b	18,353	3,632	5.05	1.21	12.53	4.42	2.83	12.6	3.2	Acceptable but CO/CO ₂ ratio is borderline.
120707c	15,036	2,925	5.14	1.50	12.45	4.45	2.80	12.6	3.2	Acceptable but CO/CO ₂ ratio is borderline.
120707d	11,056	2,219	4.98	1.98	11.09	5.31	2.09	12.6	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable
120707e	9,194	1,483	6.20	2.97	10.94	5.52	1.98	12.6	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable
111507f	5,703	1,174	4.86	3.75	8.33	6.53	1.28	12.6	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable

112007c	4,654	907	5.13	4.85	6.73	7.63	0.88	12.6	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable
112007f	3,972	847	4.69	5.20	6.92	7.34	0.94	12.6	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable

Exhibit 19: Burner test data: 50% stoichiometric.

Acceptable or Not Acceptable performance was determined by flame observation, checking the Bacharach number of the flue gasses leaving the furnace and measuring the CO and CO₂ content of the flue gasses. Other work in Phase I and Phase II of the Project had determined that a CO content of about 12.6% and a CO/CO₂ ratio of about 3.2 is required in order to prevent forming scale in the soak zone of a reheat furnace. Equilibrium calculations for Pittsburgh natural gas showed that an air to gas ratio of about 5/1 (about 50% stoichiometric) was required to achieve this.

The above Table shows that the CO level and CO/CO₂ ratio fell well short of the required values when the burner was turned down by more than about 1.5/1 (67% of nominal capacity). Review of the detailed data contained in Appendix 1 will provide other criteria regarding visual observations of flame appearance and furnace flue gas Bacharach numbers that substantiates these Acceptable or Not Acceptable comments.

Recording and observing the CO/CO₂ ratio and the Bacharach number provided crucial information as to the actual burner performance. The recorded air to gas ratio only substantiated that the burner was firing at the required 5/1 air/gas ratio. There were times when the furnace chamber looked acceptable and the air/gas ratio was correct but the CO/CO₂ ratio was below equilibrium values. This indicated that the combustion reaction did not achieve equilibrium at these points. Methane and/or free carbon were actually present in the flue gasses and the CO/CO₂ ratio was therefore lower than expected. Typically at these same conditions, the Bacharach number was very high proving the existence of pure soot.

3.3 Conclusions from Tests

The actual achieved turndown resulting in an acceptable atmosphere was well below the desired when the burner was operating at the expected soak zone firing ratio of 50% stoichiometric. The following Table provides the desired versus successful turndown ratio of the test burner operating at 50% stoichiometric.

BURNER TURNDOWN 50% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	1.5

Exhibit 20: Burner turndown 50% stoichiometric.

The required turndown level of 7.8/1 is only the turndown level needed when the burner is operating in the soak zone of a furnace that is being operated in SFH conditions. It must be remembered that the same burner has to also be operated as a conventional burner firing at stoichiometric conditions whenever the furnace is being operated in CH conditions. This actually increases the overall turndown level of the burner a great deal. By referring to the original Burner Specification provided above, Figure 4, the overall turndown of a burner that is used in the soak zone of furnace that has to run as either a CH furnace or as a SFH furnace can be determined. This is summarized in the following table.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	7.924 MMBtu/HR
MINIMUM SFH RATE	1.016 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	1.931 MMBtu/HR
MINIMUM CH RATE	0.248 MMBtu/HR
CH TURNDOWN	7.8
OVERALL SFH to CH TURNDOWN	31.95

Exhibit 21: Soak zone burner turndown.

Therefore, the total performance level of the soak zone burner cannot be completed until the same burner is operated in the CH mode over the specified range for that mode. The performance results of the burner operating in the CH mode, that is the 100% stoichiometric mode, is covered in a later Section of this report.

4 70% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted and the test results and conclusions for the test burner operated at the specified 70% stoichiometric conditions.

4.1 Description of Tests

The burner was operated at the specified 70% stoichiometric ratio, which would be the expected conditions for burners in the heat zone of a furnace that was operated under SFH conditions.

The specified versus the tested operating conditions for a burner in the heat zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: HEAT ZONE											
BURNER FOR	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A / G	AIR (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	GAS (scfh)	A / G	T / D

FURNACE	56,622	8,089	7	43,556	6,222	7	1.3	7,259	1,037	7	7.8
TESTED	31,442	4,492	7	24,186	3,455	7	1.3	4,031	576	7	7.8

Exhibit 22: Burner specification/testing: heat zone.

4.2 Results of Tests

As described, extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 70% stoichiometric tests is provided in the Appendix. Please see Data Appendix, Section 37. The following table summarizes the performance of the test burner when firing at 70% stoichiometric conditions.

BURNER TEST DATA: 70% STOICHIOMETRIC										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO	CO ₂	CO/CO ₂	DESIRE D CO	DESIRE D CO/CO ₂	COMMENTS
121207a	28,822	4,291	6.72	1.05	7.73	7.15	1.08	8.2	1.3	Acceptable and CO/CO ₂ ratio is good.
121207b	26,134	3,720	7.03	1.21	8.02	7.06	1.14	8.2	1.3	Acceptable and CO/CO ₂ ratio is good.
121207c	21,887	3,004	7.29	1.50	7.21	7.72	0.92	8.2	1.3	Acceptable but CO/CO ₂ ratio is borderline.
121207d	16,063	2,268	7.08	1.98	6.56	8.23	0.80	8.2	1.3	Acceptable but CO/CO ₂ ratio is borderline.
121207e	10,587	1,538	6.88	2.92	6.68	8.16	0.82	8.2	1.3	Acceptable but CO/CO ₂ ratio is borderline.
121207f	8,229	1,243	6.62	3.61	4.17	9.84	0.42	8.2	1.3	Not Acceptable, CO/CO ₂ ratio is not acceptable
121207g	6,169	868	7.10	5.17	4.36	9.83	0.44	8.2	1.3	Not Acceptable, CO/CO ₂ ratio is not acceptable

Exhibit 23: Burner test data: 70% stoichiometric.

Acceptable or Not Acceptable performance was determined by flame observation, checking the Bacharach number of the flue gasses leaving the furnace and measuring the CO and CO₂ content of the flue gasses. Other work in Phase I and Phase II of the Project has determined that a CO content of about 8.2% and a CO/CO₂ ratio of about 1.3 is required in order to prevent forming scale in the heat zone of a reheat furnace. Equilibrium calculations for Pittsburgh natural

gas showed that an air to gas ratio of about 7/1 (about 70% stoichiometric) is required to achieve this.

The above Table shows that the CO level and CO/CO₂ ratio fell well short of the required values when the burner was turned down by more than about 3/1 (33% of nominal capacity). Review of the detailed data contained in Appendix 2 will provide other criteria regarding visual observations of flame shape and furnace flue gas Bacharach numbers that substantiates these Acceptable or Not Acceptable comments.

4.3 Conclusions from Tests

The actual achieved turndown resulting in an acceptable atmosphere was well below the desired when the burner was operating at the expected soak zone firing ratio of 70% stoichiometric. The following Table provides the desired versus successful turndown ratio of the test burner operating at 70% stoichiometric.

BURNER TURNDOWN 70% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	3

Exhibit 24: Burner turndown 70% stoichiometric.

The required turndown level of 7.8/1 is only the turndown level needed when the burner is operating in the heat zone of a furnace that is being operated in SFH conditions. It must be remembered that the same burner has to also be operated as a conventional burner firing at stoichiometric conditions whenever the furnace is being operated in CH conditions. This actually increases the overall turndown level of the burner a great deal. By referring to the original Burner Specification provided above, the overall turndown of a burner that is used in the heat zone of furnace that has to run as either a CH furnace or as a SFH furnace can be determined. This is summarized in the following table.

HEAT ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	8.089 MMBtu/HR
MINIMUM SFH RATE	1.037 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	4.680 MMBtu/HR
MINIMUM CH RATE	600 MMBtu/HR
CH TURNDOWN	7.8
OVERALL SFH to CH TURNDOWN	13.48

Exhibit 25: Heat zone burner turndown.

So, the total performance level of the heat zone burner cannot be completed until the same burner is operated in the CH mode over the specified range for that mode. The performance results of the burner operating in the CH mode, that is the 100% stoichiometric mode, is covered in the following Section of this report.

5 100% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted and the test results and conclusions for the test burner operated at the specified 100% stoichiometric conditions.

5.1 Description of Tests

The burner was operated at the specified 100% stoichiometric ratio, which would be the expected conditions for burners in the soak and heat zones of a furnace that was operated under CH conditions. Note that in SFH conditions the charge zone burners are expected to be off at all times and only burn down air will be flowing through them. Therefore, burners in the charge zone would be sized for CH requirements only. The specified versus the tested operating conditions for a burner in the soak and heat zone are summarized in the following table.

BURNER SPECIFICATION/TESTING: STOICHIOMETRIC SOAK ZONE											
BURNER FOR FURNACE	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	T/D	AIR (scfh)	GAS (scfh)	A/G	T/D
FURNACE	19,314	1,931	10	14,857	1,486	10	1.3	2,476	248	10	7.8
TEST	10,725	1,073	10	8,250	825	10	1.3	1,375	138	10	7.8
BURNER SPECIFICATION/TESTING: STOICHIOMETRIC HEAT ZONE											
BURNER FOR FURNACE	CONNECTED			DESIGN				TURNDOWN			
	AIR (scfh)	GAS (scfh)	A/G	AIR (scfh)	GAS (scfh)	A/G	T/D	AIR (scfh)	GAS (scfh)	A/G	T/D
FURNACE	46,800	4,680	10	36,000	3,600	10	1.3	6,000	600	10	7.8
TEST	25,988	2,599	10	19,990	1,999	10	1.3	3,332	333	10	7.8

Exhibit 26: Burner specification/testing: stoichiometric soak and heat zone.

From the start of CH testing, the focus was largely on the Soak Zone burner since the desired parameters presented the worst-case scenario for turndown and flame appearance. Due to the high turndown required, orifice runs had to be very carefully chosen so that proper resolution could be maintained during turndown testing. As a result, after the furnace was setup for CH testing for the Soak Zone, it was not possible to obtain Heat Zone flow values. Faced with this problem, along with dwindling time due to testing delays, it was decided to gather complete data for the Soak Zone burner and forgo additional testing regarding CH with the Heat Zone burner. This decision was made with strong confidence for several reasons. First, most of the Heat Zone burner turndown points were an overlap of the Soak Zone turndown points as seen in the table below.

Comparison of Heat Zone and Soak Zone Firing Rates CH Testing									
TD		1	2	3	4	5	6	7	8
HEAT ZONE	NATURAL GAS (scfh)	2,599	1,300	866	650	520	433	371	325
SOAK ZONE	NATURAL GAS (scfh)	1,073	537	358	268	215	179	153	134

Exhibit 27: Comparison of heat zone and soak zone firing rates; CH testing.

Due to this overlap, only nominal firing and 2/1 turndowns would be left unexplored. In fact, original plans for Heat Zone testing were only going to include these points because of this. Secondly, this specific burner chosen for testing has previously undergone extensive turndown testing. The test burner was originally designed as a 4.6 MMBtu/Hr capacity burner to be fired at 10.5 or 11 air to fuel ratio. Testing completed as of August 2004 with a cold air turndown lance reports that this burner was stable at nominal conditions through 4/1 turndown (resulting in gas flows of 4600-1150 SCFH), which easily covers the remaining portion of Heat Zone testing. For these reasons, additional Heat Zone testing was deemed unnecessary at this juncture.

As mentioned, previous testing has shown turndown performance to be greatly aided by the use of a low-pressure air turndown lance. Therefore, all CH testing was completed with a cold air lance installed into the secondary air slot, providing 10% of the total nominal airflow. This value was held constant for all turndowns during testing.

For each test point in CH, once the furnace was at testing temperature, the burner was adjusted to the desired turndown at stoichiometric conditions. After the flow settings were set in correctly, test point data was collected. Static pressures, temperatures, differential pressures, and emission values were recorded by hand, with emissions also being collected via tracking software. Of note, since much less carbon monoxide was expected in CH, it was measured by the Rosemount Analytical Model 880A CO Analyzer in parts per million during testing. Video was also taken of the furnace chamber appearance along with handwritten notes.

5.2 Results of Tests

Extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 100% stoichiometric tests is provided in the Data Appendix Section 37. The following table summarizes the performance of the test burner when firing at 100% stoichiometric conditions.

BURNER TEST DATA: 100% STOICHIOMETRIC									
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO (ppm)	CO/CO ₂	DESIRED CO	DESIRED CO/CO ₂	COMMENTS
122008a	11,530	1,038	11.11	1.03	104.23	0	0	0	Acceptable flame appearance and stability.
122008b	5,755	527	10.92	2.04	4.46	0	0	0	Acceptable flame appearance and

									stability.
122008c	3,974	355	11.20	3.02	4.15	0	0	0	Acceptable flame appearance and stability.
122008d	3,072	281	10.95	3.82	4.15	0	0	0	Acceptable flame appearance and stability.
122008e	2,506	216	11.62	4.98	4.40	0	0	0	Acceptable flame appearance and stability.
122308a	1,817	179	10.17	6.01	1.71	0	0	0	Acceptable flame appearance and stability.
122308b	1,713	155	11.08	6.94	0.98	0	0	0	Acceptable flame appearance and stability.
122308c	1,407	125	11.25	8.58	0.98	0	0	0	Acceptable flame appearance and stability.

Exhibit 28: Burner test data: 100% stoichiometric.

Acceptable or Not Acceptable performance was determined by visual flame observation. An Acceptable flame was a flame that was properly anchored to the burner baffle or turndown lance with a stable appearance and no flashing or otherwise undesirable behavior.

The above table shows that flame appearance and stability all were found to be acceptable with the cold air turndown lance even at 8/1 turndown (12.5 % of nominal capacity). Further detailed data can be reviewed for 100% stoichiometric testing in Data Appendix Section 37. 3. For comparison sake, the lance was shut off once at 8/1 TD to highlight the improvement the turndown lance provided. Pictures of these firing conditions can be seen below. The turndown lance was on in the image displayed on the left hand side. left.

Exhibit 29: Burner firing and flame at turndown

5.3 Conclusions from Tests

The actual achieved turndown met the desired parameters at every point when the burner was operating at the expected charge zone firing ratio of 100% stoichiometric in a CH furnace. The

following Table provides the desired versus achieved turndown ratio of the test burner operating at 100% stoichiometric.

BURNER TURNDOWN 100% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	8

Exhibit 30: Burner turndown 100% stoichiometric.

6 60% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted and the test results and conclusions for the test burner operated at 60% stoichiometric conditions. The 60% stoichiometric conditions were requested after the original burner specification was developed and issued. This request was due to the possibility raised that 50% stoichiometric conditions may not quite have to be fully met for SFH, pending further research with test coupons. Additionally, testing with 50% stoichiometric had already proved to be unsuccessful at turndown conditions and it was thought 60% might provide much needed performance improvement.

6.1 Description of Tests

There was no specified operating ranges for the burner operating at 60% of stoichiometric so the testing consisted of the burner being re-rated for 50% stoichiometric gas flow with increased airflow to provide a 6/1 air/gas ratio (60% stoichiometric).

6.2 Results of Tests

Extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 60% stoichiometric tests is provided in Section 37. The following table summarizes the performance of the test burner when firing at 60% stoichiometric conditions.

BURNER TEST DATA: 60% STOICHIOMETRIC										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO	CO ₂	CO/CO ₂	DESIRE D CO	DESIRE D CO/CO ₂	COMMENTS
120407a	26,284	4,364	6.02	1.01	10.73	5.37	2.00	10.50	2.15	Acceptable and CO/CO ₂ ratio is good.
120407b	22,078	3,675	6.01	1.20	10.83	5.36	2.02	10.50	2.15	Acceptable and CO/CO ₂ ratio is good.
120407c	17,658	2,935	6.02	1.50	10.66	5.42	1.97	10.50	2.15	Acceptable and CO/CO ₂ ratio is good.
120407d	13,176	2,200	5.99	2.00	9.30	6.32	1.47	10.50	2.15	Marginal Chamber Appearance.

										CO/CO ₂ ratio is not acceptable
120407e	8,924	1,454	6.14	3.03	8.43	7.14	1.18	10.50	2.15	Not Acceptable, CO/CO ₂ ratio is not acceptable

Exhibit 31: Burner test data: 60% stoichiometric.

Acceptable or Not Acceptable performance was determined by flame observation, checking the Bacharach number of the flue gasses leaving the furnace and measuring the CO and CO₂ content of the flue gasses. Other work in Phase I and Phase II of the Project has determined that a CO content of about 10.5% and a CO/CO₂ ratio of about 2.2 is required in order to produce a 60% stoichiometric environment. Equilibrium calculations for Pittsburgh natural gas showed that an air to gas ratio of about 6/1 (about 60% stoichiometric) is required to achieve this.

The above Table shows that the CO level and CO/CO₂ ratio fell well short of the required values when the burner was turned down by more than about 1.5/1 (67% of nominal capacity). Review of the detailed data contained in Appendix 4 will provide other criteria regarding visual observations of flame shape and furnace flue gas Bacharach numbers that substantiates these Acceptable or Not Acceptable comments.

6.3 Conclusions from Tests

There is no specified turndown established for 60% stoichiometric at this time. As noted above, these test runs were requested in order to explore a situation where 50% stoichiometric was not completely necessary for SFH as well as providing a look at possible turndown improvement. The actual achieved turndown is well below that which would probably be required. Interestingly enough, turndown at 60% stoichiometric was not considerably improved over turndown at 50% stoichiometric, however, with both only achieving 1.5/1 turndown (67% of nominal capacity) successfully.

7 DISCUSSION AND RECOMMENDATIONS

The burner testing and demonstration results concluded that the burner fell well short of specified operating ranges for the 50%, 70% and 100% stoichiometric operating ranges required. Project Team discussions and meeting were held to determine future direction.

The Project Team is fairly confident that the operating range of the burner in all three stoichiometric ranges can be extended by additional testing and development of air and/or gas nozzle arrangement and sizing. However, such testing would take additional time and money and delay testing of other burner technology that needed to be explored in order to address the entire SFH potential market.

It was pointed out by Bloom that “pulse firing” could eliminate the need for the currently specified turndown ranges and if so, the existing burner may be applicable as is. “Pulse firing” utilizes the burner firing at maximum capacity all of the time and effects turndown by shutting the burner off in “pulses”. Bloom currently has multiple installations of pulse-fired Cyclops burners in soak zone applications.

It was considered that the top priority for testing and/or development of a SFH/CH had been given to the 1000°F preheated air burner for new furnaces based on the Phase I conclusions that this

technology had the best overall payback. Expectations of success were reinforced with the quotation from Bloom for a CH/SFH burner that met the burner specification while utilizing an existing ultra low NO_x burner series. But now the additional time needed to test and develop the burner further in order to extend its potential range of operation was questioned. Pulse firing was a consideration that could eliminate the need for the wider range of turndown and other burner technologies needed to be considered in order to address the retrofit market of SFH.

Phase I had identified a potential market for SFH of approximately 65 million tons per year of reheated steel in rebar, merchant, specialty and hot strip mills. But market considerations started in Phase I and completed early in Phase II concluded that less than 10% of this market would be in new furnaces with more than 90% being retrofit of existing furnaces from CH to CH/SFH. The economic studies completed in Phase I had also demonstrated the long term economic advantage of a preheated air, SFH burner that achieved SFH and CH combustion requirements without the aid of oxygen enrichment. The payback of a furnace designed with only preheated air was better than a furnace designed for a combination of preheated and oxygen enriched air that had the additional annual cost of oxygen. This background combined with Bloom's Proposal had indicated that such a burner was close at hand and the initial Burner Demonstration Task of Phase II had rightfully focused on this burner.

But preliminary economic studies in Phase I also indicted that preheated air combined with oxygen enrichment would most likely yield the best payback in retrofits where the existing furnace and auxiliary equipment footprint would preclude the ability to install the much larger recuperator and piping needed for a preheat air only burner. Even though the preheated, oxygen enriched air system had a higher monthly operating cost due to the cost of oxygen, the retrofit to SFH was possible and practical due to the compact nature of the burner and piping and the use of the existing recuperator system as is. Therefore, Phase II was started with the knowledge that a burner designed for CH/SFH utilizing preheated, oxygen enriched air also needed to be tested and/or developed in order to address the retrofit market.

Additional consideration of the retrofit market conducted in the early stages of Phase II soon pointed out that about 50% of the potential retrofit furnace market utilized flat flame burners in at least one zone of the furnace. This pointed to the need of a flat flame burner that could also meet the CH/SFH requirements of a furnace converted from CH to CH/SFH.

Therefore, three distinct burners have been identified in order to address the full range of expected furnaces and burners in the potential 65 MM ton per year market for SFH. The distinguishing characteristics of these burners are summarized in the following table.

SCALE FREE HEATING BURNER MARKET				
BURNER TYPE	COMBUSTION AIR	MARKET	% MARKET OF 65MM TPY	BURNER TEST/DEVELOP PRIORITY
Longitudinal	Preheated to 1000°F	New Furnaces	10%	1
Longitudinal	Exiting preheat (750°F) plus O2 Enrichment to 1000°F Equivalent	Retrofit	90%	2
Flat Flame	? TBD by Bloom	Retrofit	50% of 90%	3

Exhibit 32: Scale free heating burner market.

Based on the above, the Project Team concluded and recommended that the development/testing of the preheat air CH/SFH burner be terminated and this Report be written and issued.

Burner development/testing work would immediately be directed to the preheated air burner utilizing additional oxygen enriched air to achieve the required CH/SFH operating ranges.

A Burner Specification for this preheated air/oxygen burner would be issued to Bloom similar to the Burner Specification for the preheated air burner.

Appendix D: Oxygen Enriched Burner Report

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1 INTRODUCTION

During the early stages of Phase II, the project team spent a great deal of time reviewing the market analysis that began in Phase I and was subsequently completed as Phase II began. Markedly, the Phase I report had concluded that there was a potential SFH market of approximately 65 million tons per year of reheated steel in rebar, merchant, specialty, and hot strip mills. As the market analysis was concluded in greater detail at the onset of Phase II, however, the team became aware that in actuality, less than 10% of this market would be in new furnaces, with the remaining 90% of applications representing retro-fit installations. Further consideration also revealed that of this retrofit market, 50% involved flat flame burners in at least one zone. As a result, the team identified the need for three distinct burners in order to meet the total potential SFH market. In response to the new furnace market where preheat capabilities were expected to meet 1000°F, a hot air only longitudinal fired burner was chosen for development and was subsequently tested and reported upon in the Preheated Air Burner Report. In answer to non-flat flame burner retrofits, where preheat temperature capability was estimated at 750°F, the team chose an oxygen enriched longitudinal fired burner which is the main focus of this report. As for the remaining flat-flame installations, where preheat capability was also approximated around 750°F, the team settled on the third burner, an oxygen enriched flat flame design which is detailed in Appendix E.

The range of sizes for burners that are to be used on a reheat furnace to achieve both Conventional Heating (CH) and Scale Free Heating (SFH) was based on a typical state of the art, walking beam type reheat furnace described in the Phase I Final Report. The following sketch and table summarizes the range and size of burners required in the different zones for either CH or SFH.

CONVENTIONAL HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	187	84	41	312
% of total input =	60.0%	27.0%	13.0%	100%
Air/gas ratio =	10/1	10/1	10/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	10.4	4.7	1.9	
SCALE FREE HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	0	146	166	312
% of total input =	0.0%	46.7%	53.3%	100%
Air/gas ratio =		7/1	5/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	0.0	8.1	7.9	

Exhibit 1: Range and size of burners for CH or SFH

The basis of the % total input in each zone for either CH or SFH and the Air/gas ratio in each zone is discussed in detail in the Phase I Final Report. As also detailed in that write-up, the Phase I work assumed an air preheat of 1000°F would be required in order to achieve the desired 50% stoichiometric conditions. When the additional burners were identified for future

development in the early stages of Phase II, the expectations of retrofit preheater capability fell closer to 750°F as mentioned. The first approach taken by the team to account for the lower air preheat temperature was to oxygen enrich the combustion air to the point that the available heat of the enriched air matched that of 1000°F preheated air. However, as hot air burner testing was completed, it was observed that 1000°F preheated air was actually on the edge of acceptable SFH performance, as turndown performance was significantly worse than desired. With the previous testing in mind, it was decided by the project team to increase the level of oxygen enrichment to match the available heat of 1200°F preheated combustion air, which resulted in a combustion mixture oxygen content of 29.7% by volume. That is to say, a preheated, oxygen enriched air mixture of 750°F, 29.7% oxygen has an equivalent available heat to that of 1200°F preheated standard air. The above table was used in conjunction with this decision in order to generate the detailed burner specification sent to Bloom Engineering for their evaluation of a burner series that could achieve the wide range of operation required for CH and SFH. This specification is provided below.

Burner Specification Submitted to Bloom Engineering

SCALE FREE HEATING BURNER SPECIFICATION: PREHEATED, 29.7 %OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	26.022	3.233	7.924	3.692	20.016	2.487	6.095	3.692	3.336	415	1.016	3.692	SOAK	21	166
HEAT	35.084	4.359	8.089	4.876	26.987	3.353	6.222	4.876	4.497	559	1.037	4.876	HEAT	18	146
CHARGE	43.073	5.351	0	NA	33.134	4.116	0	NA	5.523	685	0	NA	CHARGE	0	0
													FURNACE	39	312

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: No burners are required for Charge Zone. Number of burners shown for Soak and Heat Zones are for both top and bottom heating zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

Percent Stoichiometric: Soak Zone Fired at 53% of Stoichiometric, Heat Zone at 70% Stoichiometric, Charge Zone Burndown to 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

CONVENTIONAL HEATING BURNER SPECIFICATION: PREHEATED, 29.7% OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	12.566	1.561	1.931	7.31	9.666	1.201	1.486	7.31	1.611	200	248	7.31	SOAK	21	41
HEAT	30.448	3.783	4.680	7.31	23.422	2.910	3.600	7.31	3.904	485	600	7.31	HEAT	18	84
CHARGE	67.662	8.406	10.400	7.31	52.048	6.466	8.000	7.31	8.675	1,078	1,333	7.31	CHARGE	18	187
													FURNACE	57	312

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Percent Stoichiometric: All zones fired at 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 2: Burner specification for conventional heating

As test burner sizing and installation were later examined by Bloom, however, further discussion with the project team concluded that oxygen enrichment would only be utilized during SFH firing for several reasons. First and foremost, by eliminating oxygen enrichment during conventional firing, the overall burner turndown requirements through SFH and CH would be greatly improved. Turndown performance, as stated previously, was a large concern based upon previous testing. Consequently, CH testing would be performed with 750°F combustion air only. Therefore, Bloom Engineering developed a corresponding Demonstration Burner Specification based upon the supplied Burner Specification, taking into account the reduced percentage of available heat (≈49%) associated with the non-enriched CH combustion air as compared to the original 29.7% O₂ enriched specification (≈57% available heat). The resulting specification was then ratified by the project team and is provided on the following page for review. It should be noted, at this point

however, that oxygen enriched CH is expected to actually be favorable in certain retrofits. As such, any required burner modifications associated with oxygen enriched CH firing will have to be reviewed and implemented on a case by case basis as the need arises in the future since there could be a concern of high NO_x emissions with the combination of preheated air and oxygen enrichment.

Demonstration Burner Specification Developed by Bloom Engineering

DEMONSTRATION BURNER SPECIFICATIONS: PREHEATED, 29.7% OXYGEN ENRICHED AIR													
MODE	ZONE	CONNECTED				DESIGN				TURNDOWN			
		AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G
SFH	SOAK	14,450	1,795	4,400	3.692	11,115	1,381	3,385	3.692	1,853	230	564	3.692
	HEAT	19,482	2,421	4,492	4.876	14,986	1,862	3,455	4.876	2,498	310	576	4.876
CH	SOAK	12,476	0	1,248	10	9,597	0	960	10	1,599	0	160	10
	HEAT	30,230	0	3,023	10	23,254	0	2,325	10	3,876	0	388	10
ZONE	MODE												
SOAK	SFH	14,450	1,795	4,400	3.692	11,115	1,381	3,385	3.692	1,853	230	564	3.692
	CH	12,476	0	1,248	10	9,597	0	960	10	1,599	0	160	10
HEAT	SFH	19,482	2,421	4,492	4.876	14,986	1,862	3,455	4.876	2,498	310	576	4.876
	CH	30,230	0	3,023	10	23,254	0	2,325	10	3,876	0	388	10

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Air and Gas Pressure: To be provided by Burner Supplier.

NO_x: Burners should be equivalent to BACT, say 0.05 lbs NO_x/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 3: Demonstration burner specification.

2 DESCRIPTION OF TESTS

The Project Team met and reviewed the Burner Specification that was submitted as the basis for burner testing. The general burner type to be tested, test furnace, and instrumentation was agreed upon and is described in detail in the following sections.

2.1 Test Burner

Based on the Burner Specification submitted, the Cyclops burner series was chosen as the prime candidate for implementation given the wide range of testing parameters. This burner series was originally created as an ultra low NO_x solution based on the concept of staged combustion. This concept is the scenario where total combustion is delayed through various methods such as air staging, which reduces NO_x as a result of the slow mixing and a natural internal furnace atmosphere re-circulation that tends to occur simultaneously. In order to achieve burner stability during furnace start-up and conditions below auto-ignition while balancing low emissions at higher furnace temperatures, the Cyclops burners are typically designed to vary air splits between primary and secondary airflows. A larger percentage of primary airflow during start-up and low temperature conditions provides for stronger flame anchoring and shape due to faster primary mixing. During high temperature conditions where flame stability is easier to maintain, the percentage of primary air can be reduced, thus delaying combustion and aiding in minimizing NO_x emissions.

These design characteristics aligned almost perfectly with the desired capabilities of the proposed oxygen enriched SFH burner. During SFH mode, a large percentage of enriched primary airflow provided for very rapid initial mixing of fuel and air, providing the best possible conditions for combustion to be completed while maintaining a satisfactory atmosphere without formation of soot. Due to absence of free oxygen in the SFH mode furnace atmosphere, NO_x formation was anticipated to be very low despite the increased oxygen-enriched primary airflow. During the proposed CH mode, the burner would then be able to switch over to the standard firing conditions

with a much lower percentage of non-enriched primary air, resulting in ultra low NO_x emissions. Additionally, the Cyclops burner has also been previously designed for stability down to 10:1 turndown with the addition of a turndown air lance. Given the need for extreme turndown, essentially down to 28:1 turndown based upon gas flow from the noted Burner Specification, this burner series was put into favorable consideration and was ultimately chosen for testing.

At the project onset, however, it was quickly realized that testing the burner as designed would not be practical due to the high input of the capacities specified (≈ 8 MMBtu/hr) and the resulting size of the test furnace and equipment. This was not viewed with much concern, though, as Bloom Engineering often encounters this situation in the highly variable combustion product market. Burners are usually designed with the interest of maintaining the ability to scale up or down in capacity in order to allow for such cases and to reduce application limitations of burner designs. In fact, the convention of scaling burners down for lab testing and research is a common practice and has shown to provide reliable results in a plethora of cases. Confident in prior scaling results, a standard 1610-013 Cyclops burner already appropriately sized for lab furnaces and located in the lab facilities was chosen as the test burner. Ultimately, the final burner configuration resulted in only two design variations from the original standard configuration in order to meet SFH firing atmosphere requirements. One change was the use of a 45° based gas nozzle, which was used in SFH firing in place of the standard CH axial design. The second modification involved the 50% reduction in primary air outlet area. Photographs of the final test burner can be seen below. Also, the resulting capacity scaling can be seen in the provided table below.

Exhibit 4: Final test burner.

SPECIFIED VERSUS TESTED BURNER SIZE		
ZONE @ % STOICHIOMETRIC	SPECIFIED (MMBtu/hr)	TESTED (MMBtu/hr)
SOAK @ 50% STOICHIOMETRIC	7.924	4.400
SOAK @ 105% STOICHIOMETRIC	1.931	1.248*

Exhibit 5: Specified vs. tested burner size.

**Value corrected for available heat variance due to non-enriched during CH.*

combustion air

It should be observed in the above table that the Heat Zone burner sizing has been omitted, which serves to highlight an important caveat of testing. From the start of longitudinal oxygen enriched SFH burner testing, the focus was largely on the Soak Zone burner since the desired parameters presented the worst-case scenario for turndown and flame appearance. For instance, a review of the Demonstration Burner Specification reveals a Soak Zone fuel turndown of 27.5 and combustion air turndown of 9.0 with non-enriched conventional heating. In comparison, the Heat Zone fuel turndown was a mere 11.6 with a combustion air turndown of only 5.0, resulting in much less overall restriction of the burner. Secondly, previous testing had verified that the Heat Zone burner stoichiometric ratio of 70% was much more forgiving than the more stringent 50% stoichiometric ratio associated with the Soak Zone burner. A review of the Preheated Air Burner Report records a realized turndown of 3:1 turndown for the Heat Zone burner compared to a turndown of 1.5:1 for the Soak Zone burner despite nearly identical burner dimensions. Additionally, no stability issues were reported as a result of the slightly higher fuel and air flows associated with the Heat Zone burner. Regarding CH, the vast majority of Heat Zone burner turndown points were in fact, an overlap of the Soak Zone turndown points as seen in the table below.

Comparison of Heat Zone and Soak Zone Firing Rates - CH Testing									
TD		1	2	3	4	5	6	7	8
HEAT ZONE	NATURAL GAS (scfh)	3,023	1,511	1,008	756	605	504	432	378
SOAK ZONE	NATURAL GAS (scfh)	1,248	624	416	312	250	208	178	156

Exhibit 6: Comparison of heat zone and soak zone firing rates; CH testing.

Due to this overlap, only conventional heating nominal firing and 2:1 turndowns would be left unexplored. Further supporting their exclusion, the test burner was originally designed as a 4.6 MMBtu/Hr capacity burner to be fired at 10.5 or 11 air to fuel ratio (non-enriched). Testing completed as of August 2004 with a cold air turndown lance stated that this burner was stable at nominal conditions through 4:1 turndown (resulting in gas flows of 4600-1150), which easily covered the remaining portion of CH Heat Zone testing. Aside from this, the high turndown required during testing resulted in carefully selected orifice runs in order to maintain proper resolution throughout the setting range. This meant that once the burner was set up for CH testing for the Soak Zone, it was not possible to obtain Heat Zone flow values. Upon considering all of these factors as well as project time constraints, the team chose to simply gather complete data for the Soak Zone burner and forgo Heat Zone burner testing.

As an additional note on the selected test burner, previous testing had indeed indicated that turndown performance was greatly improved by the use of a low-pressure air turndown lance during conventional heating. Therefore, all burner testing was completed with a cold air lance installed into the secondary air slot, providing approximately 10% of the total nominal airflow (based on CH). The lance airflow was held constant for all turndowns during testing.

Finally, the team also agreed on a slight deviation for the lab tested demonstration burner. As installation of the major burner air piping was completed and the oxygen injection method was

being mapped out, it became obvious that dual controls for oxygen flow to the separate secondary and primary air lines was not feasible either for control or proper monitoring. Upon inspecting the test burner air splits, it was observed that approximately 10% of nominal airflow was dedicated for the low-pressure air lance as mentioned. Of the remaining combustion air, 95% was dedicated to the primary air line during SFH. After reviewing all options, the project team agreed to simply inject the full oxygen flow exclusively into the primary airline, resulting in a desired air mixture oxygen content of 30.7%. It was felt that this relatively minor variation was not significant enough to overtly affect the resulting test data and was therefore implemented during all SFH testing detailed in this report.

2.2 Furnace Facility

The test furnace chosen for this project was done so for a variety of reasons. First of all, there were two fairly large preheaters setup in the lab facility that were originally designed to provide hot combustion air to several furnaces for various testing needs. Either preheater was capable of providing the required preheat temperature of 750°F, but the designated furnace needed to be located as close as possible to one of them in order to minimize heat losses in the piping. Secondly, the furnace had to be large enough to accommodate a 4.492 MMBtu/Hr burner, yet small enough that the furnace could be heated to testing temperatures of 2200°F -2300°F in a reasonable amount of time as well as providing for positive furnace pressure. Thirdly, and perhaps most importantly, since the excess gas input during SFH had to be burned down outside the chamber, a refractory lined flue was desired to prevent excessive damage to the flue stack.

Given these parameters, the 4ft. Lab Furnace became the clear choice. This furnace is a cylindrical furnace 4' in diameter and 12' long internally, with external dimensions of 5.5' diameter and 13.5' long. As stated, the furnace made use of a refractory lined flue stack that extended outside of the main lab enclosure.

Exhibit 7: Bloom Laboratory furnace used for testing .

A port for the insertion of a water-cooled emissions probe was located on the flue just after the junction with the furnace. Additional ports were located on the side of the furnace facing the center of the lab and these were used to collect Bacharach smoke data during testing.

Exhibit 8: Ports used to collect Bacharach smoke data.

Air, gas, and oxygen flows were controlled manually through high temperature butterfly valves on the air lines and a ball valve on the gas and oxygen lines. Flows were accordingly manipulated by trimming each valve as necessary. Each trim valve was installed downstream of an orifice run, which was the chosen method of setting and measuring various flows via static and differential pressures. The oxygen flow was injected into the combustion air after the preheater via hose connection and a high velocity stainless steel nozzle which mounted into a sufficiently long vertical piping run to promote uniform mixing as confirmed through CFD development.

Exhibit 9: Piping arrangement

In order to measure furnace temperature accurately, eight ceramic-shielded Type K thermocouples were evenly spaced along the side of the furnace facing the lab wall. These not only provided local furnace temperatures, but also allowed for an average furnace temperature to be easily surveyed. Additional unshielded Type K thermocouples were installed into the primary and secondary air lines to monitor air preheat accurately.

Exhibit 10: Temperature measurement

Viewing windows were found on the lab-inward side of the furnace as well as the end of the furnace. These viewing ports allowed for visual observance of flame appearance as well as collection of video and photographic data.

Exhibit 11: Viewing ports.

As mentioned previously, a single preheater furnace was run in order to meet the 750°F air preheat required for SFH testing. Pictures of the furnace can be seen below.

Exhibit 12: Air preheater furnace.

In order to provide for the actual burn down of the excess fuel during SFH, a large pilot was installed at the top of the flue stack. When actually in SFH, this pilot was lit via spark igniter and provided a source of flame for the fuel and other products of combustion exiting the stack. Located opposite this pilot was the flue damper controller, which allowed the flue to be open or closed to create proper furnace pressure during testing. As a final note on the furnace equipment, a schematic detailing the arrangement of the preheaters, test furnace, burner, gas controls, and air controls can be found following the pilot and flue controller photographs.

Exhibit 13: Pilot for furnace flue gases

Exhibit 14: Tests schematic L1300 – setup 1610-013 Cyclops burner.

2.3 Instrumentation

The test furnace instrumentation includes a large variety of items and is perhaps best discussed via column-by-column review of the Test Data Sheet provided in Section 44. below. The primary, secondary, and lance air columns are identical in nature and will be discussed first.

Primary, Secondary, & Lance Air

- *Run* – This column serves a dual purpose in providing an identification number for each data point while also keeping the test date readily visible. The format was simply the date of testing followed by alphanumeric coding in chronological order regarding test points taken the same day.
- *S.P. @ Orifice; "Hg* – This column represents the upstream static pressure of the pre-heated air in inches of mercury. This data was collected at the upstream side of the corresponding (Primary/Secondary) orifice run by Meriam Instrument U-Tube Mercury Manometers scaled in 0.1" Hg.
- *Temp. @ Orifice; °F* – This column provides the preheated air temperature in degrees Fahrenheit. This data was collected just after the orifice runs and right before the burner via Omega Type-K Unshielded Thermocouples as mentioned previously.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the respective (Primary/Secondary) orifice plate in inches of water column. This data was recorded across the orifice by a panel of inclined oil manometers due to improved resolution of 0.01" W.C. below 2.00" W.C., in comparison to the Meriam Instrument's U-Tube Water and/or Oil Manometer design scaled in 0.1" W.C. throughout the entire scale range. Due to limited inclined manometer availability, however, lance airflow data was monitored by the aforementioned U-Tube Manometer product.

Exhibit 16: Instruments used for testing

- *Q; SCFH* – This column represents the real-time actual airflow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using orifice plates designed and calibrated by Bloom.
- *S.P. @ Burner; "W.C.* – Data in this column refers to the static pressure of the air right at the burner inlets and is given in inches of water column. These values represent the pressure drop across the burner. This data is provided by Meriam Instrument U-Tube Water Manometers.

Oxygen

- *Run* – This column remains the same as previously discussed with Primary and Secondary Air.
- *S.P. @ Orifice; psig* – This column represents the upstream static pressure of the O_2 in pounds per in². This data was collected at the upstream side of the orifice run by a US Gauge 0-100 psig pressure gauge scaled in 2 psig increments.
- *Temp. @ Orifice; °F* – This column provides the O_2 temperature in degrees Fahrenheit. This data was collected just after the orifice run via a Weksler Instruments 20-240°F temperature gauge marked in 2°F increments.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the O_2 orifice plate in inches of water column. This data was recorded across the orifice by a Meriam Instrument U-Tube Water Manometer scaled in 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual oxygen flow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using an orifice plate designed and calibrated by Bloom.
- *% O_2 in Line* – This column represents the percent by volume of oxygen in the primary combustion air line. This data was recorded just before the burner intake by a NTRON Model C5 % O_2 Analyzer, which displayed % O_2 to a tenth of a percent.

Natural Gas

- *Run* – This column remains the same as previously discussed with Primary and Secondary Air.
- *S.P. @ Orifice; psig* – This column represents the upstream static pressure of the fuel in pounds per in². This data was collected at the upstream side of the orifice run by a Reotemp 0-30 psig pressure gauge scaled in 0.5 psig increments.
- *Temp. @ Orifice; °F* – This column provides the natural gas temperature in degrees Fahrenheit. This data was collected just before the orifice run via a Weksler Instruments 20-240°F temperature gauge marked in 2°F increments.

- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the gas orifice plate in inches of water column. This data was recorded across the orifice by a Meriam Instrument U-Tube Water Manometer scaled in 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual natural gas flow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using an orifice plate designed and calibrated by Bloom.
- *S.P. @ Burner; psig* – Values in this column refer to the static pressure of the natural gas right at the burner inlet and is given in pounds per in². These results indicate the pressure drop across the gas nozzle. This data is provided by a US Gauge 0-30 psig pressure gauge scaled in 1.0 psig increments.

Emissions – All emissions samples were taken via a water-cooled stainless steel emissions probe connected to a pump station and water chiller regulated down to 12 psig output. Images of this setup can be seen below. The emission samples were then pumped into a control room where they were sent through a Drierite-filled canister before being sent to individual analyzers that are described in greater detail below. This setup allowed for all of the moisture to be removed from the flue gas before reaching the analyzers, resulting in all readings and measurements being taken on a "dry" basis. The analyzers themselves output analog signals, which are then picked up by Bloom's computer software for visual display and trend recording.

Exhibit 17: Sampling probe arrangement

- *Run* – This column remains the same as previously discussed.
- *Furnace Temp.; °F* – This column expresses the average furnace temperature in °F for the specific test point. The average is taken from the eight-shielded thermocouples discussed under Furnace Facility.
- *NOx; ppm* – Data in this column displays the Nitrous Oxide emissions in parts per million. This was provided by a Rosemount Analytical Model 951A NO/NOx Analyzer set on 0-100 ppm range resulting in +/- 5.0 ppm error.
- *CO; ppm* – This column represents the Carbon Monoxide emissions in parts per million, which was the preferred scale for furnace warm-up and CH. This data was provided by a Rosemount Analytical Model 880A CO Analyzer with a 0-5000 ppm range resulting in +/- 20.5 ppm error.
- *% O2* – Data in this column displays the Oxygen content of emissions based upon volumetric percentage, which was the preferred scale during furnace warm-up and CH. This data was provided by a Teledyne Brown Engineering Portable Oxygen Analyzer.
- *% CO* – This column presents the Carbon Monoxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.

- **% CO₂** – This column presents the Carbon Dioxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.
- **CO/CO₂ Ratio** – This column displays the ratio of the recorded Carbon Monoxide emissions to the corresponding data point's Carbon Dioxide emissions.
- **Desired CO/CO₂ Ratio** – This column presents the corresponding desired emissions ratio for the particular test point being reviewed. Review of this number allows for a triple-check on the burner settings versus complete combustion during SFH testing.
- **Smoke #** – Data in this column displays the smoke number results of the Bacharach Smoke Test during SFH. This test was performed with a handheld pump used to draw flue emissions across special filter paper that left a darkened circle. This darkened circle was then measured against a Bacharach provided scaling to develop a smoke number. Smoke test results that were even darker than the highest scale value of 9 were rated a 9+ simply to provide a way to make note of such a scenario. This testing is a common method of checking the amount of soot produced during firing. However, if the emissions are drawn too close to flame, they often present higher scale readings than actually experienced. Photos of the Bacharach Smoke Testing equipment and scale can be seen on the following page.

Exhibit 18: Bacharach smoke testing equipment.

- **Calculated TD** – Values displayed in this column display the data point's actual turndown. This is calculated from the burner's nominal gas flow rating and the actual gas flow recorded.
- **Desired TD** – This column presents the data points desired turndown, which was used when setting in airflow and gas flow differential pressure values.
- **Calculated AFR** – Values in this column present the actual air to fuel ratio experienced based upon the flow results calculated from orifice data. This data served as a check against desired flow rates and settings.
- **Desired AFR** – This column displays the desired air to fuel ratio for a data point.
- **Chamber Appearance** – These values show the visual review of the furnace chamber appearance. Acceptable notes were given to points where the chamber remained relatively clear, allowing a view of burner components on the opposite chamber wall.
- **NO_x; Lbs/MMBtu** – This data column shows the NO_x emissions in pounds per million Btu. These values were corrected based upon the %O₂ and NO_x (ppm) results during CH and the calculated PFR, NO_x (ppm), and oxygen enrichment during SFH.

2.4 50% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted, the test results and conclusions for the test burner operated at the specified 50% stoichiometric conditions.

2.5 Description of Tests

The burner was operated at the specified 50% stoichiometric ratio, which would be the expected conditions for burners in the soak zone of a furnace that was operated under SFH conditions.

The specified versus the tested operating conditions for a burner in the soak zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: SOAK ZONE														
BURNER FOR	CONNECTED				DESIGN					TURNDOWN				
	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D
FURNACE	26,022	3,233	7,924	3.69	20,016	2,487	6,095	3.69	1.3	3,336	415	1,016	3.69	7.8
TESTED	14,450	1,795	4,400	3.69	11,115	1,381	3,385	3.69	1.3	1,853	230	564	3.69	7.8

Exhibit 19: Burner specification/testing: soak zone.

Each day, prior to actual recording of data, all emissions equipment was calibrated, the pre-heated air furnace was brought up to proper temperature, and the test furnace was lit off and brought to the specified operating temperature. Initial furnace warm-up was achieved by firing the test burner at or near stoichiometric conditions without oxygen enrichment.

For each test point in SFH, the burner was first adjusted to the corresponding turndown at stoichiometric conditions with oxygen enriched combustion air. This allowed for the desired air and oxygen flows to be set in prior to venturing into SFH, as well as providing a check on emission oxygen content against the flow settings, ensuring air and fuel flows followed the developed settings. The gas flow was then increased to SFH values. A few examples of the stoichiometric to SFH transition can be seen in the following table.

STOICHIOMETRIC TO SFH TRANSITION (50% STOICHIOMETRIC VALUES)								
T D	STOICHIOMETRIC				SFH			
	PRIMARY AIR (scfh)	OXYGEN (scfh)	SECONDARY AIR (scfh)	NATURAL GAS (scfh)	PRIMARY AIR (scfh)	OXYGEN (scfh)	SECONDARY AIR (scfh)	NATURAL GAS (scfh)
1	12,657	1,795	666	2,095	12,657	1,795	666	4,400

2	5,793	898	305	1048	5,793	898	305	2,200
3	3,505	598	184	698	3,505	598	184	1,467

Exhibit 20: Stoichiometric to SFH transition (50% stoichiometric values)

Once the flow settings were at 50% stoichiometric conditions, test point data was collected. Static pressures, temperatures, differential pressures, and emission values were recorded by hand, with emissions also being collected via tracking software. Video was also taken of the furnace chamber appearance along with handwritten notes. The Bacharach probe was inserted into a side port and pumped accordingly to develop a smoke number for the test point. With all data collected, the burner was then taken back to stoichiometric conditions in preparation of the next test point.

2.6 Results of Tests

As described, extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 50% stoichiometric tests is provided in Section 44. The following table summarizes the performance of the test burner when firing at 50% stoichiometric conditions.

BURNER TEST DATA: 50% STOICHIOMETRIC											
R U N	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A/ G	T/D	%CO	%CO ₂	CO/C O ₂	DESIRE D %CO	DESIRE D CO/CO ₂	COMMENTS
11 14 08 b	14,869	1,660	4,62 1	3.5 8	0.9 5	17.51	5.22	3.35	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.
11 14 08 c	11,046	1,241	3,30 8	3.7 1	1.3 3	17.15	5.60	3.06	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.
11 14 08 d	7,335	845	2,35 0	3.4 8	1.8 7	16.54	5.97	2.77	17.0	3.2	Not Acceptable, CO/CO ₂ ratio is not acceptable.

Exhibit 21: Burner test data: 50% stoichiometric.

Acceptable or Not Acceptable performance was determined by flame observation, checking the Bacharach number of the flue gases leaving the furnace and measuring the CO and CO₂ content of the flue gasses. Other work in Phase I and Phase II of the Project had determined that a CO content of about 17.0% and a CO/CO₂ ratio of about 3.2 is required in order to prevent forming scale in the soak zone of a reheat furnace with oxygen enriched (29.7% by volume) 750°F preheated combustion air. Equilibrium calculations for Pittsburgh natural gas showed that an air to gas ratio of about 3.69/1 (about 50% stoichiometric) was required to achieve this.

The above Table shows that the CO level and CO/CO₂ ratio began to fall short of the required values when the burner was turned down by more than about 1.33/1 (75% of nominal capacity). Review of the detailed data contained in Appendix 1 will provide other criteria regarding visual observations of flame appearance and furnace flue gas Bacharach numbers that substantiates these Acceptable or Not Acceptable comments.

Recording and observing the CO/CO₂ ratio and the Bacharach number provided crucial information as to the actual burner performance. The recorded air to gas ratio only substantiated that the burner was firing at the required 3.69/1 air/gas ratio. There were times when the furnace chamber looked acceptable and the air/gas ratio was correct but the CO/CO₂ ratio was below equilibrium values. This indicated that the combustion reaction did not achieve equilibrium at these points. Methane and/or free carbon were actually present in the flue gasses and the CO/CO₂ ratio was therefore lower than expected. Typically at these same conditions, the Bacharach number was very high proving the existence of pure soot.

2.7 Conclusions from Tests

The actual achieved turndown resulting in an acceptable atmosphere was well below the desired point when the burner was operating at the expected soak zone firing ratio of 50% stoichiometric. The following Table provides the desired versus successful turndown ratio of the test burner operating at 50% stoichiometric.

BURNER TURNDOWN 50% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	1.33

Exhibit 22: burner turndown 50% stoichiometric.

The required turndown level of 7.8/1 is only the turndown level needed when the burner is operating in the soak zone of a furnace that is being operated in SFH conditions. It must be remembered that the same burner has to also be operated as a conventional burner firing at stoichiometric conditions whenever the furnace is being operated in CH conditions. This actually increases the overall turndown level of the burner a great deal. By referring to the Demonstration Burner Specification, the overall turndown of a burner that is used in the soak zone of a furnace that has to run as either a CH furnace without oxygen enrichment or as a SFH furnace with oxygen enrichment can be determined. This is summarized in the following table.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	4.400 MMBtu/HR
MINIMUM SFH RATE	0.564 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	1.248 MMBtu/HR
MINIMUM CH RATE	0.160 MMBtu/HR
CH TURNDOWN	7.8

OVERALL SFH to CH TURNDOWN	27.50
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Exhibit 23: Soak zone burner turndown.

Therefore, the total performance level of the soak zone burner cannot be completed until the same burner is operated in the CH mode over the specified range for that mode. The performance results of the burner operating in the CH mode, that is the 100% stoichiometric mode, is covered in the following section of this report.

3 100% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted and the test results and conclusions for the test burner operated at the specified 100% stoichiometric conditions.

3.1 Description of Tests

The burner was operated at the specified 100% stoichiometric ratio, which would be the expected conditions for burners in the soak zone of a furnace that was operated under CH conditions. The specified versus the tested operating conditions for a burner in the soak zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: STOICHIOMETRIC SOAK ZONE														
BURNER FOR	CONNECTED				DESIGN					TURNDOWN				
	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D
FURNACE	12,566	1,561	1,931	7.31	9,666	1,201	1,486	7.31	1.3	1,611	200	248	7.31	7.8
TESTED	12,476	0	1,248*	10	9,597	0	960*	10	1.3	1,599	0	160*	10	7.8

Exhibit 24: burner specification/testing: stoichiometric soak zone.

**Values corrected for available heat variance due to non-enriched combustion air during CH.*

At the onset of CH testing, the project team came to the realization that modification testing resulting from SFH performance requirements of the oxygen-enriched burner had left little additional testing time if a flat-flame burner was to also be explored. In response to the impending project deadline, Bloom Engineering carefully reviewed the current status of CH testing requirements as well as burner configuration. As mentioned previously, the final oxygen enriched SFH burner configuration resulted in a modified 45° based gas nozzle instead of the standard axial design as well as a 50% reduction in the primary port air outlet. Realistically, a conventional firing of the burner with all components as tested for SFH would have been possible. While the primary port reduction was considered to be of little or no concern due to the almost negligible primary airflow during the conventionally fired Cyclops mode, the gas nozzle posed a

possible detriment to the desired Ultra Low NO_x performance. Upon consideration of all alternatives, Bloom decided that testing would proceed with an initial nominal NO_x trend in order to define the modified gas nozzle's impact on NO_x emissions. If NO_x performance remained acceptable, a full run of turndown testing would be completed with the modified gas nozzle and the burner would be finalized as tested for SFH. However, if NO_x emissions were found to be unacceptably compromised, this meant that the final burner configuration would result in the addition of a separate axial gas feed to be utilized only during conventional firing conditions.

This second scenario would essentially end testing for several reasons. First and foremost, the rapidly approaching project deadline made the design and installation of the separate axial feed impossible if flat flame burner testing were to be explored at all. As discussed in the report Introduction, flat flame burners actually composed 50% of the retrofit market, meriting at least initial design and testing consideration, especially considering how close to a final design the oxygen enriched longitudinal burner already was.

Secondly, the axial gas feed design would certainly be based off the 1000°F Hot-Air-Only Burner design already reported on since the testing requirements were nearly identical for both burners in non-enriched CH as seen in the table below.

BURNER SPECIFICATION / TESTING: STOICHIOMETRIC SOAK ZONE														
BURNER FOR	CONNECTED				DESIGN					TURNDOWN				
	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D
TESTED HOT-AIR ONLY	10,725	0	1,073	10	8,250	0	825	0	1.3	1,375	0	138	10	7.8
TESTED O2 ENRICHED	12,476	0	1,248*	10	9,597	0	960*	10	1.3	1,599	0	160*	10	7.8

Exhibit 25: Burner specification/testing: stoichiometric soak zone.

Notably, the vast majority of burner turndown would in fact be an overlap of previously tested points. Coinciding with this, as detailed in the Preheated Air Burner Report, the 1000°F Hot-Air Only design operated exactly as desired during CH, with turndown capability of 8:1 being obtained easily. It is fully expected that basing the additional feed line off of the Hot-Air Only design would result in nearly identical, if not improved emission results due to the lower combustion air preheat temperature (750°F versus 1000°F). It is also expected that flame stability would be maintained throughout the range of testing completed for the Hot-Air Only Burner design. Due to this overlap, only the nominal CH firing point would be left unexplored. However, as outlined in the report section Test Burner, there was little concern in excluding this test point as with the heat zone burner testing in its entirety. A review of this section is recommended at this point, but as a reminder the following excerpt has been repeated for convenience.

“...the test burner was originally designed as a 4.6 MMBtu/Hr capacity burner to be fired at 10.5 or 11 air to fuel ratio (non-enriched). Testing completed as of August 2004 with a cold air turndown lance stated that this burner was stable at nominal conditions through 4:1 turndown (resulting in gas flows of 4600-1150), which easily covered the remaining portion of CH Soak Zone testing.”

Finally, the concept of mode-specific gas feeds is a commonly implemented solution utilized by Bloom Engineering throughout a variety of applications. Due to Bloom's extensive experience with the design and installation of this type of apparatus, it was felt there was no particular challenge in the development of a production design that would reinstate the burner's Ultra Low NOx capabilities if necessary.

With this decision in mind, nominal NOx trend testing was completed first. Once the furnace was at operating temperature, the burner was taken to nominal Cyclops firing settings. After the flow settings were set in correctly, test point data was collected over a range of furnace temperatures. Static pressures, temperatures, differential pressures, and emission values were recorded by hand, with emissions also being collected via tracking software. Of note, since much less carbon monoxide was expected in CH, it was monitored by the Rosemount Analytical Model 880A CO Analyzer in parts per million during testing. Video was also taken of the furnace chamber appearance along with handwritten notes.

3.2 Results of Tests

Extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 100% stoichiometric tests is provided in Section 44. The following table summarizes the performance of the test burner when firing at 100% stoichiometric conditions.

BURNER TEST DATA: 100% STOICHIOMETRIC 45° NOZZLE ONLY										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO (ppm)	CO/CO ₂	NO _x (#/MMBtu)	DESIRE D CO/CO ₂	Furnace Temp. (°F)	COMMENTS
021009d	12,475	1,171	10.65	1.07	4.88	0	0.0662	0	1,873	Acceptable flame appearance and stability. NOx performance Not Acceptable.
021009e	12,570	1,170	10.74	1.07	4.88	0	0.0666	0	1,922	Acceptable flame appearance and stability. NOx performance Not Acceptable.
021009g	12,534	1,162	10.79	1.07	4.88	0	0.0648	0	2,076	Acceptable flame appearance and stability. NOx performance Not Acceptable.

Exhibit 26: Burner test data: 100% stoichiometric 45° Nozzle only.

Acceptable or Not Acceptable flame appearance was determined by visual flame observation. An Acceptable flame was a flame that was properly anchored to the burner baffle or turndown lance with a stable appearance and no flashing or otherwise undesirable behavior. Acceptable or Not Acceptable NO_x performance was based upon the Phase I developed requirement of 0.05 #/MMBtu during nominal firing conditions. Acceptable performance was, of course, NO_x emissions that were less than or equal to the chosen basis.

The above table shows that flame appearance and stability were all found to be acceptable with the 'as tested' SFH configuration. However, NO_x performance was found to be significantly impacted by the modified gas nozzle. Further detailed data can be reviewed for 100% stoichiometric testing in Section 44.

3.3 Conclusions from Test

The 45° based gas nozzle was found to negatively impact NO_x performance to an unacceptable level, thus resulting in the need for a separate CH axial gas feed line as discussed previously and in effect concluding 100% stoichiometric testing. To reiterate, the axial feed to be designed and utilized in a production version of the test burner would be largely based upon the 1000°F Hot-Air-Only burner design previously reported on. As detailed in the Preheated Air Burner Report, the Hot-Air-Only Burner performed with positive results in all related CH testing and it is fully expected that basing the separate feed line on this design will yield nearly identical, if not slightly improved results. For convenience, the 1000°F Hot-Air-Only Burner test data is provided below for reference.

BURNER TEST DATA: 100% STOICHIOMETRIC HOT-AIR-ONLY BURNER										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO (ppm)	CO/CO ₂	NO _x (#/MMBtu)	DESIRED CO/CO ₂	Furnace Temp. (°F)	COMMENTS
122008a	11,530	1,038	11.11	1.03	104.23	0	0.0237	0	2,100	Acceptable flame appearance and stability. NO _x performance Acceptable .
122008b	5,755	527	10.92	2.04	4.46	0	0.0201	0	1,992	Acceptable flame appearance and stability. NO _x performance Acceptable .
122008c	3,974	355	11.20	3.02	4.15	0	0.0260	0	1,910	Acceptable flame appearance and stability. NO _x performance Acceptable .
122008d	3,072	281	10.95	3.82	4.15	0	0.0204	0	1,862	Acceptable flame appearance and stability. NO _x performance Acceptable .
122008e	2,506	216	11.62	4.98	4.40	0	0.0276	0	1,828	Acceptable flame appearance and stability. NO _x performance Acceptable .
122308a	1,817	179	10.17	6.01	1.71	0	0.0594	0	1,899	Acceptable flame appearance and stability. NO _x performance Not Acceptable , but unimportant due to turndown.
122308b	1,713	155	11.08	6.94	0.98	0	0.0709	0	1,812	Acceptable flame appearance and stability. NO _x performance Not Acceptable , but unimportant due to turndown.
122308c	1,407	125	11.25	8.58	0.98	0	0.0756	0	1,836	Acceptable flame appearance and stability. NO _x performance Not Acceptable , but unimportant due to turndown.

Exhibit 27: Burner test data: 100% stoichiometric hot air only burner.

Further regarding the 1000°F Hot-Air-Only Burner design, the burner met all desired turndown parameters as previously described at the expected charge zone firing ratio of 100% stoichiometric in a CH furnace. The following Table has been reproduced in order to detail the 1000°F Hot-Air-Only burner achieved versus desired turndown ratio results.

BURNER TURNDOWN 100% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	8

Exhibit 28: Burner turndown 100% stoichiometric.

4 DISCUSSION AND RECOMMENDATIONS

The burner testing and demonstration results concluded that the burner fell well short of specified operating ranges for the 50% and 100% stoichiometric operating ranges required. Project Team discussions and meeting were held to determine future direction.

The Project Team is fairly confident that the operating range of the burner in all three stoichiometric ranges (including Heat Zone conditions) could be extended by additional testing and development of air and/or gas nozzle arrangement and sizing. However, such testing would have taken additional time and money and delay testing of other burner technology that needed to be explored in order to address the entire SFH potential market as previously discussed.

It was pointed out by Bloom Engineering that “pulse firing” could be used to eliminate the need for the currently specified turndown ranges and as a result, the existing burner could be considered applicable as is, which was similarly concluded for the 1000°F Hot-Air-Only Burner design. “Pulse firing” utilizes the burner firing at maximum capacity all of the time and effects turndown by shutting the burner off in “pulses”. Bloom currently has multiple installations of pulse-fired Cyclops burners in soak zone applications.

It was considered that the top priority for testing and/or development of a SFH/CH burner had been originally given to the 1000°F preheated air burner for new furnaces based on the Phase I conclusions that this technology had the best overall payback. Expectations of success were reinforced with the quotation from Bloom for a CH/SFH burner that met the burner specification while utilizing an existing ultra low NO_x burner series. But the additional time needed to test and develop the 1000°F Hot-Air-Only burner further in order to extend its potential range of operation was eventually questioned. Pulse firing was a consideration observed that would effectively eliminate the need for the wider range of turndown and other burner technologies needed to be considered in order to address the retrofit market of SFH.

As a reminder, Phase I had identified a potential market for SFH of approximately 65 million tons per year of reheated steel in rebar, merchant, specialty and hot strip mills. But market considerations started in Phase I and completed early in Phase II concluded that less than 10% of this market would be in new furnaces with more than 90% being retrofit of existing furnaces from CH to CH/SFH. The economic studies completed in Phase I had also demonstrated the long term economic advantage of a preheated air, SFH burner that achieved SFH and CH combustion requirements without the aid of oxygen enrichment. The payback of a furnace designed with only preheated air was better than a furnace designed for a combination of

preheated and oxygen enriched air that had the additional annual cost of oxygen. This background combined with Bloom's Proposal had indicated that such a burner was close at hand and the initial Burner Demonstration Task of Phase II had rightfully focused on this burner.

But, again, preliminary economic studies in Phase I also indicted that preheated air combined with oxygen enrichment would most likely yield the best payback in retrofits where the existing furnace and auxiliary equipment footprint would preclude the ability to install the much larger recuperator and piping needed for a preheat air only burner. Even though the preheated, oxygen enriched air system had a higher monthly operating cost due to the cost of oxygen, the retrofit to SFH was possible and practical due to the compact nature of the burner and piping and the use of the existing recuperator system as is. Therefore, Phase II had rightfully continued on with the design and testing of the required longitudinal burner for CH/SFH utilizing preheated, oxygen enriched air as focused upon in this report.

It should not be forgotten, however, that analysis of the retrofit market conducted in the early stages of Phase II also pointed out that about 50% of the potential retrofit furnace market utilized flat flame burners in at least one zone of the furnace. This statistic emphasized the additional need for a flat flame burner that could also meet the CH/SFH requirements of a furnace converted from CH to CH/SFH.

As a result, two of the three distinct burners identified had been accordingly developed and tested to an acceptable level of production viability, leaving the flat flame burner development as the highest project priority remaining. For convenience and review, the distinguishing characteristics of all three burners are summarized in the following table.

SCALE FREE HEATING BURNER MARKET				
BURNER TYPE	COMBUSTION AIR	MARKET	% MARKET OF 65MM TPY	BURNER TEST/DEVELOP PRIORITY
Longitudinal	Preheated to 1000°F	New Furnaces	10%	1
Longitudinal	Exiting preheat (750°F) plus O2 Enrichment to 1200°F Equivalent	Retrofit	50% of 90%	2
Flat Flame	Exiting preheat (750°F) plus O2 Enrichment to 1200°F Equivalent	Retrofit	50% of 90%	3

Exhibit 29: Scale free heating burner market.

Based on the above, the project team concluded and recommended that the development/testing of the preheated oxygen-enriched CH/SFH burner be terminated and this report be written and issued. Burner development/testing work would immediately be directed to the flat flame burner also utilizing preheated oxygen enriched air to achieve the required CH/SFH operating ranges. A Burner Specification for this burner would be largely based off of the Burner Specification already provided for the longitudinal oxygen-enriched preheated air burner.

Appendix E: HTR Burner Report

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1 INTRODUCTION

During the early stages of Phase II, the project team spent a great deal of time reviewing the market analysis that began in Phase I and was subsequently completed as Phase II began. Markedly, the Phase I report had concluded that there was a potential SFH market of approximately 65 million tons per year of reheated steel in rebar, merchant, specialty, and hot strip mills. As the market analysis was concluded in greater detail at the onset of Phase II, however, the team became aware that in actuality, less than 10% of this market would be in new furnaces, with the remaining 90% of applications representing retro-fit installations. Further consideration also revealed that of this retrofit market, 50% involved flat flame burners in at least one zone. As a result, the team identified the need for three distinct burners in order to meet the total potential SFH market. In response to the new furnace market where preheat capabilities were expected to meet 1000°F, a hot air only longitudinal fired burner was chosen for development and was subsequently tested and reported upon in the Preheated Air Burner Report. In answer to non-flat flame burner retrofits, where preheat temperature capability was estimated at 750°F, the team chose an oxygen enriched longitudinal fired burner which was reported on in the O₂ Enriched Burner Report. As for the remaining flat-flame installations, where preheat capability was also approximated around 750°F, the team settled on the third burner, an oxygen enriched flat flame design which is detailed in this report.

The range of sizes for burners that are to be used on a reheat furnace to achieve both Conventional Heating (CH) and Scale Free Heating (SFH) was based on a typical state of the art, walking beam type reheat furnace described in the Phase I Final Report. The following sketch and table summarizes the range and size of burners required in the different zones for either CH or SFH.

CONVENTIONAL HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	187	84	41	312
% of total input =	60.0%	27.0%	13.0%	100%
Air/gas ratio =	10/1	10/1	10/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	10.4	4.7	1.9	
SCALE FREE HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	0	146	166	312
% of total input =	0.0%	46.7%	53.3%	100%
Air/gas ratio =		7/1	5/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	0.0	8.1	7.9	

Exhibit 1:: The range and size of burners for CH/SFH.

The basis of the % total input in each zone for either CH or SFH and the Air/gas ratio in each zone is discussed in detail in the Phase I Final Report. As also detailed in that write-up, the Phase I work assumed an air preheat of 1000°F would be required in order to achieve the desired 50% stoichiometric conditions. When the additional burners were identified for future development in the early stages of Phase II, the expectations of retrofit preheater capability fell closer to 750°F as mentioned. The first approach taken by the team to account for the lower air preheat temperature was to oxygen enrich the combustion air to the point that the available heat of the enriched air matched that of 1000°F preheated air. However, as hot air burner testing was completed, it was observed that 1000°F preheated air was actually on the edge of acceptable SFH performance, as turndown performance was significantly worse than desired. With the previous testing in mind, it was decided by the project team to increase the level of oxygen enrichment to match the available heat of 1200°F preheated combustion air, which resulted in a combustion mixture oxygen content of 29.7% by volume. That is to say, a preheated, oxygen enriched air mixture of 750°F, 29.7% oxygen has an equivalent available heat to that of 1200°F preheated standard air in a soak zone of a reheat furnace. The above table was used in conjunction with this decision in order to generate the detailed burner specification sent to Bloom Engineering for their evaluation of a burner series that could achieve the wide range of operation required for CH and SFH. This specification is provided below.

Burner Specification Submitted to Bloom Engineering

SCALE FREE HEATING BURNER SPECIFICATION: PREHEATED, 29.7 %OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	26,022	3,233	7,924	3.692	20,016	2,487	6,095	3.692	3,336	415	1,016	3.692	SOAK	21	166
HEAT	35,084	4,359	8,089	4.876	26,987	3,353	6,222	4.876	4,497	559	1,037	4.876	HEAT	18	146
CHARGE	43,073	5,351		NA	33,134	4,116		NA	5,523	685		NA	CHARGE	0	0
													FURNACE	39	312

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: No burners are required for Charge Zone. Number of burners shown for Soak and Heat Zones are for both top and bottom heating zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

Percent Stoichiometric: Soak Zone Fired at 53% of Stoichiometric, Heat Zone at 70% Stoichiometric, Charge Zone Burndown to 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

CONVENTIONAL HEATING BURNER SPECIFICATION: PREHEATED, 29.7% OXYGEN ENRICHED AIR															
ZONE	CONNECTED				DESIGN				TURNDOWN				ZONE	NUMBER OF BURNERS	CONNECTED INPUT (MMBtu/hr)
	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G			
SOAK	12,566	1,561	1,931	7.31	9,666	1,201	1,486	7.31	1,611	200	248	7.31	SOAK	21	41
HEAT	30,448	3,783	4,680	7.31	23,422	2,910	3,600	7.31	3,904	485	600	7.31	HEAT	18	84
CHARGE	67,662	8,406	10,400	7.31	52,048	6,466	8,000	7.31	8,675	1,078	1,333	7.31	CHARGE	18	187
													FURNACE	57	312

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Percent Stoichiometric: All zones fired at 5% excess air equivalent based on a total of 29.7% oxygen in the preheated air.

Air, Gas, and Oxygen Pressure: To be provided by Burner Supplier.

NOx: Burners should be equivalent to BACT, say 0.05 lbs NOx/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 2: Burner Specification: preheated, 29.7% oxygen enriched air.

test burner sizing and installation were later examined by Bloom, however, further discussion with the project team concluded that oxygen enrichment would only be utilized during SFH firing for several reasons. First and foremost, by eliminating oxygen enrichment during conventional firing, the overall burner turndown requirements through SFH and CH would be greatly improved. Turndown performance, as stated previously, was a large concern based upon previous testing. Consequently, CH testing would be performed with 750°F combustion air only. Therefore, Bloom Engineering developed a corresponding Demonstration Burner Specification based upon the supplied Burner Specification, taking into account the reduced percentage of available heat

(≈49%) associated with the non-enriched CH combustion air as compared to the original 29.7% O₂ enriched specification (≈57% available heat). The resulting specification was then ratified by the project team and is provided below. It should be noted, at this point however, that oxygen enriched CH is fully expected to actually be favorable in certain retrofits. As such, any required burner modifications associated with oxygen enriched CH firing will have to be reviewed and implemented on a case by case basis as the need arises in the future since there could be a concern of high NO_x emissions with the combination of preheated air and oxygen enrichment.

The subsequent Phase II work involved, demonstrating that the proposed burners could achieve the specified ranges for both CH and SFH and, if necessary, further developing the burner series in order to achieve the specified ranges.

DEMONSTRATION BURNER													
MODE	ZONE	CONNECTED				DESIGN				TURNDOWN			
		AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G	AIR (scfh)	OXYGEN (scfh)	GAS (scfh)	A/G
SFH	SOAK	16,420	2,040	5,000	3.692	12,630	1,569	3,846	3.692	2,105	262	641	3.692
	HEAT	22,138	2,751	5,104	4.876	17,029	2,116	3,926	4.876	2,838	353	654	4.876
CH	SOAK	14,177	0	1,418	10	10,906	0	1,091	10	1,818	0	182	10
	HEAT	34,353	0	3,435	10	26,425	0	2,643	10	4,404	0	440	10
ZONE	MODE												
SOAK	SFH	16,420	2,040	5,000	3.692	12,630	1,569	3,846	3.692	2,105	262	641	3.692
	CH	14,177	0	1,418	10	10,906	0	1,091	10	1,818	0	182	10
HEAT	SFH	22,138	2,751	5,104	4.876	17,029	2,116	3,926	4.876	2,838	353	654	4.876
	CH	34,353	0	3,435	10	26,425	0	2,643	10	4,404	0	440	10

Fuel: Natural gas @ 1044 Btu/cf (Pittsburgh Natural Gas)

Burner Notes: Number of burners shown are for both top and bottom zones. All zones are longitudinally fired.

Preheat Air Temperature: 750°F

Air and Gas Pressure: To be provided by Burner Supplier.

NO_x: Burners should be equivalent to BACT, say 0.05 lbs NO_x/MMBtu

Zone Temperatures: Say 2250°F

Exhibit 3: Demonstration burner performance.

2 DESCRIPTION OF TESTS

The Project Team met and reviewed the Burner Specification that was submitted as the basis for burner testing. The general burner type to be tested, test furnace, and instrumentation was agreed upon and is described in detail in the following sections.

2.1 Test Burner

Based on the Burner Specification submitted, the High Thermal Release (HTR) burner series was chosen as the prime candidate for implementation given the wide range of testing parameters. Flames generated by these burners have a high negative pressure at their centers. Because of this negative pressure region, considerable volumes of furnace gases are drawn into these flames allowing for rapid combustion and reduced NO_x. All burners of this series utilize two common components. First, is Bloom Engineering's patented block stabilization which takes advantage of the Coanda effect to produce a short flat flame. Second is a round metallic nozzle which has a large center bore and numerous converging compound-angle drillings on the nozzle's outer radius. Air supplied through the outer drillings mixes rapidly with axial-supplied fuel entering through the center bore.

The specific HTR burner chosen was from Bloom's 2180-series. In addition to the natural flue gas recirculation previously mentioned, this patented burner uses air staging to accomplish ultra low NO_x combustion. However, for all testing discussed in this document air was introduced as primary air only, as all staged air passages were plugged. This was done in order to ensure

sufficient momentum for mixing the gas and oxygen enriched air in scale free mode. In applications which would require ultra low NO_x during conventional firing it would be desirable to alter the burner body so that the primary air is introduced independent of any staged air. With the appropriate valves, this would allow for both scale free firing using primary air only as well as ultra low NO_x conventional firing with staged combustion. Bloom Engineering has successfully utilized similar arrangements with other burner series.

As originally specified the burner would have required a rated capacity in excess of 8 MMBtu/hr. No burner of this size would have been practical for lab testing due to limitations in the size of the test furnace and auxiliary equipment. This was not viewed with much concern, though, as Bloom Engineering often encounters this situation in the highly variable combustion product market. Burners are usually designed with the interest of maintaining the ability to scale up or down in capacity in order to allow for such cases and to reduce application limitations of burner designs. In fact, the convention of scaling burners down for lab testing and research is a common practice and has shown to provide reliable results in a plethora of cases. Confident in prior scaling results, a 2180-060 HTR burner was chosen as the test burner. Photographs of the final test burner can be seen below. Also, the resulting capacity scaling can be seen in the provided table below.

Exhibit 4: Final test burner. X

SPECIFIED VERSUS TESTED BURNER SIZE			
ZONE	@	%	
STOICHIOMETRIC			
SPECIFIED			TESTED
(MMBtu/hr)			(MMBtu/hr)
SOAK	@	50%	
STOICHIOMETRIC			
8.273			5.220
SOAK @ 105%			
STOICHIOMETRIC			
2.016			1.480*

Exhibit 5: Specified vs. tested burner size.

**Value corrected for available heat variance due to non-enriched combustion air during CH.*

It should be observed in the above table that the Heat Zone burner sizing has been omitted, which serves to highlight an important caveat of testing. Due to time constraints the decision was made to focus solely on testing a burner that would be suited for the Soak Zone. It was believed that the Soak Zone burner presented the worst-case scenario for turndown and flame appearance due to its required firing parameters. For instance, a review of the Demonstration

Burner Specification reveals a Soak Zone fuel turndown of 27.5 and combustion air turndown of 9.0 with non-enriched conventional heating. In comparison, the Heat Zone fuel turndown was a mere 11.6 with intended combustion air turndown of 12.1, which ended up only being 7.8, due to other factors that will be explained in the Discussions and Recommendations section of this report. Furthermore, earlier testing of the longitudinal hot air only SFH burner revealed that the Heat Zone burner stoichiometric ratio of 70% in scale free mode was much more forgiving than the more stringent 50% stoichiometric ratio associated with the Soak Zone burner in scale free mode.

2.2 Furnace Facility

The test furnace chosen for this project was done so for a variety of reasons. First of all, there were two fairly large preheaters setup in the lab facility that were originally designed to provide hot combustion air to several furnaces for various testing needs. When used in series, these preheaters were more than capable of providing the required preheat temperature of 750°F granted the designated test furnace was located relatively close to both of them in order to minimize heat losses in the combustion air piping. Secondly, the furnace had to be large enough to accommodate a 5 MMBtu/Hr burner, yet small enough that the furnace could be heated to testing temperatures of 2200°F -2300°F in a reasonable amount of time, as well as providing for positive furnace pressure. Thirdly, and perhaps most importantly, since the excess gas input during SFH had to be burned down outside the chamber, a refractory lined flue was desired to prevent excessive damage to the flue stack.

Given these parameters, the 4ft. Lab Furnace became the clear choice. This furnace is a cylindrical furnace 4' in diameter and 12' long internally, with external dimensions of 5.5' diameter and 13.5' long. As stated, the furnace made use of a refractory lined flue stack that extended outside of the main lab enclosure.

Exhibit 6: 4 ft. lab furnace. X

A port for the insertion of a water-cooled emissions probe was located on the flue just after the junction with the furnace. Additional ports were located on the side of the furnace facing the center of the lab and these were used to collect Bacharach smoke data during testing.

Exhibit 7: Ports used to collect Bacharach smoke data. X

Air, gas, and oxygen flows were controlled manually through high temperature butterfly valves on the air lines and a ball valve on both the gas and oxygen lines. Flows were accordingly manipulated by trimming each valve as necessary. Each trim valve was installed downstream of an orifice run, which was the chosen method of setting and measuring various flows via static and differential pressures. The oxygen flow was injected into the combustion air after the preheater via hose connection and a high velocity stainless steel nozzle which mounted into a sufficiently long vertical piping run to promote uniform mixing as confirmed through CFD development.

Exhibit 8: Piping arrangement

In order to measure furnace temperature accurately, eight ceramic-shielded Type K thermocouples were evenly spaced along the side of the furnace facing the lab wall. All type K thermocouples used were rated to accurately measure temperatures up to 2454°F. These not only provided local furnace temperatures, but also allowed for an average furnace temperature to be easily surveyed. An additional unshielded Type K thermocouple was installed into the primary air line to monitor air preheat accurately.

Exhibit 9: Temperature measurement

Viewing windows were found on the lab-inward side of the furnace as well as the end of the furnace. These viewing ports allowed for visual observance of flame appearance as well as collection of video and photographic data.

Exhibit 10: Viewing ports.

As mentioned previously, two preheater furnaces were run in order to meet the 750°F air preheat required for SFH testing. Pictures of the furnaces can be seen below.

Exhibit 11: Air preheater furnaces.

A flue damper was used to adjust the furnace pressure during testing. An arm extending from the damper was connected via a cable to a manual crank at ground level. The picture below shows the top of the flue as viewed from the ground.

Exhibit 12: Pilot for flue gases

As a final note on the furnace equipment, a schematic detailing the arrangement of the preheaters, test furnace, burner, gas controls, and air controls is provided below.

2.3 Instrumentation

The test furnace instrumentation includes a large variety of items and is perhaps best discussed via column-by-column review of the Test Data Sheet identified as Appendices 1 and 2 below.

Primary Air

- *Run* – This column serves a dual purpose in providing an identification number for each data point while also keeping the test date readily visible. The format was simply the date of testing followed by alphanumeric coding in chronological order regarding test points taken the same day.
- *S.P. @ Orifice; "Hg* – This column represents the upstream static pressure of the pre-heated air in inches of mercury. This data was collected at the upstream side of the primary orifice run by Meriam Instrument U-Tube Mercury Manometers scaled in 0.1" Hg.
- *Temp. @ Orifice; °F* – This column provides the preheated air temperature in degrees Fahrenheit. This data was collected at the burner body via Omega Type-K Unshielded Thermocouples as mentioned previously.
- *DP @ Orifice; "W.C.* – Data in this column refers to the differential pressure across the primary orifice plate in inches of water column. This differential was measured using a Meriam Instrument's U-Tube Water Manometer with a designed scale of 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual airflow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using orifice plates designed and calibrated by Bloom.
- *S.P. @ Burner; "W.C.* – Data in this column refers to the static pressure of the air right at the burner inlets and is given in inches of water column. This data is provided by Meriam Instrument U-Tube Water Manometers.

Oxygen

- *Run* – This column remains the same as previously discussed with Primary Air.
- *S.P. @ Orifice; psig* – This column represents the upstream static pressure of the O₂ in pounds per in². This data was collected at the upstream side of the orifice run by a US Gauge 0-100 psig pressure gauge scaled in 2 psig increments.
- *Temp. @ Orifice; °F* – This column provides the O₂ temperature in degrees Fahrenheit. This data was collected just after the orifice run via a Weksler Instruments 20-240°F temperature gauge marked in 2°F increments.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the O₂ orifice plate in inches of water column. This data was recorded across the orifice by a Meriam Instrument U-Tube Water Manometer scaled in 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual oxygen flow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using an orifice plate designed and calibrated by Bloom.
- *% O₂ in Line* – This column represents the percent by volume of oxygen in the primary combustion air line. This data was recorded just before the burner intake by a NTRON Model C5 % O₂ Analyzer, which displayed %O₂ to a tenth of a percent.

Natural Gas

- *Run* – This column remains the same as previously discussed with Primary Air.
- *S.P. @ Orifice; psig* – This column represents the upstream static pressure of the fuel in pounds per in². This data was collected at the upstream side of the orifice run by either a USG 0-

5 psig pressure gauge scaled in 0.0625 psig increments or a Meriam Instrument U-Tube Mercury Manometers scaled in 0.1" Hg.

- *Temp. @ Orifice; °F* – This column provides the natural gas temperature in degrees Fahrenheit. This data was collected just before the orifice run via a Weksler Instruments 20-240°F temperature gauge marked in 2°F increments.
- *DP @ Orifice; "W.C.* – Data in this column refers to the Differential Pressure across the gas orifice plate in inches of water column. This data was recorded across the orifice by a Meriam Instrument U-Tube Water Manometer scaled in 0.1" W.C.
- *Q; SCFH* – This column represents the real-time actual natural gas flow in standard cubic feet per hour. This value is based off of the recorded static pressure, temperature, and differential pressure already discussed using an orifice plate designed and calibrated by Bloom.

Emissions – All emissions samples were taken via a water-cooled stainless steel emissions probe connected to a pump station and water chiller regulated down to 12 psig output. Images of this setup can be seen below. The emission samples were then pumped into a control room where they were sent through a Drierite-filled canister before being sent to individual analyzers that are described in greater detail below. This setup allowed for all of the moisture to be removed from the flue gas before reaching the analyzers, resulting in all readings and measurements being taken on a "dry" basis. The analyzers themselves output analog signals, which are then picked up by Bloom's computer software for visual display and trend recording.

- *Run* – This column remains the same as previously discussed.
- *Furnace Temp.; °F* – This column expresses the average furnace temperature in °F for the specific test point. The average is taken from the eight-shielded thermocouples discussed under Furnace Facility.
- *NO_x; ppm* – Data in this column displays the Nitrous Oxide emissions in parts per million. This was provided by a Rosemount Analytical Model 951A NO/ NO_x Analyzer set on 0-100 ppm range for testing in Scale Free mode or 0-250 ppm range when testing in Conventional Mode. The error in this unit is +/- 5.0 ppm when using the 0-100 ppm range and +/- 9.25 ppm when using the 0-250 range.
- *CO; ppm* – This column represents the Carbon Monoxide emissions in parts per million, which was the preferred scale for furnace warm-up and CH. This data was provided by a Rosemount Analytical Model 880A CO Analyzer with a 0-5000 ppm range resulting in +/- 20.5 ppm error.
- *% O₂* – Data in this column displays the Oxygen content of emissions based upon volumetric percentage, which was the preferred scale during furnace warm-up and CH. This data was provided by a Teledyne Brown Engineering Portable Oxygen Analyzer.
- *% CO* – This column presents the Carbon Monoxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.
- *% CO₂* – This column presents the Carbon Dioxide content of emissions based upon volumetric percentage, which was the preferred scale during SFH. This data was provided by a California Analytical Model 602 NDIR Analyzer.
- *CO/CO₂ Ratio* – This column displays the ratio of the recorded Carbon Monoxide emissions to the corresponding data point's Carbon Dioxide emissions.
- *Desired CO/CO₂ Ratio* – This column presents the corresponding desired emissions ratio for the particular test point being reviewed. Review of this number allows for a triple-check on the burner settings versus complete combustion during SFH testing.

- *Smoke #* – Data in this column displays the smoke number results of the Bacharach Smoke Test during SFH. This test was performed with a handheld pump used to draw flue emissions across special filter paper that left a darkened circle. This darkened circle was then measured against a Bacharach provided scale to develop a smoke number. Smoke test results that were even darker than the highest scale value of 9 were rated a 9+ simply to provide a way to make note of such a scenario. This testing is a common method of checking the amount of soot produced during firing. However, if the emissions are drawn too close to flame, they often present higher scale readings than actually experienced. Photos of the Bacharach Smoke Testing equipment and scale can be seen below.

Exhibit 13: Bacharach smoke testing equipment.

- *Calculated TD* – Values displayed in this column display the data point's actual turndown. This is calculated from the burner's nominal gas flow rating and the actual gas flow recorded.
- *Desired TD* – This column presents the data points desired turndown, which was used when setting in airflow and gas flow differential pressure values.
- *Calculated AFR* – Values in this column present the actual air to fuel ratio experienced based upon the flow results calculated from orifice data. This data served as a check against desired flow rates and settings.
- *Desired AFR* – This column displays the desired air to fuel ratio for a data point.
- *Chamber Appearance* – These values show the visual review of the furnace chamber appearance. Acceptable notes were given to points where the chamber remained relatively clear, allowing a view of burner components on the opposite chamber wall.
- *NO_x; Lbs/MMBtu* – This data column shows the NO_x emissions in pounds per million Btu. These values were corrected based upon the %O₂ and NO_x (ppm) results during CH and the calculated PFR, NO_x (ppm), and oxygen enrichment during SFH.

3 50% STOICHIOMETRIC TESTS

The following sections provide detailed information on the description of tests conducted, the test results and conclusions for the test burner operated at the specified 50% stoichiometric conditions.

3.1 Description of Tests

The burner was operated at the specified 50% stoichiometric ratio, which would be the expected conditions for burners in the soak zone of a furnace that was operated under SFH conditions.

The specified versus the tested operating conditions for a burner in the soak zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: SOAK ZONE														
BURNER FOR	CONNECTED				DESIGN					TURNDOWN				
	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A/ G	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A/ G	T / D	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A/ G	T / D
FURNACE	26,022	3,233	7,924	3.69	20,016	2,487	6,095	3.69	1.3	3,336	415	1,016	3.69	7.8
TESTED	16,420	2,040	5,000	3.69	12,630	1,569	3,846	3.69	1.3	2,105	262	641	3.69	7.8

Exhibit 14: Burner specification/testing: soak zone.

Each day, prior to actual recording of data, all emissions equipment was calibrated, the pre-heated air furnaces were brought up to their proper temperatures, and the test furnace was lit off and brought to the specified operating temperature. Initial furnace warm-up was achieved by firing the test burner at or near stoichiometric conditions without oxygen enrichment.

For each test point in SFH above 3:1 turndown, the burner air was first adjusted followed by the O₂. This allowed for the desired air and oxygen flows to be set in prior to adding the remaining fuel necessary to achieve a 50% stoichiometric ratio.

Once the flow settings were at 50% stoichiometric conditions, test point data was collected. Static pressures, temperatures and differential pressures were recorded by hand, with emissions and temperature data also being collected via tracking software. Video was taken to provide record of the furnace chamber appearance. The Bacharach probe was inserted into a side port and pumped accordingly to develop a smoke number for each test point. With all data collected, the burner was then taken back to stoichiometric conditions so the furnace could reheat in preparation for the next test point.

3.2 Results of Tests

As described, extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 50% stoichiometric test is provided in Section 52. The following table summarizes the performance of the test burner when firing at 50% stoichiometric conditions.

BURNER TEST DATA: 50% STOICHIOMETRIC											
RUN	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A/ G	T/D	%CO	%CO ₂	CO/CO ₂	DESIRE D %CO	DESIRE D CO/CO ₂	COMMENTS
022709d	-	2202	5426	-	0.92	17.96	5.41	3.32	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.
022709e	-	1491	3827	-	1.31	17.68	5.23	3.38	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.

022709f	-	1329	3379	-	1.48	18	5.27	3.42	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.
022709g	-	1071	2829	-	1.77	17.69	5.01	3.53	17.0	3.2	Acceptable and CO/CO ₂ ratio is good.
40609b	8697	1035	2494	3.49	2.00	17.52	5.96	2.94	17.0	3.2	Acceptable and CO/CO ₂ ratio is border line.
40609c	5412	605	1654	3.27	3.02	16.74	6.13	2.73	17.0	3.2	Not Acceptable and CO/CO ₂ ratio is low

Exhibit 15: Burner test data: 50% stoichiometric.

Acceptable or Not Acceptable performance was determined by flame observation, checking the Bacharach number of the flue gases leaving the furnace and measuring the CO and CO₂ content of the flue gasses. Other work in Phase I and Phase II of the Project had determined that a CO content of about 17.0% and a CO/CO₂ ratio of about 3.2 is required in order to prevent forming scale in the soak zone of a reheat furnace with oxygen enriched (29.7% by volume) 750°F preheated combustion air. Equilibrium calculations for Pittsburgh natural gas showed that an air to gas ratio of about 3.69/1 (about 50% stoichiometric) was required to achieve this.

The above table shows that the burner performed acceptably to a turndown of 2 (50% capacity). Below this turndown the CO/CO₂ ratio began to fall off even though a low air to fuel ratio was maintained. The data from run 40609c shows the highest CO/CO₂ that could be achieved at a turndown of 3.02 (33% capacity) while maintaining an acceptable furnace atmosphere. At this turndown, further reduction of the air to fuel ratio would be required to obtain an acceptable CO/CO₂ ratio which would in turn increase free carbon (soot) in the furnace chamber to an unacceptable level.

3.3 Conclusions from Tests

The actual achieved turndown resulting in an acceptable atmosphere was much lower than desired when the burner is operating at the expected soak zone firing ratio of 50% stoichiometric. The following Table provides the desired versus successful turndown ratio of the test burner operating at 50% stoichiometric.

BURNER TURNDOWN 50% STOICHIOMETRIC	
REQUIRED	7.8
ACTUAL	2.0

Exhibit 16: Burner turndown 50% stoichiometric.

The required turndown level of 7.8/1 is only the turndown level needed when the burner is operating in the soak zone of a furnace that is being operated in SFH conditions. It must be remembered that the same burner has to also be operated as a conventional burner firing at stoichiometric conditions whenever the furnace is being operated in CH conditions. This actually increases the overall turndown level of the burner a great deal. By referring to the Demonstration Burner Specification, the overall turndown of a burner that is used in the soak zone of a furnace

that has to run as either a CH furnace without oxygen enrichment or as a SFH furnace with oxygen enrichment can be determined. This is summarized in the following table.

SOAK ZONE BURNER TURNDOWN	
MAXIMUM SFH RATE	5.22 MMBtu/HR
MINIMUM SFH RATE	0.669 MMBtu/HR
SFH TURNDOWN	7.8
MAXIMUM CH RATE	1. 48 MMBtu/HR
MINIMUM CH RATE	0.190 MMBtu/HR
CH TURNDOWN	7.8
OVERALL SFH to CH TURNDOWN	27.50

Exhibit 17: Soak zone burner turndown.

Therefore, the total performance level of the soak zone burner cannot be completed until the same burner is operated in the CH mode over the specified range for that mode. The performance results of the burner operating in the CH mode, that is the 100% stoichiometric mode, is covered in the following section of this report.

4 100% STOICHIOMETRIC TESTS

The following Sections provide detailed information on the description of tests conducted and the test results and conclusions for the test burner operated at the specified 100% stoichiometric conditions.

4.1 Description of Tests

The burner was operated at the specified 100% stoichiometric ratio, which would be the expected conditions for burners in the soak zone of a furnace that was operated under CH conditions. The specified versus the tested operating conditions for a burner in the soak zone are summarized in the following table.

BURNER SPECIFICATION / TESTING: STOICHIOMETRIC SOAK ZONE														
BURNER FOR	CONNECTED				DESIGN					TURNDOWN				
	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D	AIR (scfh)	O ₂ (scfh)	GAS (scfh)	A / G	T / D
FURNACE	12,566	1,561	1,931	7.31	9,666	1,201	1,486	7.31	1.3	1,611	200	248	7.31	7.8
TESTED	14,177	0	1,418*	10	10,906	0	1,091*	10	1.3	1,818	0	182*	10	7.8

Exhibit 18: burner specification/testing: stoichiometric soak zone.

**Values corrected for available heat variance due to non-enriched combustion air during CH.*

Giving the compressed time frame for the development of a flat-flame burner 100% stoichiometric testing was limited to firing the burner as initially installed for Scale Free testing. As was mentioned earlier when discussing the Test Burner, it would be possible to modify the burner body design to allow for air staging when firing in CH mode and subsequently reduce NO_x.

Prior to actual recording of data, all emissions equipment was calibrated. Of note, since much less carbon monoxide was expected in CH, it was monitored by the Rosemount Analytical Model 880A CO Analyzer in parts per million during testing. Next, the pre-heated air furnaces were brought up to their proper temperatures, and the test furnace was lit off and brought to the specified operating temperature. Once the desired furnace temperature was obtained, the burner was fired at ever increasing turndowns for 5 to 10 minutes each. Testing continued in this fashion until the greatest turndown that could be achieved with this setup was achieved.

4.2 Results of Tests

Extensive data was recorded for numerous operating points of the burner during the tests. The entire data set for the 100% stoichiometric tests is provided in the Appendix. Please see Section 52. The following table summarizes the performance of the test burner when firing at 100% stoichiometric conditions.

BURNER TEST DATA: 100% STOICHIOMETRIC										
RUN	AIR (scfh)	GAS (scfh)	A/G	T/D	CO (ppm)	CO/CO ₂	NO _x (#/MMBtu)	DESIRE D CO/CO ₂	Furnac e Temp. (°F)	COMMENTS
031209a	-	1424	-	1.0	1.22	0	0.201	0	2237	Acceptable flame appearance and stability. NO _x performance Not Acceptable .
031209b	-	1184	-	1.2	1.22	0	0.183	0	2199	Acceptable flame appearance and stability. NO _x performance Not Acceptable .
031209c	-	957	-	1.4 7	1.22	0	0.171	0	2137	Acceptable flame appearance and stability. NO _x performance Not Acceptable .
031209d	-	709	-	2.0	1.22	0	0.155	0	2037	Acceptable flame appearance and stability. NO _x performance Not Acceptable .
031209e	-	355	-	4.0	2.12	0	0.135	0	1808	Acceptable flame appearance and stability. NO _x performance Not Acceptable .
031209f	-	257	-	5.5 6	13.35	0	0.093	0	1692	Acceptable flame appearance and stability. NO _x performance Not Acceptable .

Exhibit 19: Burner test data: 100% stoichiometric.

Acceptable or Not Acceptable flame appearance was determined by visual flame observation. An Acceptable flame was a flame that was properly anchored to the burner port block and had a stable appearance and no flashing or otherwise undesirable behavior. Acceptable or Not

Acceptable NO_x performance was based upon the Phase I developed requirement of 0.05 #/MMBtu during nominal firing conditions. Acceptable performance was, of course, NO_x emissions that were less than or equal to the chosen basis.

The above table shows that flame appearance and stability were all found to be acceptable through the turndown range tested. Further turndown to 7.8 could not be accomplished due to leakage through the primary air trim valve. There was simply insufficient time before the project deadline to address the trim valve leakage and conduct additional testing.

NO_x emissions were found to be significantly greater than the desired amount of 0.05 #/MMBtu. Again, further data detail can be reviewed for 100% stoichiometric testing in Section 52.

4.3 Conclusions from Test

In order to achieve the desired NO_x emissions with this burner, it would be necessary to modify it so that air staging could be used when firing in CH mode. This change would make the burner functionally equivalent to Bloom's standard 2180-060 burner which is known to comply with the intended NO_x limit of 0.05 #/MMBtu, through previous lab testing as well as field installations. Below, figures have been provided that show first a standard 2180-060 burner followed by a conceptualized 2180-060 burner that would allow for both SFH and ultra low NO_x CH.

Exhibit 20: Standard 2180-060 burner.

5 ADDITIONAL TESTING

In order to gauge the overall NO_x produced by a furnace operating in SF mode a series of tests were designed that would simulate “burning down” the POC from the Soak Zone of a furnace operating at an air to fuel ratio of 5:1 to a final air to fuel ratio of 11:1 that would be seen in the Charge Zone.

5.1 Description of Test

Prior to these tests, a brick wall was built to divide the furnace into two sections referred to as Front and Rear. A picture of the wall along with a schematic of the divided furnace has been provided below. The wall was designed so that the open area above it was roughly equal to the open area of the flue (445 in^2 to 452 in^2) respectively.

Exhibit 22: Furnace dividing wall

Exhibit 23: Front and rear sections of the furnace.

The first test was designed to simulate burning down the POC generated by the Soak Zone burners in the Heat Zone. In order to do this, the burner was fired into the Rear section of the furnace at an air to fuel ratio of 5:1. At the same time sufficient air was supplied to the Front chamber, via two 2 ½ couplings built into the furnace wall, so that an air to fuel ratio of 8:1 could be obtained. Emissions data was collected in each zone summarized in the following table.

Burn Down Test (5:1 → 8:1 Air/Fuel Ratio)		
Approximate Air/Fuel Ratio	CO/CO ₂	NO _x (lb/MMBtu)
5:1	3.82	0.0142
8:1	0.80	0.0396

Exhibit 24: Burn down test (5:1 → 8:1 Air/Fuel Ratio)

The second test was designed to simulate burning down the POC generated by the Heat Zone in the Charge Zone. For this test, the fuel supplied to the burner was reduced until the Rear chamber reached an air to fuel ratio of 8:1. At the same time sufficient air was supplied to the Front chamber so that a final air to fuel ratio of 11:1 was obtained. Again, emissions data was collected in each Zone and has been summarized in the following table.

Burn Down Test (8:1 → 11:1 Air/Fuel Ratio)		
Approximate Air/Fuel Ratio	CO/CO ₂	NO _x (lb/MMBtu)
8:1	0.62	0.2499
11:1	0.0	0.2553

Exhibit 25: Burn down test (8:1 → 11:1 Air/fuel ratio).

5.2 Conclusions from Test

Because these tests could only roughly replicate true burn down scenarios, the focus should not be on the exact NO_x data but should rather on the relative increase between NO_x in one portion of the furnace to another. For instance, the NO_x measured in the rear chamber when firing at 50% Stoich was 0.0142 lbs/MMBtu while the NO_x measured during scale free testing was only 0.00828 lbs/MMBtu. What this test does show is that the overall NO_x could very well increase significantly between the Soak Zone and the Heat Zone (179% in this test). This result indicates the increased need to optimize the burn down process between the Soak Zone and Heat Zone by carefully determining the location and method for introducing air. However, a very small increase was seen when simulating burn down of the Heat Zone POC in the Charge Zone (2.2% in this test). This may indicate that less attention will be required when burning down between the Heat Zone and the Charge Zone.

6 DISCUSSION AND RECOMMENDATIONS

The burner testing and demonstration results concluded that the burner fell well short of specified operating ranges for the 50% and 100% stoichiometric operating ranges required. Project Team discussions and meeting were held to determine future direction.

It was pointed out by Bloom Engineering that “pulse firing” could be used to eliminate the need for the currently specified turndown ranges and as a result, the existing burner could be considered applicable as is, which was similarly concluded for the 1000°F Hot-Air-Only Burner design and the O₂ Enriched Burner design. “Pulse firing” utilizes the burner firing at maximum capacity all of the time and effects turndown by shutting the burner off in “pulses”.

Previously, when discussing the test burner’s design it was mentioned that testing was limited to the Soak Zone burner because it was believed to represent the worst case scenario for turndown and flame appearance due to its required firing parameters. However, it was noted that the original design called for a greater air turndown with the Heat Zone Burner (12.1 vs. 9.0). While this is true, the use of pulse firing with these burners when operating in SFH mode would reduce the maximum air turndown of the Heat Zone burner to 7.8. Because the Soak Zone Burner requires the greatest air turndown (9.0) in CH mode and not SFH mode like the Heat Zone Burner, the decision to focus testing on the Soak Zone burner was in fact correct. This unique situation was anticipated before testing began due to the test results of the O₂ Enriched Cyclops burner.

It was considered that the top priority for testing and/or development of a SFH/CH burner had been originally given to the 1000°F preheated air burner for new furnaces based on the Phase I conclusions that this technology had the best overall payback. Expectations of success were reinforced with the quotation from Bloom for a CH/SFH burner that met the burner specification while utilizing an existing ultra low NO_x burner series. But the additional time needed to test and develop the 1000°F Hot-Air-Only burner further in order to extend its potential range of operation was eventually questioned. Pulse firing was a consideration observed that would effectively eliminate the need for the wider range of turndown and other burner technologies needed to be considered in order to address the retrofit market of SFH.

As a reminder, Phase I had identified a potential market for SFH of approximately 65 million tons per year of reheated steel in rebar, merchant, specialty and hot strip mills. But market considerations started in Phase I and completed early in Phase II concluded that less than 10% of this market would be in new furnaces with more than 90% being retrofit of existing furnaces from CH to CH/SFH. The economic studies completed in Phase I had also demonstrated the long term economic advantage of a preheated air, SFH burner that achieved SFH and CH combustion requirements without the aid of oxygen enrichment. The payback of a furnace designed with only preheated air was better than a furnace designed for a combination of preheated and oxygen enriched air that had the additional annual cost of oxygen. This background combined with Bloom’s Proposal had indicated that such a burner was close at hand and the initial Burner Demonstration Task of Phase II had rightfully focused on this burner.

But, again, preliminary economic studies in Phase I also indicted that preheated air combined with oxygen enrichment would most likely yield the best payback in retrofits where the existing furnace and auxiliary equipment footprint would preclude the ability to install the much larger recuperator and piping needed for a preheat air only burner. Even though the preheated, oxygen enriched air system had a higher monthly operating cost due to the cost of oxygen, the retrofit to SFH was possible and practical due to the compact nature of the burner and piping and the use of the existing recuperator system as is. Therefore, Phase II had rightfully continued on with the design and testing of the required longitudinal burner for CH/SFH utilizing preheated, oxygen enriched air.

It should not be forgotten, however, that analysis of the retrofit market conducted in the early stages of Phase II also pointed out that about 50% of the potential retrofit furnace market utilized

flat flame burners in at least one zone of the furnace. This statistic emphasized the additional need for a flat flame burner that could also meet the CH/SFH requirements of a furnace converted from CH to CH/SFH.

As a result, all three distinct burners identified have been accordingly developed and tested to an acceptable level of production viability. At this point it is felt that the project focus should shift accordingly to actual applications for these burners. For convenience and review, the distinguishing characteristics of all three burners developed are summarized in the following table.

SCALE FREE HEATING BURNER MARKET				
BURNER TYPE	COMBUSTION AIR	MARKET	% MARKET OF 65MM TPY	BURNER TEST/DEVELOP PRIORITY
Longitudinal	Preheated to 1000°F	New Furnaces	10%	1
Longitudinal	Exiting preheat (750°F) plus O ₂ Enrichment to 1200°F Equivalent	Retrofit	50% of 90%	2
Flat Flame	Exiting preheat (750°F) plus O ₂ Enrichment to 1200°F Equivalent	Retrofit	50% of 90%	3

Exhibit 26: Scale free heating burner market.

DATA APPENDIX 1

1.1 Data Appendix 1: Detailed data table for 50% stoichiometric tests.

Results of 1610-013 Cyclops Burner (4.4 MMBtu/Hr @ 50 % Stoichiometric)
*101807 data was standard design with 95/5 Primary Air Split, 2:1 TD Air Flow Set, and Various AFR
*101807g data was standard design with 30/70 Primary Air Split, 1.1:1 Turndown Cyclops NOx Run
*102207 data was standard design with 95/5 Primary Air Split, 2:1 TD Air Flow Set, and Various AFR
*111507 data was standard design with 95/5 Primary Air Split, and Various AFR and TD
*112007 data was standard design with 95/5 Primary Air Split, and Various AFR and TD
*120707 data was standard design with 95/5 Primary Air Split, at 5:1 AFR and Various TD

Primary Air					
Run	S.P. @ Orifice " Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
101807a	1.7	1041	22.4	20071	8.6
101807b	1.7	1042	23.1	20376	7.8
101807c	1.7	1042	22.4	20065	8.6
101807d	1.7	1043	22.0	19878	9.1
101807e	1.7	1044	22.4	20051	8.5
101807f	2.4	997	5.7	10390	2.5
101807g	1.3	946	6.3	10928	1.9
102207a	1.7	1008	21.6	19930	7.9
102207b	2	1008	21.7	20071	8.6
111507a	3	924	2.5	7125	1.0
111507b	3	920	2.5	7136	1.0
111507c	3	917	2.5	7143	1.0
111507d	3.1	948	1.4	5294	0.4
111507e	3.1	940	1.4	5310	0.4
111507f	3.1	929	1.4	5331	0.4
112007a	3.1	897	0.9	4324	0.2
112007b	3.1	884	0.9	4345	0.2
112007c	3.1	881	0.9	4350	0.2
112007d	3.1	903	0.65	3667	0.2
112007e	3.1	883	0.65	3694	0.2
112007f	3.1	872	0.65	3709	0.2
120707a	2.2	1000	9.9	21441	8.2
120707b	2.3	994	6.5	17436	5.7
120707c	2.6	984	4.3	14297	3.9
120707d	2.7	977	2.30	10498	2.7
120707e	2.9	963	1.6	8826	1.2

Secondary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
101807a	2.0	584	0.05	1723	0.1
101807b	1.9	585	0.05	1719	0.1
101807c	1.9	584	0.05	1720	0.9
101807d	1.9	586	0.05	1719	0.7
101807e	2	586	0.05	1721	0.2
101807f	2.3	603	0.05	1715	0.5
101807g	0.6	1028	14.4	23947	4.4
102207a	1.8	571	0.05	1728	0.1
102207b	1.9	569	0.05	2576	1.7
111507a	3	387	1	479	5.2
111507b	3	382	1	480	5.2
111507c	3	377	1	481	0.1
111507d	3	393	0.6	369	0.1
111507e	3	390	0.6	370	-0.1
111507f	3.1	385	0.6	372	-0.1
112007a	2.9	391	0.4	302	-0.2
112007b	2.9	385	0.4	303	-0.2
112007c	2.9	378	0.4	304	-0.2
112007d	2.9	392	0.3	261	-0.2
112007e	2.9	387	0.3	262	-0.2
112007f	2.9	382	0.3	263	-0.2
120707a	2.4	433	5.7	1103	0.2
120707b	2.6	429	3.9	917	0.1
120707c	2.7	420	2.5	739	0.1
120707d	2.8	407	1.4	558	0.5
120707e	2.9	396	0.6	368	0.1

Natural Gas					
Run	S.P. @ Orifice psig	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner psig
101807a	16.5	92	2.0	2013	2.25
101807b	16.0	94	9.9	4435	8.0
101807c	16.0	92	6.9	3709	6.25
101807d	16.25	92	5.1	3202	4.75
101807e	16.5	92	3.9	2811	4.0
101807f	17.0	94	2.5	2265	2.75
101807g	16.5	102	6.7	3652	6.25
102207a	15.50	90	2.3	2128	2.5
102207b	15.50	90	10.3	4503	8.75
111507a	8.75	80	0.5	882	0.5
111507b	8.25	82	0.8	1102	1.0
111507c	8.00	83	1.5	1499	2.0
111507d	8.50	83	0.3	678	0.5
111507e	8.75	83	0.4	787	0.5
111507f	8.50	83	0.9	1174	1.0
112007a	16.50	83	0.2	642	0.25
112007b	16.50	84	0.3	785	0.25
112007c	16.50	84	0.4	907	0.5
112007d	16.50	86	0.2	554	0.0
112007e	16.50	86	0.2	640	0.0
112007f	16.50	86	0.4	847	0.5
120707a	14.25	100	10.0	4305	8.25
120707b	15.0	97	6.9	3632	6.0
120707c	15.5	97	4.4	2925	4.0
120707d	16.0	99	2.5	2219	2.5
120707e	16.75	104	1.1	1483	1.0

Emissions															
Run	Furnace Temp. Deg. F	NOx ppm	CO ppm	% O2	% CO	% CO2	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	Desired TD	Calculated AFR	Desired AFR	Chamber Appearance	NOx lbs/mmBTU
101807a	-	187.77	-	1.62	0	11.36	-	0	-	2.19	1	10.83	11	Acceptable	0.20855
101807b	-	27.78	-	0.12	11.98	4.81	2.490644	3.2	9	0.99	1	4.98	5	Acceptable	0.01586
101807c	-	30.16	-	0.12	10.65	5.44	1.957721	2.15	9	1.19	1	5.87	6	Acceptable	0.01968
101807d	-	41.21	-	0.12	8.26	6.81	1.212922	1.3	9	1.37	1	6.74	7	Acceptable	0.03017
101807e	-	44.63	-	0.15	6.12	8.1	0.76	0.66	-	1.57	1	7.74	8	Acceptable	0.03675
101807f	-	33.64	-	0.12	8.97	7.16	1.252793	3.2	9	1.94	2	5.35	5	Unacceptable	0.02033
101807g	-	83.25	Maxed	0.34	-	-	-	-	-	1.20	1.1	9.55	11	Acceptable	0.06229
102207a	2332	171.31	-	2.2	0	11.06	-	0	-	2.07	1	10.18	10.5	Acceptable	0.19617
102207b	2233	20.45	-	0.15	12.24	4.71	2.598726	3.2	9	0.98	1	5.03	5	Acceptable	0.01177
111507a	2095	61.54	-	0.27	2.9	10.37	0.279653	0.2	9	4.99	3	8.62	9	Acceptable	0.05559
111507b	2044	37.68	-	0.31	5.79	8.48	0.682783	1.3	9	3.99	3	6.91	7	Acceptable	0.02816
111507c	1992	24.44	-	0.34	9.31	4.94	1.884615	3.2	9+	2.93	3	5.09	5	Unacceptable	0.01419
111507d	2144	55.31	-	0.46	2.35	10.7	0.219626	0.2	9	6.49	4	8.36	9	Acceptable	0.04864
111507e	2083	36.9	-	0.46	4.91	9.07	0.541345	1.3	9	5.59	4	7.22	7	Acceptable	0.02861
111507f	2056	18.83	-	0.46	8.33	6.53	1.275651	3.2	9+	3.75	4	4.86	5	Unacceptable	0.01054
112007a	2035	32.45	-	0.27	4.18	9.71	0.430484	1.3	9+	6.85	5	7.21	7	Unacceptable	0.02513
112007b	1988	25.35	-	0.27	5.73	8.52	0.672535	2.15	9+	5.60	5	5.92	6	Unacceptable	0.01664
112007c	1952	23.52	-	0.27	6.73	7.63	0.882045	3.2	9+	4.85	5	5.13	5	Unacceptable	0.01375
112007d	2079	49.43	-	0.27	1.35	11.34	0.119048	1.3	9+	7.94	6	7.08	7	Unacceptable	0.03772
112007e	2008	22.83	-	0.24	5.14	9.14	0.562363	2.15	9+	6.87	6	6.18	6	Unacceptable	0.01553
112007f	1965	21.17	-	0.27	6.92	7.34	0.942779	3.2	9+	5.20	6	4.69	5	Unacceptable	0.01152
120707a	2247	25.30	-	0.03	12.41	4.45	2.788764	3.2	9	1.02	1	5.24	5	Acceptable	0.01503
120707b	2309	21.61	-	0.03	12.53	4.42	2.834842	3.2	9	1.21	1.2	5.05	5	Acceptable	0.01248
120707c	2274	19.71	-	0.03	12.45	4.45	2.797753	3.2	9+	1.50	1.5	5.14	5	Acceptable	0.01154
120707d	2250	21.86	-	0.03	11.09	5.31	2.088512	3.2	9+	1.98	2	4.98	5	Unacceptable	0.01248
120707e	2255	20.59	-	0.03	10.94	5.52	1.981884	3.2	9+	2.97	3	6.20	5	Unacceptable	0.01405

Exhibit 1: Detailed data tables for 50% stoichiometric tests

1.2 Data Appendix 2: Detailed data table for 70% stoichiometric tests.

Results of 1610-013 Cyclops Burner (4.49 MMBtu/Hr @ 70% Stoichiometric)

*121207 data was standard design with 95/5 Primary Air Split, 7:1 AFR and Various TD

Primary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
121207a	1.9	1005	11.7	27435	14.3
121207b	2.1	1000	9.5	24841	12.7
121207c	2.3	1001	6.6	20763	8.5
121207d	2.6	985	3.5	15274	5.2
121207e	2.9	977	1.5	10073	2.5
121207f	3.0	970	0.9	7834	1.5
121207g	3.1	975	0.5	5838	0.9

Secondary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
121207a	2.1	443	0.2	1387	0.6
121207b	2.3	448	8.0	1293	0.5
121207c	2.5	447	6.0	1124	0.4
121207d	2.7	435	2.9	789	0.6
121207e	2.8	415	1.2	514	0.3
121207f	2.9	409	0.7	395	0.1
121207g	3.1	429	0.5	331	0.1

Natural Gas					
Run	S.P. @ Orifice psig	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner psig
121207a	15.25	94	9.5	4291	7.25
121207b	15.0	94	7.2	3720	6.0
121207c	15.5	92	4.8	3004	4.50
121207d	15.75	92	2.60	2268	2.75
121207e	15.75	94	1.2	1538	1.5
121207f	15.25	96	0.80	1243	1.0
121207g	14.75	100	0.40	868	0.5

Emissions															
Run	Furnace Temp. Deg. F	NOx ppm	CO ppm	% O2	% CO	% CO2	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	Desired TD	Calculated AFR	Desired AFR	Chamber Appearance	NOx lbs/mmBTU
121207a	2351	-	-	0.21	7.73	7.15	1.0811888	1.3	3	1.05	1.1	6.72	7	Acceptable	-
121207b	2330	-	-	0.15	8.02	7.06	1.13597734	1.3	6	1.21	1.2	7.03	7	Acceptable	-
121207c	2334	93.33	-	0.15	7.21	7.72	0.93393782	1.3	8	1.50	1.5	7.29	7	Acceptable	0.07295
121207d	2328	88.38	-	0.15	6.56	8.23	0.79708384	1.3	9	1.98	2	7.08	7	Acceptable	0.06744
121207e	2217	82.12	-	0.18	6.68	8.16	0.81862745	1.3	9	2.92	3	6.88	7	Acceptable	0.06117
121207f	2235	69.65	-	0.12	4.17	9.84	0.42378049	1.3	9	3.61	4	6.62	7	Unacceptable	0.05020
121207g	2231	60.21	-	0.09	4.36	9.83	0.44354018	1.3	9	5.17	5	7.10	7	Unacceptable	0.04605

Exhibit 2: Detailed data tables for 70% stoichiometric tests.

1.3 Data Appendix 3: Detailed data table for 100% stoichiometric tests.

Results of 1610-013 Cyclops Burner (1.073 MMBtu/Hr @ 100% Stoichiometric)

*012208 data was standard design with 5/95 Primary Air Split, with 5% XSA at 1.073 MMBtu/Hr

*012308 data was standard design with 5/95 Primary Air Split, with 5% XSA at 1.073 MMBtu/Hr

Primary Air					
Run	S.P. @ Orifice " Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
012208a	2.9	567	4.3	519	0.3
012208b	3.1	552	0.9	240	0.1
012208c	3.1	536	0.3	140	0.1
012208d	3.1	519	0.1	81	0.1
012208e	3.1	483	0.05	59	0.1
012308a	3.2	498	0.02	37	0.1
012308b	3.2	471	0.01	26	0.1
012308c	3.2	398	0	0	0.1

Secondary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
012208a	2.8	914	15.9	9876	0.1
012208b	3.1	870	3.0	4380	0.1
012208c	3.1	824	1.1	2699	0.1
012208d	3.1	774	0.5	1856	0.0
012208e	3.1	776	0.25	1312	0.0
012308a	3.2	777	0.06	643	0.0
012308b	3.2	667	0.04	550	0.0
012308c	3.2	711	0.01	270	0.0

Lance Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
012208a	4.0	85	1.9	1135	26.1
012208b	4.0	85	1.9	1135	25.6
012208c	4.0	85	1.9	1135	25.2
012208d	4.0	85	1.9	1135	24.9
012208e	4.0	85	1.9	1135	24.1
012308a	4.1	85	1.9	1137	23.9
012308b	4.1	85	1.9	1137	23.5
012308c	4.1	85	1.9	1137	23.7

Natural Gas					
Run	S.P. @ Orifice psig	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner psig
012208a	15.0	88	7.1	1038	1.0
012208b	15.5	88	1.8	527	0.0
012208c	16.0	86	0.8	355	0.0
012208d	16.0	86	0.5	281	0.0
012208e	15.5	86	0.3	216	0.0
012308a	16.5	88	0.2	179	0.0
012308b	16.5	88	0.2	155	0.0
012308c	16.0	90	0.1	125	0.0

Emissions								
Run	Furnace Temp. Deg. F	NOx ppm	CO ppm	% O2	Calculated TD	Desired TD	Calculated AFR	NOx lbs/mmBTU
012208a	2100	22.03	104.23	0.95	1.03	1	11.11	0.02365
012208b	1992	18.29	4.46	1.43	2.04	2	10.92	0.02012
012208c	1910	20.93	4.15	3.66	3.02	3	11.20	0.02600
012208d	1862	17.00	4.15	3.08	3.82	4	10.95	0.02043
012208e	1828	19.78	4.40	5.53	4.98	5	11.62	0.02756
012308a	1899	36.65	1.71	7.69	6.01	6	10.17	0.05941
012308b	1812	34.51	0.98	10.47	6.94	7	11.08	0.07085
012308c	1836	30.48	0.98	12.27	8.58	8	11.25	0.07563

Exhibit 3: Detailed data tables for 100% stoichiometric tests.

1.4 Data Appendix 4: Detailed data table for 60% stoichiometric tests.

Results of 1610-013 Cyclops Burner (4.4 MMBtu/Hr @ 60% Stoichiometric)

*120407 data was standard design with 35.5 Primary Air Split, with 6:1 AFR at 4.4 MMBtu/Hr

Primary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
120407a	2.2	1019	13.6	24968	11.9
120407b	2.4	1012	9.5	20982	8.5
120407c	2.6	1003	6.0	16778	6.0
120407d	2.9	999	3.3	12517	3.4
120407e	3.1	993	1.5	8482	1.8

Secondary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
120407a	2.5	445	8.2	1316	0.1
120407b	2.5	446	5.7	1096	0.1
120407c	2.7	434	3.6	880	0.4
120407d	2.9	432	2.0	659	0.4
120407e	2.9	432	0.9	442	0.1

Natural Gas					
Run	S.P. @ Orifice psig	Temp. @ Orifice Deg. F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner psig
120407a	14.75	89	9.9	4364	7.5
120407b	15.0	84	6.9	3675	6.0
120407c	15.0	84	4.4	2935	4.0
120407d	15.0	90	2.50	2200	2.5
120407e	15.0	94	1.1	1454	1.5

Emissions													
Run	Furnace Temp. Deg. F	NOx ppm	CO ppm	% O2	% CO	% CO2	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	Desired TD	Calculated AFR	Desired AFR
120407a	2320	55.41	-	0.09	10.73	5.37	1.9981	2.15	6	1.01	1	6.02	6
120407b	2266	47.01	-	0.06	10.83	5.36	2.0205	2.15	7	1.20	1.2	6.01	6
120407c	2231	44.97	-	0.12	10.66	5.42	1.9668	2.15	7	1.50	1.5	6.02	6
120407d	2230	41.90	-	0.12	9.3	6.32	1.4715	2.15	9+	2.00	2	5.99	6
120407e	2194	36.90	-	0.06	8.43	7.14	1.1807	2.15	9+	3.03	3	6.14	6

Exhibit 4: Detailed data tables for 60% stoichiometric tests

DATA APPENDIX 2

1.1 Appendix 1. Detailed Data Tables for 50% Stoichiometric Tests

Results of Modified 1610-013 Cyclops Burner (4.4 MMBtu/Hr @ 50% Stoichiometric)
*111408 Data Was O2 Enriched With 95/5 Primary Air Split & 45° Spray Nozzle (1/2 Primary Area - Uniform)

Primary Air						Secondary Air					
Run	S.P. @ Orifice "Hg	Temp. @ Orifice °F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC	Run	S.P. @ Orifice "Hg	Temp. @ Orifice °F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC
111408b	1.7	680	23.9	13067	5.1	111408b	2.0	314	8.9	690	0.1
111408c	1.9	662	12.2	9441	3.1	111408c	2.0	305	4.5	493	0.3
111408d	2.1	627	4.6	5908	1.2	111408d	2.1	293	1.80	315	0.1

Lance Air						Oxygen				
Run	S.P. @ Orifice "Hg	Temp. @ Orifice °F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner "WC	Run	S.P. @ Orifice psig	Temp. @ Orifice °F	DP @ Orifice "WC	Q SCFH
111408b	3.0	91	1.9	1112	-	111408b	9.5	103	11.9	1660
111408c	3.0	91	1.9	1112	-	111408c	10.0	102	6.5	1241
111408d	3.0	91	1.9	1112	-	111408d	10.0	99	3.0	845

Natural Gas					
Run	S.P. @ Orifice psig	Temp. @ Orifice °F	DP @ Orifice "WC	Q SCFH	S.P. @ Burner psig
111408b	12.75	93	25.2	4621	-
111408c	13.0	93	12.8	3308	-
111408d	13.25	93	6.4	2350	-

Emissions														
Run	Furnace Temp. °F	NOx ppm	% O2	% CO	% CO2	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	TD	Calculated AFR	Desired AFR	Chamber Appearance	NOx #/MMBtu
111408b	2181	71.43	0.00	17.51	5.22	3.35	3.125	8	0.95	1	3.58	3.69	Acceptable	0.03989
111408c	2184	81.20	0.00	17.15	5.60	3.06	3.125	8	1.33	1.33	3.71	3.69	Acceptable	0.04535
111408d	2089	123.71	0.00	16.54	5.97	2.77	3.125	9+	1.87	2	3.48	3.69	Unacceptable	0.06909

Exhibit 1: Detailed Data Tables for 50% Stoichiometric Tests

Appendix 2. Detailed Data Tables for 100% Stoichiometric Tests

Results of 1610-013 Cyclops Burner (1.248 MMBtu/Hr @ 100% Stoichiometric)

*021009 Testing was a nominal NOx Trend

Primary Air										
Primary Air - Gemini					Primary Air - Cyclops					
Run	S.P. @ Orifice	Temp. @ Orifice	ΔP	Q	S.P. @ Orifice	Temp. @ Orifice	ΔP	Q	Total Primary Q	S.P. @ Burner
#	"Hg	°F	"W.C.	SCFH	"Hg	°F	"W.C.	SCFH	SCFH	"W.C.
021009a	3.3	594	8.6	4037	3.3	594	0.1	63	4100	0.7
021009b	3.3	596	8.6	4033	3.3	596	0.1	63	4096	0.7
021009c	3.3	600	8.6	4026	3.3	600	0.1	63	4088	0.5
021009d	3.3	477	0.0	0	3.3	477	11.0	699	699	0.2
021009e	3.3	433	0.0	0	3.3	433	8.3	622	622	0.2
021009f	3.2	498	6.6	3704	3.2	498	0.1	66	3770	0.4
021009g	3.2	419	0.0	0	3.2	419	8.2	622	622	0.2

Secondary Air						
Run	S.P. @ Orifice	Temp. @ Orifice	ΔP	Q	S.P. @ Burner	Secondary Airsplit
#	"Hg	°F	"W.C.	SCFH	"W.C.	%
021009a	3.1	753	10.2	7391	0.6	64.3%
021009b	3.1	756	11.4	7804	0.7	65.6%
021009c	3.1	751	11.0	7682	0.4	65.3%
021009d	3.0	779	21.8	10675	0.8	93.9%
021009e	3.0	784	22.6	10847	0.9	94.6%
021009f	2.9	767	24.3	11308	0.9	75.0%
021009g	3.0	770	22.2	10812	0.8	94.6%

Lance Air					
Run	S.P. @ Orifice	Temp. @ Orifice	ΔP	Q	S.P. @ Burner
#	"Hg	°F	"W.C.	SCFH	"Hg
021009a	3.8	83	1.8	1103	1.6
021009b	3.8	83	1.8	1103	1.6
021009c	3.8	85	1.8	1101	1.6
021009d	3.8	85	1.8	1101	1.6
021009e	3.8	85	1.8	1101	1.6
021009f	3.8	86	1.8	1100	1.6
021009g	3.8	86	1.8	1100	1.6

Natural Gas					
Run	S.P. @ Orifice	Temp. @ Orifice	ΔP	Q	S.P. @ Burner
#	psig	°F	"W.C.	SCFH	"Hg
021009a	16.0	80	5.2	867	0.9
021009b	16.0	82	9.4	1164	1.6
021009c	15.75	88	9.6	1165	1.6
021009d	16.0	87	9.6	1171	1.6
021009e	16.0	88	9.6	1170	1.6
021009f	16.0	94	15.8	1492	2.5
021009g	16.25	94	9.5	1162	1.6

Emissions & Other										
Run	Total Airflow	O2	NOx	NOx	CO	Furnace Pressure	Furnace Temp.	TD	Mode	Calculated AFR
#	SCFH	%	ppm	#/MMBtu	ppm	"W.C.	°F	#	-	-
021009a	12594	6.90	28.25	0.04361	1.22	0.2	1356	1	Gemini	14.52
021009b	13003	2.26	33.63	0.03905	4.88	0.2	1477	1	Gemini	11.17
021009c	12871	2.08	26.01	0.02992	4.88	0.1	1816	1	Gemini	11.05
021009d	12475	2.08	57.58	0.06623	4.88	0.2	1873	1	Cyclops	10.66
021009e	12570	2.17	57.58	0.06655	4.88	0.2	1922	1	Cyclops	10.75
021009f	16178	1.56	74.46	0.08335	6.11	0.1	2097	1	Modified	10.84
021009g	12534	2.41	55.34	0.06478	4.88	0.1	2076	1	Cyclops	10.79

Exhibit 1: Detailed Data Tables for 100% Stoichiometric Tests

DATA APPENDIX 3

1.1 Appendix 3-1. Detailed Data Table for 50% Stoichiometric Tests

Results of 2180-060 HTR Burner (5.22 MMBtu/Hr @ 50% Stoichiometric)

Primary Air						Oxygen					
Run	S.P. @ Orifice ("Hg)	Temp. @ Orifice (°F)	DP @ Orifice ("WC)	Q (SCFH)	S.P. @ Burner ("WC)	Run	S.P. @ Orifice (psig)	Temp. @ Orifice (°F)	DP @ Orifice ("WC)	Q (SCFH)	O2 in Line (%)
022709d	Due to a suspected manometer leak the primary air data that was collected may be incorrect. The measured CO/CO2 ratio provided the basis for determining if the desired firing conditions were met.					022709d	17.0	104	16.0	2202	29.7-29.8
022709e						022709e	9.0	103	9.8	1491	29.4
022709f						022709f	21.0	96	5.1	1329	29.8
022709g						022709g	25.0	100	3.0	1071	29.7
040609b	5.7	644	9.1	8697	7.8	040609b	24.5	100	2.84	1035	29.7
040609c	5.8	624	3.45	5412	3.5	040609c	28.5	100	0.88	605	29.4

Natural Gas				
Run	S.P. @ Orifice ("Hg)	Temp. @ Orifice (°F)	DP @ Orifice ("WC)	Q (SCFH)
022709d	8.00	73	23.5	5426
022709e	8.80	73	11.5	3827
022709f	9.0	74	8.9	3379
022709g	9.30	75	6.2	2829
040609b	8.8	77	4.9	2494
040609c	9.1	80	2.15	1654

Emissions												
Run	Furnace Temp. (°F)	NOx (ppm)	O2 (%)	CO (%)	CO2 (%)	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	Desired AFR	Chamber Appearance	NOx (#/MMBtu)
022709d	2258	13.44	0.03	17.96	5.41	3.32	3.2	3	0.92	3.69	Acceptable	0.00751
022709e	2208	9.22	0.03	17.68	5.23	3.38	3.2	5	1.31	3.69	Acceptable	0.00515
022709f	2208	10.05	0.03	18.00	5.27	3.42	3.2	7	1.48	3.69	Acceptable	0.00561
022709g	2163	11.62	0.03	17.69	5.01	3.53	3.2	9	1.77	3.69	Acceptable	0.00649
040609b	2184	14.83	0.00	17.52	5.96	2.94	3.2	4	2.00	3.69	Acceptable	0.00828
040609c	2123	21.86	0.00	16.74	6.13	2.73	3.2	9+	3.02	3.69	Acceptable	0.01221

Emissions												
Run	Furnace Temp. (°F)	NOx (ppm)	O2 (%)	CO (%)	CO2 (%)	CO/CO2 Ratio	Desired CO/CO2 Ratio	Smoke #	Calculated TD	Desired AFR	Chamber Appearance	NOx (#/MMBtu)
022709d	2258	13.44	0.03	17.96	5.41	3.32	3.2	3	0.92	3.69	Acceptable	0.00751
022709e	2208	9.22	0.03	17.68	5.23	3.38	3.2	5	1.31	3.69	Acceptable	0.00515
022709f	2208	10.05	0.03	18.00	5.27	3.42	3.2	7	1.48	3.69	Acceptable	0.00561
022709g	2163	11.62	0.03	17.69	5.01	3.53	3.2	9	1.77	3.69	Acceptable	0.00649

1.2 Appendix 3-2. Detailed Data Tables for 100% Stoichiometric Tests

Results of 2180-060 HTR Burner (1.48 MMBtu/Hr @ 105% Stoichiometric)

Primary Air						Natural Gas				
Run	S.P. @ Orifice ("Hg)	Temp. @ Orifice (°F)	DP @ Orifice ("WC)	Q (SCFH)	S.P. @ Burner ("WC)	Run	S.P. @ Orifice ("Hg)	Temp. @ Orifice (°F)	DP @ Orifice ("WC)	Q (SCFH)
031209a	Due to a suspected manometer leak the primary air data that was collected may be incorrect. The measured O2% provided the basis for determining if the desired firing conditions were met.					031209a	8.25	80	13.10	1424
031209b						031209b	8.35	81	9.05	1184
031209c						031209c	8.35	82	5.93	957
031209d						031209d	8.35	86	3.28	709
031209e						031209e	8.5	86	0.82	355
031209f						031209f	8.55	90	0.43	257

Emissions								
Run	Avg. Furnace Temp. (°F)	NOx (ppm)	NOx (#/MMBtu)	Measured O2 (%)	CO (ppm)	Burner Static ("WC)	Furnace Static ("WC)	Calculated TD
031209a	2237	185.10	0.201	1.08	1.22	22.0	0.40	1.00
031209b	2199	169.60	0.183	0.97	1.22	15.0	0.30	1.20
031209c	2137	158.85	0.171	0.97	1.22	9.8	0.15	1.48
031209d	2037	144.78	0.155	0.85	1.22	5.2	0.00	2.00
031209e	1808	125.43	0.135	0.86	2.12	1.1	-0.08	3.99
031209f	1692	86.49	0.093	0.86	13.35	0.4	-0.10	5.53

Exhibit 1: Detailed data tables for 100% stoichiometric tests.

1 PHASE I FINAL REPORT

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Executive Summary

The primary objective of this program is to develop and test a scale free heating system that reduces scale formation in the steel reheating process, resulting in a substantial reduction in energy use, improvement in steel quality, and significant cost advantages for the U.S. steel industry. The program is divided in two phases. This report describes work performed, results, and conclusions for Phase I with recommendations for Phase II work to achieve the objectives and goals of the program.

Phase I of the program was carried out by a team consisting of (i) a major steel company, Steel Dynamics, Inc.; (ii) a U.S. reheat furnace supplier (Alchas, Inc. previously known as A.C. Leadbetter); (iii) an industrial gas supplier, Air Products and Chemical Company; (iv) a steel industry organization, The Steel Manufacturing Association – SMA; (v) a forging industry organization, Forging Industry Association – FIA; and (vi) an energy and environmental management company (E3M, Inc.) with extensive R&D and project management experience.

A brief summary of Phase I activities and results are given below.

1. Several options were analyzed for generating process atmosphere required for scale free heating of commonly used grades of carbon steel and options for energy use optimization through waste heat utilization. The options considered are: use of 100% oxygen, “cold” or preheated oxygen enriched air (35% and 45% O₂ in air) and preheated air for sub-stoichiometric combustion of natural gas. A detailed economic analysis model was developed under a separate task to account for effects of all major variables involved in steel reheating. The model results were discussed with the steel industry and for selection of a concept that would offer optimum economics (energy savings and economics) for a large percentage of the steel industry.
2. Several member companies of The Steel Manufacturing Association (SMA) together with Steel Dynamics Inc. (SDI) participated in the program and provided information on current practices, future needs and trends, issues related to scale produced during reheating and guidance in defining requirements for scale free reheating under commonly encountered operating practices. Their information allowed the team to perform detail economic analysis of the options mentioned above. These companies, through SMA, have expressed continuing interest in participation during the next phase of the program. Forging Industry Association, through their Technical Director guided the team to address issues related to use of scale free heating in large forging industry applications.
3. A detail technical and economic analysis model was developed to analyze economics of three possible concepts mentioned earlier. The model included parameters and operating issues such as utility (electricity, natural gas and oxygen) cost, steel charge inlet conditions (cold, warm or hot), several types of delays, operating practices, and value/cost of scale reduction and higher yield. The model was used to analyze various scenarios and design concepts to obtain energy savings and overall economics of each concept. Several cases were analyzed using common operating practices for a typical steel reheat furnace (150 tons/hour capacity),

and other parameters defined with the steel industry input. The results indicate that use of 1000 deg. F. preheated air for reheat furnaces charged at steel temperature of up to 700 deg. F. offers the best economics with less than 2 years payback period. For reheat applications using hot charge and for furnaces used in batch mode as in case of many forging furnaces, it may be necessary to use 100% oxygen or oxygen enriched air with a proper heat recovery system to achieve acceptable (< 3 years) payback. Selection of economically justifiable heat recovery system is critical for use of SFH in such applications.

4. The team with guidance from SMA member steel companies and FIA's Technical Director selected a concept that uses preheated air in continuous furnaces with cold or warm charged steel for detail design and economic analysis. These applications cover approximately 64% of the steel produced in USA. The same concept can be applied to continuous large forging furnaces such as rotary hearth furnaces for additional 3 to 5 MM tons of steel reheated for forging. Scale free heating applications for the remaining 36% of the steel producer market require added economic justification for waste heat recovery system. At current energy prices (electricity at 4 cents/kWh and natural gas at \$7.00 per million Btu) it is not possible to achieve less than 3 years payback period for this market segment using steam generation-power production system for heat recovery. It is anticipated that advances in power system equipment, increased utility prices experienced in certain regions and higher value allocation to scale reduction would improve the economics for use of scale free heating in some of these applications.
5. A preliminary analysis of the furnace requirements (combustion system, safety, effect of delays and other operating parameters in furnace operation) was carried out in cooperation with the steel industry. The analysis shows that it is possible to design, test and use a combustion system (burners) that can meet critical requirements of scale free heating without compromising safety in a steel plant. It is necessary to carry out detail analysis, design and testing for critical design issues and hardware during Phase II of the program.
6. A comprehensive summary of accomplishments of Phase I and plans for Phase II are prepared and reported in form of a Go-NoGo decision matrix.

Introduction

The primary objective of the proposed project is to develop and test a scale free heating system that reduces scale formation in steel reheating process resulting in substantial reduction in energy use, improvement in steel quality and significant cost advantages for the U.S. steel industry including the mini- mills, and integrated mills as well as other associated industries such as forging where steel reheating is used.

The U.S. steel industry reheats approximately 100 million tons of steel per year using specific energy of 1.4 Million (MM) Btu/ton to 1.8 MM Btu/ton of steel with total energy consumption of about 160 Trillion Btu (TBtu) per year. During the reheating process steel is heated to approximately 2100 deg. F. temperature before it is rolled into the desired shapes. Reheat furnaces are fired by gaseous fuels such as natural gas and, in some cases, by-product fuels such as coke oven gas. These furnaces process a large amount of steel, typically from 100 tons/hour to as much as 300 tons/hour. Typical reheating time for large cold billets and slabs vary from 1 hour to 3 hours during which time 1% to 2% of the steel being reheated oxidizes and forms scale.

Oxidation of steel or scale formation during reheating is a major concern to the steel industry. The scale represents loss of value added product and energy used to produce the steel that has to be produced from iron ore. The energy loss or energy required to replenish the steel lost as oxide amounts to additional 20 TBtu/year. This is in addition to 160 TBtu/year used for reheating process itself. In the year 2005, the U.S. steel industry uses about 2,000 TBtu per year (Ref. 1) . Thus total energy associated with steel reheating and scale loss represents about 9% of the total energy used by the U.S. steel industry. Value of the product loss due to scale formation is about 750 million dollars per year when we assign product value for steel at the reheating stage as \$500 per ton. In addition to the energy loss and product loss, significant costs are incurred by the reheat furnace operators in use of manpower and time used to collect and remove the scale and to conduct maintenance for the furnace. In economic terms scale related costs represent about 50% of the reheating cost while energy represents about 35% of the reheating cost.

In the past the steel industry has made several attempts to eliminate or reduce scale losses during reheating. These are discussed in a later section. However none of them have been widely used due to cost and difficulty in design of large systems with production rates of 100 tons/hour to 300 tons/hour. The steel industry has continued to use large furnaces that use several variations of material handling systems (pusher, roller hearth, walking beam, walking hearth etc.) with the same basic approach of reheating of steel by using combustion generated heat. None of the above mentioned proposed scale free heating systems can be designed and applied to currently used large furnaces.

The proposed system developed and analyzed during Phase I of this program uses products of sub-stoichiometric (rich) combustion of natural gas generated by a preheated air burner or oxygen enriched air burner to produce a non-oxidizing furnace within the furnace itself. The

atmosphere is “tailored” to prevent scale formation as the steel slabs or billets are heated in the furnace to minimize “chemical” and sensible heat losses from the furnace. The resulting hot furnace exhaust gases are discharged into a recuperator that is used to preheat combustion air required to generate scale free atmosphere in the furnace. Details of the system are discussed later in this report. This approach does not require any major change in basic furnace design or material handling system and can be retrofitted within the current charging and discharging system.

Detail technical and economic analysis conducted in Phase I shows that energy savings can be achieved in three areas: (a) saving of energy (0.2 MM Btu/ton of steel reheated) that is used to produce steel that is lost as scale; (b) reduction (0.18 MM Btu/ton) in energy used for reheating of steel in the furnaces; and (c) reduction in energy associated with handling and disposal steel of steel – not included in the total energy savings.

This scale free heating process can be applied to different types of reheat furnaces (walking beam, pusher, pusher hearth etc.) used for 64% of the total steel being reheated by U.S. steel industry. The system can be applied to rest of the 36% of the U.S. market that uses hot (>700 deg. F.) charging of steel with use of an appropriate and economically justifiable heat recovery system such as production of steam and power generation.

Detail analysis of the requirements for commercial application of such a furnace is conducted under Phase I and it is concluded that it is possible to build and operate a scale free heating system that can be used by large number of steel plants in the USA. Phase I results of the project were presented to about 30 industry representatives (members of SMA) at a conference held I March 2006 as well as in a widely attended conference call in August 2006. In each case the attendees expressed keen interest in development and use of such a system provided a number of issues related to furnace and combustion system, operation of the furnace and product quality are addressed in detail by using appropriate tests. These issues will be addressed during Phase II of the program.

In addition to product and process related issues raised by the steel industry representatives, results of Phase I analysis show that it is necessary to demonstrate performance of combustion system that can meet critical requirements of furnace operation under scale free as well as conventional operating conditions to meet practical operating requirements of the steel industry. This requires coordinated efforts by a furnace supplier experienced in design of large steel reheating furnaces, a combustion system (burner) supplier and the steel industry. These requirements will be met by a team consisting of a U.S. reheat furnace supplier (Alchas, Inc.), a major combustion system supplier to the steel industry (Bloom Engineering) and Steel Manufacturing Association (SMA) with its members providing input on specific requirements of the steel industry.

A detailed analysis of issues that need to be addressed for making a Go/NoGo decision is presented as a part of this report.

Background

Reheating of steel prior to rolling or forging operations to produce a number of semi-finished steel shapes such as hot rolled coils, long products, flat products or forgings is an important operation used by integrated and mini-mills as well as several major finishing companies. During this process steel slabs, billets and blooms, varying from thickness of less than 2 inch to 10 inch, are heated in reheat furnaces to approximately 2100 deg. F. starting from ambient temperature or higher temperature (about 1600 deg. F.) in the case of thin slab casting. In the U.S. most of the steel reheat furnaces use heat generated by combustion of gaseous fuels such as natural gas and, in some cases, by-product fuels such as coke oven gas. Typical reheating time for large cold billets and slabs vary from 1.5 hours to 3 hours while for thin slabs of approximately 2.5 inch thickness entering a furnace at higher temperature (1500 to 1700 F surface temperature) typical heating time varies from 12 to 20 minutes. Reheating is an energy intensive process using 1.4 to 1.8 MM Btu/ton for conventional furnaces with “cold” charge and approximately 0.6 to 0.8 MM Btu/ton for tunnel furnaces using hot, thin slabs.

Oxidation of steel represents loss of energy and value added product. Typical cost distribution of reheating of steel shown in Figure 1 below indicate that scale related costs represent 52% to 58% of the total cost and it is the highest percentage of the reheating cost. This is not only due to cost of loss of marketable steel at value added stage of steel production but during reheating furnace operations the scale presents several problems. The scale accumulates at the bottom of a furnace, affecting flow of gases and heat transfer to steel being heated, it has to be collected and removed frequently requiring production interruption with its effects on downstream operations (i.e. rolling and finishing) and it has to be reprocessed. Presence of scale also affects life of refractory/insulation and other parts within the furnace requiring additional maintenance costs.

Figure 1: Cost distribution for reheat furnace for thin slabs (left graph) and conventional walking beam reheat furnace (right graph).

Presence of scale has a major negative effect on the steel quality also. During reheating process tight scale adheres to the slab surface and it is extremely difficult to remove it even with the use of a variety of descaling techniques used by the industry. This scale then gets into the rolled product and results in defects or unacceptable physical and metallurgical properties. Scale generated on the bottom surface in a tunnel furnace is a unique and added

problem. The scale generated by the process described above is continually knocked off by the rolls within the furnace. This results in the total scale reaction never being carried to completion and a tight scale is present on the bottom surface. The tight scale is difficult to remove by the in line de-scaling process and leads to rolled in scale on the bottom surface. The primary driver for steel oxidation or scale formation is chemical reaction between iron (Fe) with oxygen bearing gases such as O_2 , CO_2 and water vapor (H_2O) at high temperature required during the reheating process. Weight of scale depends on temperature of the steel surfaces exposed to oxidizing gases, time allowed for reaction and percentages of oxidizing gases presence in the heating gases. Current methods of heating using excess air combustion of hydrocarbon based fuels such as natural gas and coke oven gas results in generation of about 12% CO_2 and 20% water vapor (H_2O). These gases are in contact with steel surfaces at temperatures from ambient (~ 80 deg. F.) to 2100 deg. F. for a time period of 1.5 to 3 hours. This results in formation of surface oxides whose weight depends on several factors such as exact composition of steel, method of material handling, “soak” and heating time distribution in the furnace, steel loading in the furnace etc.

The oxide formation can be prevented by using one or all three of the following operating procedures. They are: (i) use of non-oxidizing gases or process atmosphere; (ii) shorter heating time; and (iii) use of lower drop-out or discharge temperature. Lower discharge temperature would have major negative effects on the downstream rolling process and is likely to be the most unacceptable. Heating time is controlled by the slab inlet temperature, final temperature and thickness of the slab. For a given heating system it can be somewhat reduced by increasing surface heat flux. However use of proper non oxidizing gases can eliminate the scale formation.

The steel industry has experimented with several methods to eliminate use of combustion products in direct contact with the steel shapes reheated in a furnace or reduce heating time. such as induction heating and use of radiant tubes with non oxidizing atmosphere in furnaces to eliminate or reduce scale losses during reheating. Induction heating was attempted at 2 U.S. mini-mills while there is no recorded case of use of radiant tube based hating for large steel reheating furnaces in the U.S. A.

The “basics” of the scale free heating system have been discussed by several furnace and burner suppliers since 1960s (Ref. 2 and 3) however several issues such as energy efficiency, practical design of combustion system, particularly the burners, and furnace itself prevented the industry from use of these principles for large reheat furnaces used today.

The basics of oxidation of steel teach us that the oxidation reaction actually depends on ratio of CO/CO_2 and H_2/H_2O in the reacting gases. Theory of these reactions is discussed in the next section. Scale formation during reheating can be eliminated by controlled combustion of natural gas so that required values CO/CO_2 and H_2/H_2O are maintained of at high temperature. It is possible to use products of sub-stoichiometric (rich) combustion of natural gas generated by a preheated air burner or oxygen enriched air burner to produce a non-oxidizing furnace within the furnace itself. However use of sub-stoichiometric combustion requires consideration of several factors that can affect energy use, cost of the heating system,

operating flexibility etc.

All of these issues were addressed during Phase I of this program by a team that included experienced personnel from a furnace company, an end user steel company, a combustion system supplier with very strong name recognition in the Global steel industry, and experienced research workers. The team members, each with experience of 25 to 30 years each, in their respective fields contributed to development and analysis of a scale free heating system that can be applied to large steel reheating furnaces used by the steel industry. Details of the team member qualifications and experience are given in a later section of this report. The project was focused on development of a system that can be retrofitted to an existing furnace without making major changes to the basic furnace structure or its operating procedures, particularly the material handling system associated with charging and discharging of slabs or billets.

The system proposed and analyzed during Phase I of the program is shown in Figure 2.

Figure 2: Scale free steel reheating system for furnaces using "cold" charge

The system for reheating cold charge (slabs or billets) used by about 65% of the U.S. steel industry consists of commonly used material handling system (walking beam, pusher, pusher hearth etc.) and conventional furnace – burner arrangement. However the burners are arranged such that they are fired at highly fuel rich (sub stoichiometric) condition using preheated air in excess of 1000 deg. F. or oxygen enriched air with O₂ content in excess of about 45% to produce the required gas composition (CO/CO₂ and H₂/H₂O) ratios while maintaining the required "flame" temperature. The combustion products from the soak zone travel counter current top the flow of steel. The gases are "burned" or reacted by using

preheated air to produce more heat and change ratio of CO/CO₂ and H₂/H₂O while making sure that they still remain “non-oxidizing” for the steel as it is being heated from lower to higher temperature. Thus the furnace atmosphere is “tailored” to prevent scale formation as the steel slabs or billets are heated from in the furnace to eliminate scale formation while releasing chemical heat of the fuel and minimizing “chemical” and sensible heat losses from the furnace. The resulting hot furnace exhaust gases, with near zero CO and H₂ in them, are discharged into a recuperator that is used to preheat combustion air required to generate scale free atmosphere in the furnace.

This approach does not require any major change in basic furnace design or material handling system and can be retrofitted within the current charging and discharging system. As discussed later, for 65% of the steel reheating applications, combustion of the ‘scale free’ heating gases is completed within the furnace by using highly preheated air or oxygen enriched air. Use of higher air preheat and better furnace design using modern methods of insulation, unfired preheat section and advanced controls offers potential to reduce the energy intensity (Btu/ton of steel) for the scale free furnace design.

In addition to savings in steel material itself, use of this system to a reheating furnaces offers energy savings of (i) 0.2 MM Btu/ton that is used to replenish steel lost as scale; (ii) 0.18 MM Btu/ton in energy used for reheating of steel in the furnaces; and (iii) reduction in energy associated with handling and disposal steel of steel – not included in the total energy savings. This scale free heating process can be applied to different types of reheat furnaces (walking beam, pusher, pusher hearth etc.) used for 65% of the total steel being reheated by U.S. steel industry. The rest of the 35% of the U.S. market uses hot (>700 deg. F.) charging of steel. In such cases it is not possible to complete combustion of CO and H₂ in flue gases within the furnace itself. Flue gases discharged from this furnace could contain about 12% CO and 16% H₂ with as much as 70% of the total heat input in the furnace. A part of the heat can be used for preheating combustion air when the system uses preheated air based combustion system however a large percentage of the heat of flue gases will have to be recovered for other uses to achieve acceptable energy efficiency for the furnace. A typical system for “hot” charged furnaces is shown in Figure 3.

Possible uses for the available heat from flue gases include:

- Steam and power generation by using a conventional high pressure (>250 psig) steam generator combined with a steam turbine-generator system.
- Use of steam within the plant if the plant uses steam for other heating processes or it is required for HVAC applications.
- Reduction of iron ore by using the rich combustion products when the gases contain high percentage of CO and H₂ as in case of oxygen fired system.
- Use of heat for producing hot water and/or low pressure (~50 psig) steam for use in an absorption chiller system to produce chilled water and/or refrigeration.
- Use of non-conventional (i.e. thermo-electric) power generation

After discussing possibilities of use of these systems with the steel industry it was realized that the only practical method of using the heat is to use steam-power cycle.

Figure 3: Scale free steel reheating system for furnaces using “hot” charge

Detail analysis of costs for using a steam based power generation cycle shows that at current level of gas and electricity prices, it would be difficult to justify long payback period (in excess of 5 years). Hence the team decided to concentrate on systems that offer attractive (2 to 3 years) payback period as it can serve almost $\frac{2}{3}$ rd of the steel market.

Literature Search

During Phase I of this program an extensive search for the available literature (Ref. 4 to 6) was made and several and private industry contacts and research workers were contacted to investigate work done in the area of preventing scale or oxidation of steel under. Early attempts by companies included attempts to design furnaces similar to those used for heat treating of metal parts in which reacting atmospheres such as non-oxidizing atmospheres is used to prevent scale and/or carburize carbon steel. These atmospheres include endothermic or exothermic gases containing a mixture of nitrogen with H_2 and CO (sub stoichiometric combustion products of natural gas and other hydrocarbons such as propane). An early paper by Mr. Fred Bloom delivered at a meeting of the Association of Iron and Steel Engineers (AISE) at Chicago, IL in September 1963 mentioned that such attempts included use of radiant tubes, electrical heating elements or muffle furnaces that heated steel in presence of non-oxidizing gas mixture with proper atmosphere commonly used in heat treating operations. Apparently, requirements such as very high heating temperature requirements (in excess of 2000 deg. F.), temperature limitations of the materials for radiant tubes at that time and large furnace capacity for steel reheating applications made it difficult if not impossible to justify use of such systems.

Later attempts were proposed to use proper mixture of Carbon Monoxide (CO) and Carbon Dioxide (CO_2) with Water vapor (H_2O) and Hydrogen (H_2) generated from a direct fired burner that was operated at sub stoichiometric combustion of above mentioned fuels. The same paper describes design and operation of a pilot plant operating at one ton per hour capacity and used of heating steel slugs for an extrusion press. The system operated in a batch mode and used a burner operating at sub stoichiometric condition to heat billets and deliver them without significant amount of scale. This proved that it is possible to heat billets without forming scale by using direct fired burners.

During late ninety-sixties a paper was presented at AISE in which Seals Corporation of America described theory and practical use of direct fired flue gases for scale free heating of various types of carbon steels. Following information is derived from this paper. During reheating process steel is exposed to high temperature combustion products of fuel (i.e. natural gas) that include N_2 , H_2O vapors, CO_2 and O_2 . Composition of combustion products depends on the air (oxidant) – fuel ratio used for combustion. Use of sub stoichiometric combustion with air-fuel ratio of less than 10 for natural gas produces non-oxidizing gases such as CO and H_2 together with oxidizing gases CO_2 and H_2O . At 50% stoichiometric ratio combustion the product gases contain 10% CO and 17% H_2 with 4% CO_2 and 10% H_2O making CO/ CO_2 ratio of 2.5 and H_2/H_2O ratio of 1.7. These gases are non-oxidizing for the steel even at 2400 deg. F. steel temperature.

The amount of scale formed depends on three major factors: (i) temperature at the gas-steel interface, (ii) gas composition and (iii) time at temperature for the steel. Presence of CO and H_2 in combustion products decreases formation of oxides on the steel surface. Actual oxidation rates are dependent on ratio of CO/ CO_2 and H_2/H_2O . Higher values of these two ratios would reduce and ultimately eliminate oxidation reaction. In fact, it is possible to reduce iron oxides into iron by using very high values of these ratios. Figure 4 shows steel

loss as scale weight in terms of lbs. per sq. ft. of the surface area at different steel surface temperatures for different time exposure, varying from 0 to 7 hours while exposed to combustion products of natural gas combustion at stoichiometric air-fuel ratio. These gases, theoretically, do not contain any oxygen or combustible components, however in practical applications both of them may be present in small amounts. It is apparent that scale formation rate depends on time and temperature. Rate of scale formation is very high during the initial period and it slows down as the exposure time increases. Depending on the thickness of the steel being heated the scale could be as high as 0.3 lb/sq. ft to 0.5 lb/sq. ft. at one hour exposure.

The paper reported that Scaling is depressed by increased percentage of alloy elements such as chromium, nickel or molybdenum in the steel. The scaling process begins through formation of an iron oxide film at the metal surface and progresses by diffusion of oxygen into the resulting iron-iron oxide interface. This diffusion process of the oxygen into the metal is a function of the potential energy of the system, characterized by a general relationship that is exponential with temperature and parabolic with time. It can be represented by an equation:

$$M = a * \{t * (e^{(-b/T)})\}^{0.5}$$

Where M = Metal loss, Lbs./sq. ft.

t = time in hours

T = Temperature [deg. R, or (Deg. F. +460)]

A, b = constant for type of steel

e = Napier logarithmic base

This equation looks straight forward however the main hurdle in its use is getting values of constants a and b. They vary with the steel composition and also the gas composition (although not specifically stated in the paper) and it is necessary to derive their value by experimental data analysis. The primary driver for scale formation is chemical reaction between iron (Fe) with oxygen heating gases such as O₂, CO₂ and water vapor (H₂O). Oxidation reaction of steel and gases depend on ratio of CO/CO₂ and H₂/H₂O in the reacting gases.

The paper further describes effect of products of rich or sub stoichiometric combustion of natural gas. Figure 5 shows effect of heating steel samples in presence of natural gas combustion products at different percent of stoichiometric combustion air or air-fuel ratios.

Figure 4: Steel loss by oxidation during heating in products of natural gas combustion

Figure 5: Steel loss by oxidation during heating at various air-fuel ratios.

It gives steel loss as scale weight in terms of lbs. per sq. ft. of the surface area at different steel surface temperatures for one hour exposure and at different heating time and rich combustion air-fuel ratio. It shows that, as observed earlier, scale loss is a very strong function of temperature and the rate of scale loss goes down rapidly as the air-fuel ratio is lowered going into sub stoichiometric region. It is concluded from the previous data, that the rate of scale formation is strong function of time in the beginning but it levels off (rate goes down) as exposure time is increased.

Additional information on effect of constituents in the combustion products (CO , CO_2 , H_2 , and H_2O) is described by classical curves developed by Murphy and Jominy and by A.L. Marshall (Ref. 7). These curves (Figures 6 and 7) define the equilibrium temperature at which various gas ratios (CO_2/CO and $\text{H}_2\text{O}/\text{H}_2$) are neutral to iron. Thus for any particular steel surface temperature, if both ratios are held to the left of the curves, the gas mixture would be reducing or non-oxidizing to iron. Conversely if both ratios lie on the right side of the curves the relationship will be oxidizing. These curves can be used to define the required gas composition in terms of the ratios CO/CO_2 (or CO_2/CO) and $\text{H}_2/\text{H}_2\text{O}$ (or $\text{H}_2\text{O}/\text{H}_2$) for scale free heating of iron and steel.

The steel reheating process used by the steel industry as well as forging industry requires heating of steel in a temperature range of 2000 deg. F. to 2200 deg. F. Information derived from above can indicate that it is necessary to maintain CO_2/CO ratio below about 0.3 (or CO/CO_2 ratio above about 3.33) and $\text{H}_2/\text{H}_2\text{O}$ ratio below 0.8 (or $\text{H}_2/\text{H}_2\text{O}$ ratio above about 1.25) for scale free heating of steel in steel industry or forging industry. Practical methods of obtaining these gas compositions and its effect on fuel use as well as economics of the reheating process are investigated in detail and are described in a later

section.

Figure 6: Effect of H₂O/H₂ ratio on steel oxidation - reduction

Figure 7: Effect of CO₂/CO ratio on steel oxidation - reduction

A furnace system based on above principles was designed and used for heating of forgings. The literature search also included investigations in mechanism of formation of iron oxide, often referred to as “mill scale” or simply scale and its nature.

This information is very useful in understating scale formation in practical applications where the steel slabs and billets are subjected to movement that could affect scale formation and breakdown resulting in considerably more scale loss than predicted by the theoretical considerations discussed above.

The scale consists of three types of iron oxides, FeO₂, Fe₂O₃ and Fe₃O₄, each with slightly different Fe content. The oxides are known as Hematite (Fe₂O₃) with 69.9 iron content, Magnetite (Fe₃O₄) with 72.4% iron content and Wustite (FeO) with 77.7% content. As described in Ref. 8, the mechanism of scale formation and build up is a dynamic phenomenon. The first oxide is formed as Fe₂O₃ and it is reduced to Fe₃O₄ and FeO as the successively formed oxides react with iron (Fe). Additional Fe₂O₃ is formed at the atmosphere-surface interface and the process becomes continuous resulting in a scale composed of layers. The scale formed in reheating contains all three layers in different thickness as shown in Figure 8. As discussed earlier the total scale thickness is function of time at temperature, and composition of the gases reacting with the surface. However the ratio of relative thickness layer remains constant. Hematite is a very “tight” oxide while Wustite is a “spongy” or “flaky” scale that can be removed easily.

Figure 8: Composition of scale formed on steel surface during reheating

Scale formation for commonly used steel has been studied in detail by Schultz (Ref. 9) during late ninety sixties. The studies included oxidation of two grades of steel samples using various gas mixtures to simulate combustion products generated by sub-stoichiometric combustion of natural gas under Air/Gas ratio of 5.0 to 9.5 or 53.5% to 100% combustion air required. Within a temperature range of 1600 deg. F. to 2200 deg. F.

The results indicate that free oxygen greatly increased the oxidation rate and the scale composition was much different than the scale formed in air. It also indicated that scale formed by CO₂ and H₂O generally were gray in color as opposed to black color for the oxide formed in air. Amount of scale formed can be calculated by using the following correlation.

$$W = (Ro/K2) - [(Ro/K2) - Wo] * \exp (K2 * t)$$

Where

W = Weight of O₂ in scale (Lb. O₂/ft²) at the end of time t minutes

Wo = Weight of O₂ in scale (Lb. O₂/ft²) at the beginning of scale formation

Ro = Initial oxidation rate {Lb. O₂/(ft²-min)}

K2 = Decay constant dependant on the reaction temperature

T = time in minutes

Values of constants K2 and Ro are given in a graph form.

Work done by Schultz (Ref. 9) was used to design a number of rotary hearth furnaces supplied to a forging industry company to produce steel billets prior to forging. The test results for the furnaces indicated that it is possible to produce scale free steel for forging application. It should be noted that very little consideration was given to the fuel cost for such application since natural gas was considered extremely cheap (<\$1 per MM Btu) at the time when these furnaces were installed and operated.

The scale free process development and testing was revisited by a team consisting of A.C. Leadbetter, Inland Steel Corporation and Indugas during mid eighties. The project was supported by The Gas Research Institute. Several tests were carried out at Inland steel using various grades of steels using a small test facility.

Overview of Alternate Systems

During the last 40 years several systems have been proposed, analyzed and tested for scale free heating of steel. Only a few have been tried at commercial scale. One of the alternate systems studied is shown in Figure 9. It includes heating of steel under non oxidizing gases (commonly referred to as atmospheres) using heat transferred from radiant tubes or a muffle. In this system combustion products of fuel such as natural gas is used to heat a metal (or ceramic) tube or muffle that surrounds the steel being heated and steel is heated by primarily radiation heat transfer from the tube or muffle.

Figure 9. Use of a muffle or radiant tubes for scale free heating of steel

Such a system presents several problems when it is proposed for heating steel at large (100 to 300 tons/hour) production rates. Heat transfer considerations for large scale production would make the furnace size very large. For example a typical radiant tube can deliver heat flux of 5,000 Btu/hr. ft² at the high temperatures required for steel reheating and heat requirement per ton of steel is about 330,000 Btu/lb. The total surface area required for radiant tubes in a typical 100 tons/day furnace would require more than 200 tubes that need to operate at material temperature higher than 2200 deg. F. higher. At this time very few materials can operate at such high temperatures without presenting unmanageable maintenance problems. Similar considerations require use of a very large muffle with total surface area in excess of 3000 ft². Design considerations such as support of the muffle, allowance for thermal expansion, possible thermal creep etc. make such a design extremely challenging and unmanageable.

In modern times no company has used such a furnace for heating large tonnage of steel.

Use of electrical heating elements to supply heat directly to the steel shapes (slabs, billets, blooms etc.) present even more severe challenges. The issues that need to be addressed include selection of material for the heating elements, size and shape of the elements, their support, possibilities of contact between steel shapes and electrical heating elements, size of power supply and required controls etc. would make such design impractical.

Use of induction heating as an alternate to conventional reheating of slabs and billets has been attempted by induction heating equipment suppliers. These systems were promoted to offer an alternate to fuel fired heating furnaces with advantages of faster heating time and hence lower scaling rate for the steel. These systems used by the industry can be classified in two

major categories.

The first category of systems are smaller and used by forging industry to reheat round or rectangular billets used for forgings. These systems vary from relatively small size (200 kW for heating about 1000 lb/hr. steel) to large systems (2 Mw for heating 12,000 lb./hr steel). Several systems are installed and are operating throughout the U.S.A. These systems offer fast heating, relatively small amount of scale and eliminate issues of emissions from furnaces. The second category of systems is promoted for large steel mills where production rates are order of magnitude larger than those used by the forging industry. Induction heating systems for heating slabs are not used extensively by the steel industry. During the last 40 years two systems have been installed and operated in steel mills. These systems were installed and operated during time frame of 1970s to 90s.

A system supplied by Ajax Magnethermic Corporation was installed at Alleghany Ludlum plant (formerly Washington Steel) in 1976. The system had a power capacity of 19.8 Mw. The installation consisted of three furnaces with an energy input of 6,600 kW from each coil however it was normally run at 4,000 kW. The furnace was designed to reheat stainless steel slabs 6 inch x 4 ft. 3 inch x 26 ft. 3 inch long from ambient temperature to 2300 deg. F. It was designed to operate at maximum 60 tons/hour capacity. These furnaces were also used for heating titanium and zirconium slabs. Energy consumption for this installation is stated to be between 300 to 400 kWh per ton or approximately 1.02 MM Btu/ton to 1.36 MM Btu/ton. At a cost of 4 cents/kWh this represents \$12 to \$16 per ton of steel.

Other induction heating system was installed at Geneva Steel in 1995 and it operated for 6 years. The system had a total power capacity of 42 Mw. Figure 10 shows photographs of general arrangement of the furnaces and condition of the slab as it discharged from the furnace at Geneva Steel.

Figure 10. Slab reheating furnaces using Induction heating at Geneva Steel

The system was configured with 7 independent induction coil assemblies and power supplies rated for 6 MW. This was considered to be the largest running installation the world. Each induction coil assembly (approximately 65 inch long) was followed by a specially designed water cooled roll. The furnace was approximately 50 ft. long. It was used to reheat steel slabs up to 126 inch wide and up to 36 feet long and 8.6 inches thick. The furnace was used to heat hot slabs from soaking pits to raise slab temperature by 300 deg. F. before rolling.

Study of Alternatives for Direct Fired Scale Free Heating (SFH) Systems

Scale free heating of steel in large furnaces requires use of direct fired system that meets following requirements:

- Proper composition of combustion products, specifically ratio of CO/CO₂ and H₂/H₂O
- High enough gas temperature or “flame” temperature to achieve the required heat transfer from furnace gases to the steel charge
- Maximum possible available heat in the furnace or minimum heat content in flue gases exiting the furnace

These requirements can be met by using proper combustion of natural gas in a direct fired burner used in a furnace.

During this phase of the program extensive studies were carried out to analyze effect of key combustion parameters that would help us meet the required conditions. Thermal equilibrium analysis was used to study effect of several combustion conditions that would result in the required combustion products composition, adiabatic flame temperature and available heat when natural gas is reacted with preheated air and oxygen enriched air or 100% oxygen. The gas composition used for the calculations is given below. Composition of the natural gas in terms of % volume fraction for each constituent is given below (Table 1).

Table 1. Composition of natural gas sued for thermal equilibrium calculations

CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	CO	H ₂	CO ₂	O ₂	N ₂	TOTAL
94.15	3.01	0.42	0.28	0.00	0.01	0.71	0.01	1.41	100

Analysis was carried out for the conditions shown in Table 2.

Table 2. Combustion conditions used in thermal equilibrium calculations

Oxidant	Oxidant Temperature (Deg. F.)	Range of Stoichiometric Ratio
100% Oxygen	Cold (~ 60 deg. F.)	50% to 100%
45% Oxygen in air	Cold and 1000 deg. F.	50% to 60%
35% Oxygen in air	Cold and 1000 deg. F.	50% to 60%
21% Oxygen in air	1000 deg. F.	50% to 70%

The analysis was carried out for operating temperature of 1200 deg. C. or 2192 deg. F. that is the closet temperature to operating conditions of soak zone in a reheat furnace. Please note that scale

forming rate at lower temperature with the gas compositions defined at higher temperature is going to be much less. Table 3 shows results of the analysis carried out to obtain gas composition and available heat values used in calculations.

Table 3. Results of thermal equilibrium conditions

100% Oxygen							
Cold air	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
100% Stoich	72.4	1.7	64	2.1	31.8	37.65	15.14
80% Stoich	50.2	15.17	50.53	14.42	19.41	3.33	1.35
70% Stoich	39.2	23.1	42.6	19.4	14.4	1.84	0.74
60% Stoich	28.3	31.8	33.9	23.6	10.2	1.07	0.43
54% Stoich	21.8	37.3	28.4	25.9	8	0.76	0.31
50% Stoich	17.5	41.1	24.6	27.2	6.6	0.60	0.24

45% Oxygen							
Cold air	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
50% stoich	12.3	29.5	17.6	19.5	4.7	0.60	0.24
60% stoich	22.1	21.6	23	16	6.9	1.06	0.43

45% Oxygen							
1000 deg. F. air	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
50% stoich	16.3	29.5	17.6	19.5	4.7	0.60	0.24
54% stoich	20.55	26.2	19.9	18.1	5.6	0.76	0.31
60% stoich	26.9	21.6	23	16	6.9	1.06	0.43

35% Oxygen							
Cold air	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
50% stoich	14.7	25.7	15.4	17	4.1	0.60	0.24
54% stoich	18.8	22.6	17.2	15.7	4.8	0.76	0.31
60% stoich	25	18.5	19.7	13.7	5.9	1.06	0.43

35% Oxygen							
1000 deg. F.	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
60 Stoich.	25	18.5	19.7	13.7	5.9	1.06	0.43
50 Stoich.	14.7	25.7	15.4	17	4.1	0.60	0.24

21% Oxygen							
1000 deg. F.	Av. Heat	H ₂	H ₂ O	CO	CO ₂	H ₂ O/H ₂	CO ₂ /CO
70 Stoich.	29.6	7.12	16.56	6.18	5.82	2.33	0.94
50 Stoich.	11.5	16.87	12.13	11.39	3.31	0.72	0.29

Based on earlier analysis of oxidation of iron in presence of a mixture of gases containing CO₂, H₂O, CO and H₂ show that it is necessary to have a CO₂/CO₂ ratio of 0.32 and H₂O/H₂ ratio of 0.8 to avoid oxidation at about 2200 deg. F. temperature at the interface. By assuming interface temperature of

2200 deg. F. we are safe since the gas temperature is always higher than temperature of the material (steel in this case) being heated.

Analysis of the results indicate that for all cases it is necessary to have a stoichiometric ratio of oxidant and natural gas at 54% stoichiometric (or richer) to achieve the required values of CO₂/CO and H₂O/H₂ ratio. However there is a big difference in available heat and hence overall fuel use for the furnace. The following Table 4 shows the available heat at 54% stoichiometric combustion for various possible scenarios for natural gas combustion.

Table 4. Values of available heat at 54% stoichiometric combustion

100% O ₂ - cold oxidant	21.80	%
45% O ₂ - cold oxidant	16.22	%
45% O ₂ - 1000 Deg. F. oxidant	20.55	%
35% O ₂ - cold oxidant	18.80	%
35% O ₂ - 1000 Deg. F. oxidant	20.10	%
21% O ₂ - 1000 Deg. F. oxidant	17.78	%

The table shows that it is possible to achieve highest available heat using 100% oxygen as oxidant for sub stoichiometric combustion of natural gas required for scale free heating in a steel reheating furnace. Available heat drops as oxygen content of the oxidant (air) is reduced. However available heat can be increased by preheating the "air" or oxidant by using heat of the exhaust or flue gases from the furnace. Note that it is not practical to preheat 100% oxygen due to limitations on available material that can be used with higher temperature oxygen. However it is practical to preheat enriched air when O₂ content is in the range of 21% to 45%. The results show that preheating 45% or 35% enriched air to 1000 deg. F. allows us to get available heat that is very close to that obtained by 100% oxygen used for combustion. Use of ambient air with 21% O₂ content at 1000 deg. F. would give us available heat of 17.78%. Thus use of oxygen enriched air can help us get an additional available heat and correspondingly lower fuel use however it still requires preheating of the "air" and hence need for a heat recuperator. Oxygen enrichment also requires additional operating cost for oxygen. The following Table 5 gives amount of O₂ required for combustion in terms of cu.ft. of O₂ per cu.ft. of natural gas used in the burner.

O ₂ in "air"	Oxygen required ft ³ /ft ³ of natural gas	O ₂ cost/MM Btu input
100% O ₂	1.064	\$ 2.25
45% O ₂	0.718	\$ 1.52
35% O ₂	0.539	\$ 1.14
21% O ₂	0.000	\$ -
Note: This is 54% stoichiometric combustion conditions		

Table 5. Cost of oxygen per MM Btu burner input

This table also includes cost of oxygen per MM Btu burner input. Please note that oxygen cost is based on \$50 per ton of overall cost or 21 cents/100 scf. Obviously the total cost of oxygen delivered to the burner could be different from the value used and the user should use appropriate value for their economic calculations.

Based on evaluation of available heat, need for auxiliary equipment such as a recuperator used to preheat combustion air or oxygen enriched air (35% or 45% oxygen content) and ongoing cost of oxygen, it was decided that we will pursue two possible options, one with 1000 deg. F. combustion air and second with 100% oxygen, for further analysis.

Similar thermal equilibrium calculations were carried out to get values of available heat at different temperatures and different air-fuel ratios that will be used in the furnace zones when they are operated under scale free operating conditions. These calculations are used in performing economic analysis for furnace operations with use of 100% oxygen and preheated air.

Details of the economic analysis are given in a later section.

Scale Free Heating (SFH) process and furnace operation

SFH Versus Cold, Warm and Hot Charge:

The heating of steel to forming temperatures without creating scale is achieved by the careful balance of the surface temperature of the steel and the atmosphere surrounding the steel. Very little scale is formed at steel temperatures below about 1400°F. Above these temperatures scale will be formed. The amount of scale formed becomes a function of the actual steel temperature, the time the steel is at temperature, and the type of atmosphere the steel is in. Scale can be prevented at any temperature and for any time providing the atmosphere that the steel is in is non-oxidizing. The earlier discussion on the CO/CO₂ and H₂/H₂O ratios at various temperatures has defined the non-oxidizing atmospheres needed for heating of steel as a function of temperature.

The CO/CO₂ and H₂/H₂O ratios for a conventional heating furnace, where combustion is at or slightly above stoichiometric conditions, are zero since no CO or H₂ exists in the products of combustion. The resulting atmosphere is of course oxidizing or scaling to steel. This is demonstrated in the following graph (Figure 11).

Figure 11.
Steel

heating in conventional reheating furnaces

The burners throughout the furnace are fired at a ratio of about 10/1 which forms an oxidizing atmosphere for steel. When the steel surface temperature exceeds about 1400°F scale starts to form. The longer the steel is in the oxidizing atmosphere and hotter the steel gets the thicker the scale becomes. When steel is heated to the forming temperatures in the range of 2200°F the amount of scale formed in this conventional heating process is typically 1.5%.

The CO/CO₂ and H₂/H₂O ratios required for non-oxidizing or scale free heating represents specific air to gas ratios of combustion. Therefore, a scale free heating atmosphere can also be expressed as a function of air/gas ratio. This is done in the graph shown in Figure 12 where a scale free heating air/gas profile is superimposed on the temperature profile of steel being heated to forming temperatures.

Starting at the right side of the graph or the discharge end of the furnace, where the steel is already heated to forming temperatures, the atmosphere around the work is created by a combustion ratio of about 5/1. This provides the CO/CO₂ and H₂/H₂O ratios needed to be non-oxidizing to steel.

Moving towards the charge end of the furnace encounters lower steel surface temperatures and the combustion ratio does not have to be so low to remain non-oxidizing. This is represented by a combustion ratio of about 7/1 midway through the furnace. Even further towards the charge end air is added to the rich flue products to release more heat to the steel and essentially burn down the combustibles (CO and H₂) in the atmosphere. Finally, at the charge end of the furnace, the combustion ratio is back to 10/1, the same as that of a conventional heating furnace.

Figure 12:
Scale

free heating conditions in the proposed reheating furnaces

It is possible to superimpose this steel temperature and combustion profile on the actual profile of a continuous reheating furnace and this is done in the following schematic (Figure 13) . Gas and air are provided only to the burners in the soak and heat zones of the furnace at a 5/1 and 7/1 combustion ratio respectively. Air only is provided to the burners in the charge zone where the rich flue products generated by the soak and heat zone burners are eventually burned down to the 10/1 ratio.

The flue products leaving the furnace pass through a recuperator that is used to preheat the combustion air for the process. In fact, highly preheated air is required in order to achieve the very low combustion air/gas ratios needed in the soak and heat zone.

It is possible to create a complete, scale free, heat balance with any continuous reheating furnace that heats steel from room temperatures (cold) to forming temperatures (say 2100 to 2300°F) while remaining non-oxidizing (scale free) to the steel at all times. Enough energy is injected into the rich zones of the furnace at 5/1 and/or 7/1 combustion ratios so that the atmosphere in these zones is not only scale free to steel but also sufficient enough in volume so that burn down energy can be released in the charge end of the furnace by injecting air only. The steel surface temperatures in the charge end of the furnace are low so that scale is not formed during this burn down process.

A complete, scale free heat balance is possible because one can adjust the proportion of 5/1 or 7/1 combustion to make sure enough energy is available to heat the steel while always staying on the non-oxidizing (scale free) side of the CO/CO₂ and H₂/H₂O ratios. Also, the scale free heating process will be at least as efficient as the conventional heating process because both processes end up with 10/1 combustion flue products leaving the furnace. In fact, it will be demonstrated that the scale free heating process will generally be more efficient than the conventional heating process because very high preheat air temperatures are required to operate burners at 5/1 air/gas ratios. The preheat air temperature for scale free heating is higher (about 1050°F) than that generally used for conventional heating furnaces (about 700°F). Therefore, the scale free heating process ends up being more efficient because of this.

Figure 13.
Tempera

ture and combustion conditions for scale free heating – cold charge

The apparent flexibility of adapting the scale free heating process to all types of continuous reheating furnaces does have one notable and critical criteria, that is, the products to be heated must be cold when they are charged into the furnace. The scale free heating process becomes much more difficult to remain competitive to conventional heating if the products are hot charged into the furnace. This can be demonstrated by examining the work surface temperature and atmosphere profiles required with hot charged products. The graph shown in Figure 14 does this.

The problem is that since the work comes into the furnace hot it must be immediately surrounded by an atmosphere that is non-oxidizing to it. Therefore, the rich gasses generated by the burners operating at 5/1 and/or 7/1 cannot be burned down within the furnace proper. This not only complicates the handling of the flue products leaving the furnace but also jeopardizes the thermal efficiency of the scale free heating process.

Figure 14. Time-temperature relationship in a hot charged reheating furnace

As done earlier with the process of heating from cold, it is possible to superimpose this steel temperature and combustion profiles on the actual profile of a continuous reheating furnace and this is done in Figure 15.

Figure 15.

Temperature and combustion conditions for scale free heating – hot charge

Gas and air are provided only to the burners in the soak and heat zones of the furnace at a 5/1 and 7/1 combustion ratio respectively. Some air may be provided to the burners in the charge zone but the rich flue products generated by the soak and heat zone burners cannot be burned down to the 10/1 ratio. Therefore, rich flue products leave the furnace and have to be burned down before

entering the recuperator area. This release of energy, exterior to the furnace, results in the overall thermal efficiency of the heating process within the furnace only boundary limits being much lower than the case for heating work from cold.

The inefficiency of heating hot charged products in a scale free heating atmosphere becomes greater with higher hot charged temperatures. This is due to the fact that the flue gasses have to leave the furnace proper with more combustibles (CO and H₂) still in them. Therefore the available heat of the combustion process becomes less and less as the charge temperature becomes higher and higher. This is exemplified in Figure 16 below. At a product charge temperature of 60°F, the flue products can be completely burned down in the furnace proper and available heat of scale free heating process is 67%. If the product was hot charged into the furnace at 1400°F, very little of the scale free atmosphere could be burned down within the furnace proper. The resulting available heat of the scale free heating process is only 15%. This will increase the cost of heating by about the ratio of available heats. That is, $67\%/15\% = 4.47$. That is, the cost of heating to maintain scale free conditions will be about four half times greater than if the heating was done in the conventional, scale forming method.

Figure 16. Effect of charge temperature on available heat for scale free reheating

Obviously, at some point, the cost saved by not forming scale on the heated product will become less than the cost incurred by using more energy to heat the product in a scale free atmosphere. It now becomes necessary to determine what the defining hot charge temperature is for the economical application of scale free heating. This can be done by making some basic assumptions. Say that the typical cost of steel is \$500 per ton and that the typical amount of scale formed during the conventional reheat process is 1.5%. Then, the cost saved by not forming scale is \$7.5 per ton. With respect to the cost of heating, say that a state of the art, conventional furnace and a state of the art scale free heating furnace can both heat steel with a thermal efficiency of 67%. This has been demonstrated above for the scale free heating furnace when it is heating cold charged products and burn down can be completed within the furnace. This 67% available heat is also a very practical and achievable efficiency for a state of the art conventional furnace. But, from the graph above, we

know that the available heat of the scale free heat furnace deteriorates linearly to about 15% when the hot charge temperature of the product reaches 1400°F. The following graph (Figure 17) shows how the initial scale savings of \$7.50 per ton is lost due to deterioration of thermal efficiency of the scale free heating process with hot charge.

Figure 17. Effect of charge temperature on savings from scale elimination

All potential scale savings are lost at about 700°F hot charge temperature. Above this temperature, an overall loss is incurred because it costs more to maintain the scale free conditions than is saved in scale costs. It now becomes evident that scale free heating with hot charged products will become cost prohibitive unless some method of heat recovery can be devised that will make economical use of the rich flue products that leave the furnace proper.

SFH Versus Cold, Warm and Hot Charge Summary:

In summary, hot charged products cause an upset to the scale free heating process in terms of the heat balance. As described above, this can compromise the economics of scale free heating if the energy loss cannot be recovered economically. Scale free heating is most compromised in its application to thin slab tunnel furnaces where the work is charged at very high temperatures, (in the order of 1800°F). The breakeven point of scale free heating savings when comparing savings due to scale saved versus additional cost of heating due to incomplete combustion is about 700°F hot charge.

These results were presented to and discussed with SDI representatives for both a Thin Slab Tunnel Furnace, SDI Butler, and the Conventional Heating Walking Beam Furnace, SDI Columbia City. The conclusion for the Tunnel Furnace application was that scale free heating would not be considered until and if some effective energy recovery system could be devised that would provide a reasonable ROI. The conclusion for the Conventional Walking Beam furnace was that scale free heating would be considered with cold charge products since significant scale could be saved at no penalty to MM

Btu/ton. But if and when the hot charge temperature exceeds a certain temperature level, probably in the order of 300 to 700°F, the heating mode would be switched over to conventional heating. The point being that the end user would take advantage of the energy savings potential available with warm or hot charging in a conventional fired furnace and sacrifice the scale savings.

Emphasis now falls on the need to develop an efficient and economical energy recovery system that can work in concert with a scale free heating furnace and recover the energy that is lost when hot charged products are charged into a scale free heating furnace. Such a system would significantly expand the application market of scale free heating furnaces.

SFH Versus Delays:

Hot charged products cause an upset to the scale free heating process in terms of the heat balance. As described above, this can compromise the economics of scale free heating if the energy loss cannot be recovered economically. Another upset to the heat balance of the scale free heating process is the occurrence of delays. A delay is defined as a planned or unplanned period to time where production through the furnace is stopped. An example of a planned delay would be the scheduled stoppage of heating and rolling due to the need to change out the rolls in the mill after a particular billet or slab has been processed. Subsequent billets or slabs need to be rolled to a different final shape and therefore the roll setup within the mill stands have to be changed out. An example of an unplanned delay is a breakdown in the mill or a cobble where production has to be immediately stopped and emergency repairs or corrections to the mill have to be made.

The reheat furnace has to go into a holding mode during these planned or unplanned delays. That is, no additional work is charged into the furnace and therefore the products within the furnace continue to slowly heat up. Since no new load is being added to the furnace, the burners in the temperature control zones start cutting back in order to maintain the established zone set point. If an automatic furnace control model is being used, the control model may even begin to reduce the zone set points to avoid overheating the products and to save fuel during the holding period.

A conventional heating furnace accomplishes the above described turndown with no unique problems. Burner input is continually cut back and the work gradually creeps up to the particular zone set points. If and when production is restarted, the burners begin to fire harder as new, cold products are charged into the furnace and heated products are discharged for rolling. Little or no upset is occurs within the heating process other than a general increase in the average monthly MMBtu/ton for heating due to the losses incurred while no production was being achieved.

A scale free heating furnace does not adapt as well to planned or unplanned delays. As described earlier, a scale free heating furnace achieves thermal efficiency by being able to completely burn down rich flue products within the furnace proper. As described earlier, this cannot be achieved if the products are charged into the furnace hot and therefore the scale free heating process suffers with hot charge. Delays effect the scale free heating process the same way as hot charged products

do. That is, delays do not allow complete burn down of rich flue gasses within the furnace and therefore delays hurt the thermal efficiency of a scale free heating furnace. This can be best exemplified by the following Figure 18 as a graph.

The bottom blue line represents the production rate in tph from either a conventional or scale free heating furnace and varying between zero and some elevated tph. Two delays are represented by the breaks, one short and one long.

The upper green line represents what the plotting of the flue gas air/gas ratio leaving a conventional furnace would look like over the range of production. As noted, the air/gas ratio of the flue gas does not vary from 10/1 which would be the approximate ratio most conventional furnaces are setup at. The burners turndown as required on a 10/1 ratio and the flue gas ratio leaving the furnace does not vary. Therefore, the available heart of combustion and/or the thermal efficiency of the furnace does not vary due to the production rate of the furnace.

Figure 18. Effect of delays during operation of a scale free heating furnace

The upper red line represents what the plotting of the flue gas air/gas ratio leaving a scale free furnace would look like over the range of production. As noted, the air/gas ratio begins to decrease if and when production goes to zero. If it is a short delay the decrease in air/gas ratio leaving the furnace is not substantial and is restored to 10/1 as soon as production is resumed. But in the case of the second, long delay the air/gas ratio decreases all the way to 5/1. This occurs because there is no more thermal load being put on the furnace by incoming, cold work. The heat demand in all zones begins to drop off and the input to the burners in all zones begins to cut back. The soak and heat zones continue to fire at their established 5/1 and 7/1 air/gas ratios but at lower volumes. However, in the charge zone, where only air is being injected through the burners to burn down the rich flue gasses, the injected air is also being cut back because of lack of demand. Therefore, combustion cannot be completed in the furnace proper and air/gas ratio leaving the furnace begins to decrease from 10/1. This is where burn down would have to occur in the flue, before the recuperator, as was encountered in the case of scale free heating hot charged products. And, as in the case of trying to scale free heat hot charged products, the MMBtu/ton would increase drastically

if one tried to hold the furnace at scale free heating conditions during delays. In very long delays of say 3 hours and greater, the entire furnace would have to be held at an air/gas ratio of 5/1 because all of the work within the furnace would be at or near rolling temperatures and therefore required a 5/1 atmosphere in order to remain scale free.

Of course in an actual situation where a furnace control model or furnace operators were involved, the zone set points could and would be reduced during these very long delays to reduce the temperature of the held products and allow higher combustion ratios. But in all cases, the scale free heating furnace would not be as efficient as a conventional heating furnace during medium to long delays.

SFH Versus Delays Summary:

In summary, delays cause an upset to the scale free heating process in terms of the heat balance. As described above, this can compromise the economics of scale free heating if the delays are very long, say more than 20 minutes. These results were presented to and discussed with SDI representatives for the Conventional Heating Walking Beam Furnace, SDI Columbia City. The conclusion was that the scale free heating mode would be terminated and the furnace switched to the conventional heating mode if and when a planned or unplanned delay exceeded a few minutes. The exact amount of time would be specific to the particular furnace and mill being considered.

The implication of this decision is that some allowance needs to be made for the scale that will be generated in a furnace during these delays. This will be addressed in more detail in a later Section of this Report.

Flue Gas Heat Recovery Methods

Scale free heating requires use of gases that are non-oxidizing to steel at the steel discharge temperature, usually in the range of 2000 deg. F. to 2200 deg. F. As mentioned earlier this temperature is achieved in the soak zone of the furnace. It is necessary to use natural gas combustion products that contain large amount of CO and H₂ in the soak section. Depending on the steel charging temperature the temperature profile of steel could vary from ambient (60 deg. F. to 90 deg. F.) to the discharge temperature. As explained earlier, if the charge temperature is below 600 deg. F. to 700 deg. F. it is possible to burn down the combustibles (CO and H₂) in the heating and preheat zones of a reheat furnace without forming scale. For a case where steel billets or slabs are charged below about 700 deg. F. in scale free heating furnace, the flue gases are discharged at about 1600 deg. F. with practically zero combustibles.

Since the sub stoichiometric combustion and subsequent burn down of the “rich” gases requires use of highly preheated air it is possible to use heat of these exhaust gases to preheat combustion air. The steel industry has used air preheaters or flue gas heat recovery devices, commonly known as recuperators, for preheating combustion air to as high as 1200 deg. F. A typical recuperator design shown in Figure 19 includes a tube bundle through which combustion air is passed to raise its temperature and exhaust gases are passed around the tubes in an insulated shell.

Figure 19. Typical recuperator used for steel reheating

Savings achieved through use of combustion air preheating for a furnace are given in a graph shown in Figure 20. This graph shows that use of 1000 deg. F. preheated air at flue gas temperature of 1600 deg. F. gives fuel savings of about 26%. In this case the exhaust gas from the recuperator or the heating system is represents about 30% of the total heat input in the furnace.

Figure 20. Fuel savings with use of preheated air

A schematic of the scale free heating system using a recuperator to recover heat from flue gases and preheat combustion air is shown in Figure 21. In a scale free heating furnace the preheated air is used for rich combustion of natural gas in the soak zone and, if necessary, in heating zones to produce the required amount of CO and H₂ while maintaining the required flame temperature that allows sufficient heat transfer and offers the required available heat in the zones. The preheated air is also used for burn-down of residual combustibles in the preheat zone and/or the heating zone. The air and fuel input are adjusted to completely burn-down combustibles before the flue gases are discharged out of the furnace.

Figure 21. Schematic of the scale free heating system using a recuperator

With the use of a well designed air preheating system it is possible to achieve 67% available heat that is comparable or slightly lower than the modern reheat furnace design. It is expected that such a design would allow the user to achieve heat rate of about 1.2 MM Btu/ton while reheating steel in scale free mode.

In cases where the charge is at a higher temperature it is not possible to complete combustion of CO and H₂ in flue gases. In this case flue gases from the furnace could contain about 12% CO and 16% H₂O and 70% of the total heat input in the furnace. A part of the heat can be used if the system uses preheated air however a large percentage of the heat of flue gases will have to be recovered for other uses.

Several possible uses were considered during the project. They include:

- Steam and power generation by using conventional high pressure (>250 psig) steam generator and steam turbine.
- Reduction of iron ore by using the rich combustion products
- Use of heat for producing hot water and/or low pressure (~50 psig) steam for use in an absorption chiller system to produce chilled water and/or refrigeration.
- Use of non-conventional (i.e. thermo-electric) power generation

After discussing possibilities of use of these systems with the steel industry it was realized that the only practical method of using the heat is to use steam-power cycle.

The iron reduction option is a very attractive option however the location where iron reduction is carried out could be far away from location of a reheat furnace and it is not practical to transport hot gases containing large amount of H₂ and CO to a distance more than few feet. y of using these systems in a steel plant.

Use of hot gases to produce chilled water or refrigeration would be useful if the steel plant would require chilled water. None of the plants we contacted use large quantities of chilled water for any process within the plant. Once again finding a proper user within reasonable distance is not possible for most mills. Use of non conventional power generation was not considered since none of the technologies we reviewed offered more than a few percentage (usually less than 5%) power conversion efficiency and cost of power generation (in excess of \$2000 to \$5000) was considered un acceptable. Economics and practical application of power generation by using a steam generator – turbine was explored further. A major energy service company that builds or operates power plants for the steel industry world wide was contacted to perform economic analysis for a typical installation. The system configuration is shown in Figure 22. In this system rich exhaust gases from the furnace are burned-down in a combustion chamber integrated with a heat exchanger or recuperator that is used to preheat combustion air for the burners. A heat balance for the recuperator shows that there is more heat than required for preheating the combustion air at the required temperature of about 1000

deg. F. and it is possible to recover this heat in a secondary heat recovery system. The secondary heat recovery system could be a steam generator or a water heater or an air heater.. Since most plants do not need hot water or hot air in the vicinity of the furnace, the best option is to raise steam and use it in the plant or in a steam turbine to generate power. Once again very few mills have need for extra steam in the area a reheat furnace and the only viable option is to use a system to generate

Figure 22. Schematic of the scale free heating system with heat recovery for steam and power generation

Economics of the system depends largely on the installed cost of the system and value (\$/kWh) assigned for electricity used in the plant or, in rare cases, sold to an utility.

Figure 23 shows a heat balance for a 150 tons/hour reheating furnace with hot charge using oxygen enriched air for combustion. Total heat from the furnace is 268 MM Btu/hr. This heat is used in a heat recovery steam generator (HRSG) to generate steam at high enough pressure (>250 psig) at an average efficiency of 85% . This would allow the plant to generate 155,000 lbs. of steam per hour. This steam will be used to produce 1.8 MW power at 30% efficiency for power generation. Such a system would require installation of an auxiliary heat supply system to maintain continuity of steam – power generation during the periods when reheat furnace is down or experiences delay and the firing rate is reduced or stopped.

Figure 23. Heat balance for a hot charge scale free reheat system using oxygen enriched air and heat recovery system to generate power

A simple cost-benefit analysis shown in Table 6 shows that pay back period would be in excess of 5 years when

Parameters		21% O ₂ , 54% stoichiometric 1000 deg. F. preheat
Production rate	Tons/hr.	150
Heat input to the furnace	Btu/hr.	
Temperature of flue gases	Deg. F.	2050
Air preheat temperature (F)		1,000
Total combustion air used in furnace	cf/MM Btu gas in	5400
Heat used for air preheating	MM Btu/hr	34.98
Av. heat for furnace ex. Gases (using equations)		16.1%
Heat in flue gases (1-av. Ht)	Btu/ft ³ of n. gas in	860.42
Net heat required in furnace	MM Btu/hr	51.39
Total n. gas volume in furnaces	ft ³ of n. gas	312,235
Total input in the furnace	MM Btu/hr	320.04
Total heat content of flue gases	MM Btu/hr	268.65
Total heat content of gases to boiler	MM Btu/hr	233.67
Average efficiency of boiler		85%
Heat recovered in boiler	MM Btu/hr	198.62
Average efficiency power generation		32%
Power generated	kW	18,623
Heat required for power generation	Btu/kWh	13,500

Table 6. Example of cost-benefit analysis for scale free heating system using heat recovery system

Table 6. (Contd..) Example of cost-benefit analysis for scale free heating system using heat recovery system

Parameters		21% O ₂ , 54% stoichiometric 1000 deg. F. preheat
Power produced		19,900
Power production	Mw	19.90
Power cost	Cents/kWh	5.00
Gas cost	per MM Btu	\$ 7.00
Reduction in power cost or electrical supply credit	\$/hour	\$ 995
Annual operating hours	hrs/year	8,400
Total savings - power cost	MM \$/year	8.36
Cost of fuel for reheat furnace for SFH	MM \$/year	18.82
Current fuel cost for reheat furnace	MM \$/year	5.73
Other cost as % of power cost savings		5%
Incremental cost for scale free heating	MM/year	\$ 5.15
Cost increase/ton	\$/ton of steel	4.08
Scale reduction		1.50%
Savings - scale reduction <small>per ton of scale</small>	per ton scale	\$ 500.0
Savings due to scale reduction	\$/ton of steel	\$ 7.50
Annual savings	MM \$/year	4.30
Cost of power system	per kW	\$ 1,200.00
Additional furnace cost	MM\$	0.22
Total estimated cost of power eqp.	MM	\$ 24.10
Simple Payback	Years	5.60

The heat requirements are based on the following operating data collected for a tunnel furnace operating at one of the steel plant.

Furnace production: 150 tons./hr.	Combustion air preheat temp.: 700 deg. F.
Charge inlet temperature: 1800 deg. F.	Current scale rate: 1.5%
Charge final temperature: 2000 deg. F.	Current energy use: 0.65 MM Btu/hr

As seen in Table 6, key parameters affecting payback period are: cost of electricity, gas cost, current value of scale formation, credit assigned to elimination of scale and cost of steam-power generation equipment. The equipment cost is not greatly affected by the plant location however the energy cost vary significantly in different regions are expected to rise. Credit for scale reduction depends on current operations and value of product at a specific plant. Hence applicability of power generation option for heat recovery and justification of use of scale free heating system should be evaluated on a plant to plant basis.

Economics

A detail economic analysis of economics of use of scale free heating was carried out by using process and cost parameters available from the team members. Primary contributors include the furnace company Alchas, Inc., steel company SDI, combustion system supplier Bloom Engineering and E3M, Inc.

The analysis included considerations of the following parameters:

- Cost of utilities such as electricity, natural gas and oxygen
- Value of scale loss (cost of steel at reheating stage)
- Production rate in terms of Tons/year (TPY)
- Scale formed in terms of % of the charge weight (% scale)
- Current energy use in terms of million (MM) Btu/ton of steel produced
- Average hearth coverage for the furnace in terms of % of total furnace hearth area
- Contact time between the reheat furnace and hot rolling operations in terms of % of total operating time.
- Total delays in terms of % of operating time. This includes planned and unplanned delays.
- Planned delays in terms of % of operating time.

A simple analysis model based on MS EXCEL was carried out to calculate operating cost savings for four types of mills and furnaces commonly used by each sector by the U.S. steel industry. The analysis results using this model are given in following figures. The calculations are based on commonly used values for production rate (TPY), energy use (MM Btu/ton) and operating parameters such as contact time and delays. These parameters were obtained from several sources such as a survey of SMAS member companies (discussed in a later section), steel mill partner (SDI), furnace supplier (Alchas) etc.

The systems considered are:

- (i) Structural mill – walking beam furnace
- (ii) Merchant mill using walking hearth furnace
- (iii) Hot strip mill – walking beam furnace
- (iv) Rebar mill – pusher furnace

Analysis of a typical walking beam furnace used by structural mills is shown in Table 7.

STRUCTURAL MILL - WALKING BEAM				
	CONVENTIONAL	SFH WITH PREHEATED AIR	SFH WITH OXYGEN ENRICHED AIR	
Cost of Gas	\$8.00	SAME	SAME	\$/MMBtu
Cost of Oxygen	\$0.90	SAME	SAME	\$/1000 scf
Cost of Scale	\$500.00	SAME	SAME	\$/ton scale
TPY	1,000,000	SAME	SAME	
MMBtu/ton	1.44	SAME	SAME	MMBtu/ton
% Scale	1.50%	0.00%	0.00%	%
Gas/ton	1,440	1,440	1,440	scfh/ton
Oxygen/ton	0	0	1,977	scfh/ton
Contact Time	77%	SAME	SAME	%
Delays	18%	SAME	SAME	%
Planned Delays	0%	SAME	SAME	%
Hearth Coverage	70%	SAME	SAME	%
Cost of Gas	\$11.52	\$11.52	\$11.52	\$/ton heated
Cost of Oxygen	\$0.00	\$0.00	\$1.78	\$/ton heated
Cost of Scale	\$7.50	\$0.00	\$0.00	\$/ton heated
Gas Cost/Yr	\$11,520,000	\$11,520,000	\$11,520,000	\$/yr
Oxygen Cost/yr	\$0	\$0	\$1,779,408	\$/yr
Operating Scale Cost/yr	\$7,500,000	\$0	\$0	\$/yr
Delay Scale Cost/yr	ABOVE	\$1,508,057	\$1,508,057	\$/yr
Total Operating Cost	\$19,020,000	\$13,028,057	\$14,807,465	\$/yr
Operating Cost Savings	BASE	\$5,991,943	\$4,212,535	\$/yr

Table 7. Economics for use of scale free heating system in a structural mill walking beam furnace

The analysis includes three types of scale free heating systems: Conventional furnace using near stoichiometric combustion burners, SFH with preheated air at 1000 deg. F. and SFH with oxygen enriched air (45% O₂ content). As a first approximation the gas consumption for all three cases is assumed to be the same. In reality it is expected that use of higher air preheat and oxygen enriched air would result in fuel savings that could be 10% to 15% of the fuel used in conventional furnace.

The results indicate show comparing of total operating cost for each systems. In the case shown in the following figure, total annual operating cost for a conventional furnace is \$19.02 million, \$13.03 million and \$14.8 million. Further analysis of budget capital cost shows that relative cost for each of these furnaces are 1.0, 1.2 and 0.9 for these systems. These numbers should be considered very preliminary since the cost is highly dependent upon individual installations and specific requirements of each installation. However it is clear that SFH furnace using preheated air costs more than the conventional furnace or a furnace using oxygen enriched air system. The oxygen based system is lower since such a system does not require installation of a recuperator as well as hot air piping, burners etc.

The savings are affected by several operating parameters. Three important parameters are:

- (i) Contact time that represents the time during which the furnace is producing hot steel that can be used for rolling mill downstream. The model results shown here uses a typical value of 77% for contact time.
- (ii) Hearth coverage that represents the percentage of the furnace hearth covered by the steel being reheated. The model results shown here uses a typical value of 70% for hearth coverage.
- (iii) Delays (planned and unplanned) that represents planned maintenance delays and unplanned, unanticipated delays during the furnace operation. The model results shown here uses a typical value of 18% for the delays.

Any variation in values of these parameters would affect operating cost of the furnace. The sensitivity analysis for the case analyzed above (structural mill – walking beam furnace) is shown in following Figure 24.

Figure 24. Effect of several operating parameters on savings with use of scale free heating

This graph shows that increase in planned delays and contact time from the base values would improve savings while increase in hearth coverage would reduce savings. The model can be used to contact time would have delays experienced during the furnace operation. The several operating

parameters such as delays during the furnace operation. Effect of delays and its effect on scale formation and requirement of running the furnace under scale free or conventional mode are discussed in an earlier section.

Comparison of estimated operating cost for SFH system using preheated air and oxygen enriched air over a period of ten years is shown in Figure 25 below. For simplicity, the comparison is in terms of “cash-flow” associated with the furnace. This is not a detail financial analysis using financial tools that may be used by accountants for financial analyst. It should only be used as a first indicator of possible financial benefits of the preheated air system.

Figure 25. Simple cash flow representation for scale free heating using preheated air and oxygen enriched air

The simplified “cash-flow” analysis, based on an initial cost of \$11 million for oxygen based furnace to \$14 million for preheated air based furnace, shows that for this typical application initial higher cost for preheated air based system can be paid for within less than 2 years. Once again, these are very preliminary numbers and should be used for general conclusion that preheated air based system offers better economic return than the oxygen enriched air based system. For specific applications it is advisable to run the model to verify (or change) this conclusion.

Similar analysis is carried out for three other commonly used furnaces and their results are shown in following figures. The simple “cash-flow” analysis for each of these cases show that the in each case use of preheated air based system would have higher savings after 2 to 3 years of operation.

Obviously the savings and selection of the type of system would depend on several factors, particularly cost of oxygen and cost of natural gas. The EXCEL model developed during Phase I of the program can be used to analyze each individual case.

Table 8. Economics for use of scale free heating system in a merchant mill

walking hearth furnace

MERCHANT MILL - WALKING HEARTH				
	CONVENTIONAL	SFH WITH PREHEATED AIR	SFH WITH OXYGEN ENRICHED AIR	
Cost of Gas	\$10.00	SAME	SAME	\$/MMBtu
Cost of Oxygen	\$0.90	SAME	SAME	\$/1000 scf
Cost of Scale	\$400.00	SAME	SAME	\$/ton scale
TPY	700,000	SAME	SAME	
MMBtu/ton	1.05	SAME	SAME	MMBtu/ton
% Scale	1.50%	0.00%	0.00%	%
Gas/ton	1,050	1,050	1,050	scfh/ton
Oxygen/ton	0	0	1,442	scfh/ton
Contact Time	75%	SAME	SAME	%
Delays	18%	SAME	SAME	%
Planned Delays	0%	SAME	SAME	%
Hearth Coverage	80%	SAME	SAME	%
Cost of Gas	\$10.50	\$10.50	\$10.50	\$/ton heated
Cost of Oxygen	\$0.00	\$0.00	\$1.30	\$/ton heated
Cost of Scale	\$6.00	\$0.00	\$0.00	\$/ton heated
Gas Cost/Yr	\$7,350,000	\$7,350,000	\$7,350,000	\$/yr
Oxygen Cost/yr	\$0	\$0	\$908,240	\$/yr
Operating Scale Cost/yr	\$4,200,000	\$0	\$0	\$/yr
Delay Scale Cost/yr	ABOVE	\$1,025,325	\$1,025,325	\$/yr
Total Operating Cost	\$11,550,000	\$8,375,325	\$9,283,565	\$/yr
Operating Cost Savings	BASE	\$3,174,675	\$2,266,436	\$/yr

Table 9. Economics for use of scale free heating system in a hot strip mill walking beam furnace

HOT STRIP MILL - WALKING BEAM FURNACE				
	CONVENTIONAL	SFH WITH PREHEATED AIR	SFH WITH OXYGEN ENRICHED AIR	
Cost of Gas	\$10.00	SAME	SAME	\$/MMBtu
Cost of Oxygen	\$0.90	SAME	SAME	\$/1000 scf
Cost of Scale	\$500.00	SAME	SAME	\$/ton scale
TPY	1,500,000	SAME	SAME	
MMBtu/ton	1.32	SAME	SAME	MMBtu/ton
% Scale	1.50%	0.00%	0.00%	%
Gas/ton	1,323	1,323	1,323	scfh/ton
Oxygen/ton	0	0	1,816	scfh/ton
Contact Time	85%	SAME	SAME	%
Delays	8%	SAME	SAME	%
Planned Delays	0%	SAME	SAME	%
Hearth Coverage	85%	SAME	SAME	%
Cost of Gas	\$13.23	\$13.23	\$13.23	\$/ton heated
Cost of Oxygen	\$0.00	\$0.00	\$1.63	\$/ton heated
Cost of Scale	\$7.50	\$0.00	\$0.00	\$/ton heated
Gas Cost/Yr	\$19,837,500	\$19,837,500	\$19,837,500	\$/yr
Oxygen Cost/yr	\$0	\$0	\$2,451,320	\$/yr
Operating Scale Cost/yr	\$11,250,000	\$0	\$0	\$/yr
Delay Scale Cost/yr	ABOVE	\$1,542,047	\$1,542,047	\$/yr
Total Operating Cost	\$31,087,500	\$21,379,547	\$23,830,866	\$/yr
Operating Cost Savings	BASE	\$9,707,953	\$7,256,634	\$/yr

Table 10. Economics for use of scale free heating system in a rebar mill pusher furnace

REBAR MILL - PUSHER				
	CONVENTIONAL	SFH WITH PREHEATED AIR	SFH WITH OXYGEN ENRICHED AIR	
Cost of Gas	\$8.00	SAME	SAME	\$/MMBtu
Cost of Oxygen	\$0.90	SAME	SAME	\$/1000 scf
Cost of Scale	\$300.00	SAME	SAME	\$/ton scale
TPY	500,000	SAME	SAME	
MMBtu/ton	1.27	SAME	SAME	MMBtu/ton
% Scale	1.50%	0.00%	0.00%	%
Gas/ton	1,265	1,265	1,265	scfh/ton
Oxygen/ton	0	0	1,737	scfh/ton
Contact Time	85%	SAME	SAME	%
Delays	10%	SAME	SAME	%
Planned Delays	0%	SAME	SAME	%
Hearth Coverage	90%	SAME	SAME	%
Cost of Gas	\$10.12	\$10.12	\$10.12	\$/ton heated
Cost of Oxygen	\$0.00	\$0.00	\$1.56	\$/ton heated
Cost of Scale	\$4.50	\$0.00	\$0.00	\$/ton heated
Gas Cost/Yr	\$5,060,000	\$5,060,000	\$5,060,000	\$/yr
Oxygen Cost/yr	\$0	\$0	\$781,580	\$/yr
Operating Scale Cost/yr	\$2,250,000	\$0	\$0	\$/yr
Delay Scale Cost/yr	ABOVE	\$444,032	\$444,032	\$/yr
Total Operating Cost	\$7,310,000	\$5,504,032	\$6,285,612	\$/yr
Operating Cost Savings	BASE	\$1,805,968	\$1,024,388	\$/yr

The same model is used to calculate savings resulting from scale free operation of a furnace. The calculations show that the savings depend on the type of product and furnace used by a particular sector of the steel industry. As shown in Table 11, the savings vary from \$3.93 per annual ton for long products – rebar mill to \$6.06 for flat products. Using the annual production numbers derived from market studies by the furnace company Alchas, Inc. and discussed in a following section, it is estimated that total savings in scale prevention is about \$354 million per year for annual production of 64 million tons/year.

POTENTIAL ANNUAL SCALE SAVINGS			
TYPE OF MILL	POTENTIAL MARKET	AVERAGE SCALE SAVINGS PER ANNUAL TON	POTENTIAL ANNUAL SAVINGS
	TPY	\$/TPY	\$/YR
FLAT PRODUCT CONVENTIONAL	40,000,000	\$6.06	\$242,434,331
LONG PRODUCT REBAR MILL	2,400,000	\$3.93	\$9,420,773
LONG PRODUCT MERCHANT MILL	16,000,000	\$4.50	\$72,060,000
LONG PRODUCT SBQ MILL	5,600,000	\$5.37	\$30,099,577
	64,000,000		\$354,014,680

Table 11. Estimate of potential annual dollar savings for the U.S. steel industry
The model would be further refined during Phase II as additional information is developed based on the furnace design and other issues to be addressed during Phase II of the program.

Furnace Design Requirements

SFH Verus Safety:

The effective air/gas ratio of a scale free heating furnace varies from about 5/1 in the soak zone to 10/1 at the charge end. This air/gas ratio profile can be represented by a % combustible profile as showing in Figure 26. A 5/1 air/gas ratio with typical natural gas results in about 32% combustible gasses made up of approximately equal parts of CO and H₂. It has been described how, under normal cold charge conditions, the combustibles in the furnace atmosphere are gradually diluted and burned down so that all combustibles are eliminated at the charge end of the scale free heating furnace. Still, a large percentage of the total furnace has significant combustible gasses within it at all times. If there is a delay or warm charge there is even a possibility of having combustibles at the charge door. Reheat furnaces are generally operated at a slightly positive pressure so opening the charge or discharge door would result in highly combustible gasses pushed into the mill building. They would immediately ignite and burn with the ambient air but the relatively uncontrolled nature of this burnout would not assure one that all dangerous CO was indeed burned down.

Actually, operating high temperature furnaces with very high combustibles atmospheres is not at all new. The Heat Treat Industry has been doing it for years. A carburizing furnace operates with combustibles exceeding 60% and CO exceeding 35%. A heat treat furnace with a combustible atmosphere relies on "flame screens" at the base of the charge or discharge door to ignite the surge of atmosphere into the room when a door is opened. Hoods above the doors draw the burned down exhaust products in and conduct them outside of the building.

Figure 26. Air-fuel ratio

variation from charge end to discharge end in a scale free heating furnace.

The one advantage of a heat treat furnace is that the charge and discharge doors are normally a few square feet in opening size and opening times can be kept to a few seconds. This is not so for most reheat furnaces. Reheat furnace can be generally categorized into three types of door arrangements:

Side Charge and Side Discharge, End Charge and End Discharge, or a combination of Side and End Charging or Discharging.

Figure 27. Side charge and discharge arrangement for a reheat furnace.

A side charge and side discharge arrangement is shown in Figure 27. Relatively small charge and discharge doors are located on the sidewall of the furnace. Products enter the furnace on rolls and exit it on rolls or are pushed out by a peel bar. This type of arrangement is applicable only to long products (bars, billets, blooms, rounds, etc.) and restricts the layout to one furnace per mill.

An end charge and end discharge arrangement is shown in Figure 28. Products enter and leave the furnace through large, wide doors in the end wall of the furnace and running the full width of the furnace. This type of arrangement is the rule in strip and plate mills and allows multiple furnaces per mill. End charging and discharging or a combination of end and side charging or discharging is also often found in long product mills.

Figure 28. End charge and discharge arrangement for a reheat furnace.

The huge door area of an end charged and/or discharged furnace eliminates any consideration of trying to address and accommodate burn down of the combustible atmosphere escaping from an open door. Even if the burn down process could be safely contained and conditioned, the heat loss due to the burnout of the valuable combustibles would adversely effect the thermal efficiency of the scale free heating process.

Therefore, for both safety and efficiency concerns, a scale free heating furnace will be operated under a slightly negative pressure. Any opening will result in the infiltration of air into the furnace and immediate burn down of combustibles in the door vicinity. In essence, the exterior flame screen

concept now used by the heat treat industry will be used as an interior flame screen for a scale free heating furnace.

This will not noticeably effect the amount of scale formed on the heated product. The in rush of ambient air and the subsequent flame screen the product sees at the discharge end of a scale free heating furnace will amount to a few more seconds of its exposure to an oxidizing atmosphere that commences with its discharge into ambient air and continues until its surface temperature drops below scaling levels on the cooling bed or run out table.

The potential upset to the soak zone scale free atmosphere the flame screen burn down may have will be offset by an adjustment to the soak zone air/gas ratio while the discharge door is open. Based on the specific door size, opening sequence, and furnace negative pressure, it is possible to calculate the in rush of flame screen ambient air and therefore calculate the slight adjustment in the soak zone air/gas ratio required to maintain the zone at an effective 5/1 air/gas ratio. The zone combustion control system would automatically do this upon door opening.

SFH Versus Burner Type:

A couple of conclusions arrived at in the preceding sections of this Report have introduced very special capabilities of a burner used for scale free heating. Relative to the discussion on cold, warm or hot charge it was concluded that warm to hot charged products would not be scale free heated. This decision was due to inability to economically recover the energy loss of scale free heating warm or hot charged products. This means that a furnace, and therefore its burners, have to be capable of both scale free and conventional heating. This furnace and burner flexibility requirement was again emphasized with the conclusions relative to delays. It was concluded that a furnace would be operated as a conventional heating furnace if and when a notable delay in production was incurred.

The need for a burner to be capable of both scale free and conventional heating is a very significant requirement. A more detailed examination of how this effects the burner specification will show this.

The following table 12 summarizes the sizing of top and bottom fired walking beam reheat furnace designed to heat 200 tph and operating as either a conventional or scale free heating furnace.

Table 12. Comparison of heating system related parameters for conventional and scale free furnaces.

CONVENTIONAL HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	187	84	41	312
% of total input =	60.0%	27.0%	13.0%	100%
Air/gas ratio =	10/1	10/1	10/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	10.4	4.7	1.9	
SCALE FREE HEATING				
	CHARGE	HEAT	SOAK	TOTAL
Connected MMBtu/hr =	0	146	166	312
% of total input =	0.0%	46.7%	53.3%	100%
Air/gas ratio =		7/1	5/1	
Number of burners =	18	18	21	
MMBtu/hr per burner =	0.0	8.1	7.9	

Both furnaces would be of the same physical size with the same zone lengths and zone number. The total connected input would be the same because it is assumed that heat losses and the thermal efficiency of both furnaces would be designed to be the same. But the connected heat input per zone would be considerably different.

The typical connected input distribution for a conventional heating furnace from the charge zone to the heat and soak zone is generally in the 60%, 30%, and 10% distribution shown above. All zones would of course be fired at a 10/1 air/gas ratio and the resulting size per burner would be as shown.

The connected input per zone for the scale free heating furnace is much different. No gas input is needed in the charge zone. The heat release in this zone is achieved only from air injection through the burners and the resultant burn down of the rich flue gasses carried into the charge zone from heat and soak zones. Therefore, both the heat and soak zones have about half of the total connected input.

The significant effect sizing a burner for both conventional and scale free heating is best exemplified by studying the wide range of requirements for the soak zone burners. For conventional heating the burners have to be sized for 1.9 MMBtu/hr and operate at a 10/1 air/gas ratio. For scale free heating the burners have to be sized for 7.9 MMBtu/hr and operate at a 5/1 air/gas ratio. In either case, a burner has to be capable of turning down 6/1 from its connected capacity in order to address the wide range of inputs required between heating 200 tph versus holding at temperature. This tremendously expands the maximum to minimum air and gas flows the burner has to be capable of.

For the soak zone the maximum burner air flow is the scale free heating rating at 7.9 MMBtu/hr, 5/1 air/gas ratio which is approximately 39,500 scfh. The minimum air flow would be that for a 6/1 turndown from the conventional burner connected size of 1.9 MMBtu/hr which is approximately 3,167 scfh. On the gas flow side, the maximum gas flow is 7,900 scfh and the minimum is 317 scfh.

A literature search of scale free heating burner technology quickly identified a number of previous burner developments resulting in the ability to fire a burner at the scale free heating ratios. However, none of the references indicated that a single burner could be used interchangeably in a conventional heating or scale free heating mode.

Bloom Engineering (Bloom) was found to have done a substantial amount of work on scale free heating burners in the 60's. Bloom is also a primary supplier of current, state of the art, ultra low NO_x, reheat furnace burners. A detailed specification was therefore developed and submitted to Bloom for the burners required for a 200 tph reheat furnace capable of either conventional or scale free heating operation.

The development work done in the 1960's by Bloom indicated that the fundamental designs of Bloom burners were compatible with scale free heating. Two different styles of burners were tested at Bloom's facilities and demonstrated the ability to produce scale free heating at furnace temperatures of 2400 deg. F. In the course of these demonstrations, the burners were operated across an air/fuel ratio range of 10/1 to 5/1.

The advent of modern ultra low NO_x burners presented an opportunity to revisit the feasibility of scale free heating. An ultra low NO_x burner is required to operate in a minimum of two modes. At low temperatures (typically below 1700 deg. F.) the burners operate in a normal mode. Above 1700 deg. F. it is necessary for the burners to operate in an enhanced combustion mode capable of producing ultra low NO_x. This operational capability is achieved by incorporating elements two burner designs into a single body, with a suitable means of switching between operating modes.

The design of a scale free heating burner system for a 200 tph reheat furnace, was based upon the dual mode capability of an ultra low NO_x burner. It was recognized that the two operating modes would also require different capacities. This was particularly true for the soak zone where the gas was required to operate at a maximum flow of 25 times minimum while the maximum air flow was 12.5 times minimum. The resulting proposed burner was of special design, but the capabilities of the individual modes were within Bloom's experience.

The heat zone burner presented less of a problem. It was still of special design which required two operating capacities. The charge zone was designed from a conventional heating perspective. Accordingly, Bloom Engineering is prepared to address the necessary operating requirements.

Market Assessment

The scale free reheating process can be applied to all types of steel reheating operations used by the steel industry and forging industry. The original proposal included several assumptions regarding application of SFH in the steel industry. It was assumed that the process can be applied to furnaces used by all sectors of steel industry using cold or hot charged steel. The process heat balance, evaluation of waste heat recovery systems and their cost and operating cost analysis carried out during this phase of the program indicated that it is not possible to apply the SFH to all sectors with equally attractive payback periods. This analysis shows that it the SFH can be applied to about 65% of the U.S./ steel industry with very attractive (2 to 3 years) payback period at the prevalent (early 2006) current utility cost (Gas cost - \$10 per MM Btu, Electricity cost - \$0.05 per kWh and Oxygen cost - \$1.00 per 100 scf). As discussed earlier payback period for remaining 35% market that uses hot charge steel at temperature higher than 700 deg. F. the payback period is greater than 5 years.

As a part of the market assessment activity Alchas Inc. investigated the type of furnaces and important process parameters required to perform economic analysis for application of the SFH.

This analysis is considered four parameters that can be used to define the type of furnace used for a specific application. These are:

- (i) type of mill (structural, rebar, merchant etc.)
 - (ii) Furnace design specifications (tons/year, steel discharge temperature, product shape and size, charge temperature etc.)
 - (iii) Furnace operating practices (hearth coverage, contact time, delays etc.)
 - (iv) Cost parameters(fuel cost, scale value-cost, power cost, oxygen cost etc.)
- Relationship of all of these parameters is illustrated in Figure 29. Available information for all of these parameters were used in performing market assessment for SFH application.

Figure 29. Relationship between various steel reheat furnace parameters

Information for some of these parameters was obtained partially from a short survey of SMA member companies. A questionnaire, discussed in a later section, was sent to SMA members to get their input during the market assessment. Nine member companies responded to the questionnaire and provided information that was very helpful in supporting the information used for market assessment.

Using combination of this information, their own data base and information obtained from a survey of SMA members (discussed in a later section) they estimated that the U.S. steel reheating market is at least 100 MM tons/year with 70 MM/year for flat products and 30 MM tons/year for long products. Further division of these two sectors shows that out of 70 MM tons long products, 20 MM tons/year is processed in tunnel furnaces and it is hot charged. While the remaining 50 MM tons/year is reheated in conventional furnaces with steel charged at ambient temperature or, in a very few cases, as “warm” charge meaning at less than 700 deg. F. The SFH can be applied to 50 tons/year steel reheating using available heat recovery technology to preheat combustion air up to 1000 deg. F. or by using oxygen enriched air combustion system. The long products sector can be divided in three areas of the industry: rebar mill, merchant mill and SBQ/structural mill. The rebar mill sectors reheats about 3 MM tons/year with 0.6 MM tons hot charged and 2.4 MM tons/year cold charged. The merchant mill sectors reheats about 20 MM tons/year with 4 MM tons hot charged and 16 MM tons/year cold charged. The SBQ/structural mill sectors reheats about 7 MM tons/year with 1.4 MM tons hot charged and 5.6 MM tons/year cold charged. The 64 MM tons/year of cold charged steel can be reheated in scale free mode with very reasonable payback period (2 to 3 years) while it is necessary to allow for longer payback period (perhaps 5 years or longer) for the hot charged steel. It should be pointed out that it is possible to heat the hot charged steel using the proposed scale free heating process provided the user is willing to accept longer payback period or can identify economically justified use of the large amount of flue gas heat coming out of the reheat furnace. The above information is summarized in Figure 30 below.

Figure 30. Distribution of U.S. steel production

The assessment results were presented in a meeting attended by about 25 SMA member company representatives and they were requested to express their opinion about the validity of assumption used in this analysis. The members consented that the assessment is generally valid.

Based on results of this assessment it is concluded that about 65% of the steel industry can apply SFH in their furnaces (new or retrofitted) while it is necessary to improve economics of heat recovery methods for application of SFH to the remaining 35% of the market.

Collaboration with the U.S. steel industry

Phase I of the scale free heating system development program was carried out in close cooperation with the steel industry. The program team includes steel industry organization, Steel Manufacturers Association (SMA) with membership of more than 50 steel manufacturer's in USA. In addition to this, a major steel manufacturing company, Structural Dynamics Inc. (SDI) is one of the active team members directly contributing to the project activities.

The SMA members were contacted to provide information on operating conditions and Market assessment used in this program. A questionnaire was prepared and sent to the SMA members. Nine members responded to the questionnaire and provided detail information. Table 13 shows a copy of the questions sent to the SMA members. Their response is summarized in Table 14. This information was analyzed and used in market assessment as well as establishing base line data for energy and other operating parameters used for economic model and market assessment.

1	Product Related Information
	What is the type and size range of your product(s) to be heated?
	What is the typical temperature of your charged product? Cold, Warm (500° To 800° F) or hot (higher than 800°F)?
	What is the discharge temperature (Degree F.) of your product?
	How many tons/year do you reheat and in how many furnaces?
2	Furnace related information
	What is the design production rate (tph) of your reheat furnace(s)? Please give a typical number or high and low numbers for your furnaces.
	What is the typical, average MMBtu/ton you now realize with your product(s)?
	What is the preheat air temperature of your current reheat furnace(s)?
3	Scale Related Information
	What is the percent of scale you generate in your reheating process?
	What value, credit or cost would you assign to the scale in terms of \$/ton. Please consider all costs such as cost of steel not produced, scale removal and disposal cost, maintenance cost related to damages related to scale etc.
	Does scale formed during reheating impact on your product(s) quality?
4	Utility Cost
	What is the cost in terms of \$/Million Btu for natural gas or other fuel used for reheating?
	What is your cost of power, (\$/kWh)? Please consider all costs for actual electricity, demand charges and other charges if any and give average based on total cost.
	What is your cost of oxygen, (\$/1000 cf)? Please consider all costs such as cost related to capital investment, cost of power, operating cost etc. charged by the oxygen plant operator.
5	Other
	What payback period do you expect for justification of scale free heating ?
	Do you have need for power standby? What value or credit would you allow for availability of such power availability
	Any other comments?

Table 13. A copy of the questions sent to the SMA members.

Additional input from the steel companies was collected during Plant Operations Division meeting attended by about 30 steel industry representatives. The attendees were briefed on scale free reheating project objectives, current activities and interim results obtained for Phase I of the

program. The attendees were requested to give their input regarding the industry issues related to scale formation during reheating and their opinion about the program. A vast majority of the attendees expressed desire to cooperate in the program activities and provide necessary technical support.

This was followed up by a conference call to give an update on the program achievements. The conference call was arranged by SMA members, team members and representatives from DOE. A list of names and affiliation of the steel company representatives who attended the conference call and summary of the conf. call and response of the attendees is given in Appendix 1.

In addition to this the team members have contacted several other steel companies to get their input for the program. In all cases the companies have expressed interest and offered cooperation for this program.

Table 14. Summary of response to steel reheat furnace questionnaire sent to SMA members

	Company 1	Company 2	Company 3	Company 4	Company 5	Company 6	Company 7	Company 8	Company 9
1 Product Related Information									
What is the type and size range of your product(s) to be heated?	6" & 8" billets - Carbon & Low Alloy	Bar products - rebar 3-18, Channel - 3-6", Angle - 1-4"	100% reinforcing bar. All grades are medium carbon .30 to .45% Size #4 to #18 with around 50% of our mix being the smaller #4 and #5 bar product (both products are "silt" 3 ways)	Rebar #3 thru #14	Structural Steel - Angle, Channel, flats. From Billets - 6 1/4" sq; 6 x 8; 6 x 10	65mm Thick; 42 inches to 64 inches wide	Rebar, Rounds 1/2" to 3-1/2", Structural 1" to 6"	Steel Billets (6 1/4" x 6 1/4"), (5" x 12") and (6" x 9")...Length - 20' - 40'	17x12 to 41x14.5 Near Net Shape Blanks
What is the typical temperature of your charged product? Cold, Warm (500° To 800° F) or hot (higher than 800°F)?	Ambient Temperature	Cold/Warm = 100%	Warm 500 to 800 approximately 40% of our mix is "warm charged"	Ambient	Cold	1750 DegF to 1850 DegF	Cold-Ambient - Hot Charge Approx 20% that is greater than 300"	Cold some warm (10%)	1100°F
What is the discharge temperature (Degree F.) of your product?	2000	2100	2100 F	2150	2150 to 2200 deg F	2100 to 2150 DegF	2100° F	Hot.....2075 degrees F.	2050-2150°F
How many tons/year do you reheat and in how many furnaces?	320,000 tons in 1 furnace	700,000 in one furnace	1 furnace, 500,000 tons per year	650,000 in one furnace	535,000 - One Pusher Furnace	1 Tunnel Furnace and 1.6 million tons	800,000 tons - 1 furnace	950,000 NT.....Two gas reheat furnaces	820,000
2 Furnace related information									
What is the design production rate (tph) of your reheat furnace(s)? Please give a typical number or high and low numbers for your furnaces.	60	120 tph High = 140, Low = 30	80 tph nominal	115 t/hr	100 Ton per hour - charge tons	300tph	130 tph cold - Max 170 tph hot charge	High of 140 TPH to low of 80 TPH	200-280 TPH
What is the typical, average MMBtu/ton you now realize with your product(s)?	2.5	1.1	1.7	1.25 / ton	1.74 MMBtu/finish tons (1.64 MMBtu/ton charge tons)	.522 MMBtu/ton	.98 mmbtu/ton	1.05mmBtu/ton on new furnace.....1.45 mmbtu/ton on old furnace	1.5 MMBTU
What is the preheat air temperature of your current reheat furnace(s)?	Ambient Temperature	600-800 F	Not sure. Regenerative burners are utilized. Estimate 800 degrees combustion air temperature	850	750 deg F	650 to 750 DegF	900°	800 degrees F.	650°F
3 Scale Related Information									
What is the percent of scale you generate in your reheating process?	Estimated at 1.5-2.5%	1 - 1.5%	estimated at 2% but studies are pending	-2 to 2.5%	0.7% - 0.9%	0.50%	0.5%	1 - 2 % This is an estimate	2% Cold Charge, 1% Hot Charge
What value, credit or cost would you assign to the scale in terms of \$/ton. Please consider all costs such as cost of steel not produced, scale removal and disposal cost, maintenance cost related to damages related to scale etc.	\$350 per ton	\$3.80	Yield loss in the mill is worth around \$2/ton/%	??	Scale disposal done at no charge. (do have maint cost to remove it). Cost of steel not produced would be -- scale % (0.9%) x fin goods sales \$/ton.	\$2.02 / Ton		\$3 - \$4/ton	
Does scale formed during reheating impact on your product(s) quality?	Only if not descaled	Yes	no	no	Yes - utilize high pressure descaler to remove it.	It can	Yes	Some on surface critical products	Yes
4 Utility Cost (SMA Member Participation is OPTIONAL for these Qs)									
What is the cost in terms of \$/Million Btu for natural gas or other fuel used for reheating?	\$8 in 2005		\$9	currently - \$6.50	\$8 to \$15/MMBtu	\$11 - \$14 roughly	\$10/mmbtu	Average between \$7 - \$9/million BTU	12.15
What is your cost of power, (\$/kWh)? Please consider all costs for actual electricity, demand charges and other charges if any and give average based on total cost.	\$0.07 in 2005		10 cents	currently- \$0.04	\$0.040/kWh	\$0.045/kWh	0.055	\$0.075/kWh	0.038
What is your cost of oxygen, (\$/1000 cft)? Please consider all costs such as cost related to capital investment, cost of power, operating cost etc. charged by the oxygen plant operator.	\$13 per cubic meter		47 cents	currently - \$0.14	\$0.002/scf	Not Available	.23/cf		1.1
5 Other									
What payback period do you expect for justification of scale free heating ?	3 years	3 years - depends on the cost of the technology	2 years	??	Typically 2 year payback must be met.	2 Years or less	Capital Projects should be <2 years	Approximately 4 years	
Do you have need for power standby? What value or credit would you allow for availability of such power availability	no	No	none, we purchase power as an "unbundled" customer	no	Yes, for water cooling system only. No value assigned.	We have UPS's and emergency generators	No		
Any other comments?			NOX generation is critical in our reheat furnace as we are in an "extreme" non attainment area for NOX in southern California. Goal is to be <0.1 lbs per ton. What would goal be for the new process??	Good luck				Industry is facing stringent NOX requirements	

Benefits of Scale Free Reheating System

The steel industry has to deal with oxidation of steel or scale formation during reheating since the beginning of the modern steel industry several decades ago. Approximately 1% to 2% of the steel reheated by the U.S. industry is converted into scale or iron oxide during reheating. The scale represents loss of energy and value added product. Scale has to be collected, removed, and reprocessed. Cost related to loss of steel and energy required to produce this steel, detrimental effects on the finished steel quality together with cost of scale handling, equipment maintenance and production interruption represent the single largest cost component of the reheating operation. As discussed in a previous section of this report, scale related costs is the highest cost of reheating 52% to 58% representing the highest cost of reheating process.

Use of scale free reheating system would eliminate scale formation, reduce energy used for reheating and recovery of steel from the scale, greatly enhance product quality by eliminating commonly experienced steel surface defect problems for more than 100 million (MM) tons of steel reheated by mini-mills, integrated mills and forging.

Studies conducted during Phase I of the program show that application of this technology would result in reduction of 1.4 to 2.8 million tons of steel scale (iron oxide) per year or savings of 1 to 2 million tons of steel per year in USA. The proposed scale free heating system helps the industry save energy in many different areas. The new system with use of higher efficiency heat recovery and reduced furnace losses could offer up to 12% energy (approximately 0.18 MM Btu/ton) savings during reheating per ton of steel over the current average energy use. The process also saves energy that is used to produce steel lost as scale and it represents an equivalent of 10% to 20% of the energy (0.14 to 0.28 MM Btu/ton) used for reheating. Thus total energy savings with application of scale free reheating steel is equivalent to 22% to 32% of the current energy used for reheating.

However major benefits to the steel industry comes in terms of value of increased yield or revenue generated by saving steel that is currently lost as scale. The analysis shows that value of the steel would be about \$1,500 million during the next 10 years after commercial application of the technology.

The analysis shows that these benefits can be derived for approximately 2/3rd of the steel reheating market with less than 2 years payback periods using currently available and economically justifiable heat recovery and combustion systems. It is necessary to apply advanced heat recovery methods such as use of steam and power generation systems for economically justifiable flue gas heat recovery. The analysis shows that payback periods exceeding 5 years. The estimates assume that application of scale free technology for 25% of the steel market using “hot” charge steel can be developed during the next five years.

Reduction in Energy Consumption

The proposed scale free heating technology for steel reheating reduces energy consumption in reheating operations in three major areas. They are: reduction in energy use due to (i) improved furnace and combustion system design to make it more efficient, (ii) energy savings resulting from scale elimination that would reduce energy needs for converting the scale (practically iron ore) into steel, and (iii) in selected cases through use of waste heat recovery for power generation if the payback period of greater than 3 to 5 years is acceptable. The following analysis (Table 15) shows that potential energy savings for the U.S. steel industry can reach approximately 60 trillion Btu (T Btu) over the next 10 years.

Table 15. Estimated energy savings and cost savings by adaptation of scale free heating by the U.S. industry during the next 10 years.

Years from Pilot	0	1	2	3	4	5	6	7	8	9	10	Total for 10 years
Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	
Hot Charged Furnaces												
US Production MM tons/year	0	0	0	0	0	27.5	28	28.5	29	29.5	30	
(MM tons/year) scale free	0	0	0	0	0	2.75	5.5	8.25	11	13.75	19.25	60.50
Energy savings TBtu/(MM Tons-yr)	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.130	
Energy savings TBtu/year	0	0	0	0	0	0.3575	0.715	1.0725	1.43	1.7875	2.5025	7.87
Increased Steel shipments revenue MM \$/year (based on 2% price increase/year)	-	-	-	-	-	13.75	27.5	41.25	55	68.75	96.25	302.50
Cold/Warm Charged Furnaces												
US Production MM tons/year	64	65	67	68	69	71	72	74	75	76	78	
(MM tons/year) scale free	0	1.25	2.5	5	10	12.5	15	18.75	22.5	25	26	138.50
Energy savings TBtu/(MM Tons-yr)	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	
Energy savings TBtu/year	-	0.469	0.938	1.875	3.750	4.688	5.625	7.031	8.438	9.375	9.750	51.94
Increased Steel shipments revenue MM \$/year (based on 2% price increase/year)	0	9.5625	19.5	39.75	81	103.125	126	160.3125	195.75	221.25	234	\$ 1,190
TOTAL												
TOTAL Energy savings TBtu/year	-	0.47	0.94	1.88	3.75	5.05	6.34	8.10	9.87	11.16	12.25	59.80
TOTAL Steel shipments revenue MM \$/year	-	9.56	19.50	39.75	81.00	116.88	153.50	201.56	250.75	290.00	330.25	\$ 1,493

The assumption made for these calculations are given in Table 16. These are based on information obtained from private communications with steel companies and furnace suppliers and average costs for energy in USA.

Savings Related to Increased Yield

Application of scale free heating can reduce scale loss by 1% to 2% during reheating. Assuming an average value of 1.5% steel loss as scale and steel cost of \$500 per ton (2007

piece) it is possible to save approximately \$7.50 per ton of steel. The analysis shown in the above table shows that total dollar savings related to savings in steel for a moderate growth in application of scale free heating are about \$1,500 million over the next 10 years. These savings do not consider additional benefits of possible improvement in steel surface quality and possibility of additional markets for mini-mill products. Based on these figures it is safe to say that the scale free reheating technology offers great potential for making the US steel industries highly competitive to any other country in the world.

Table 16. Assumptions and data used for energy saving estimate

Steel production using cold/warm charging (2007)	64	MM tons/year
Scale formation (average)	1.5%	% of reheated
Steel in scale formed	0.96	MM tons/year
Energy for scale reduction	13.00	MM Btu/ton
Scale reduction related savings	12.48	TBtu/year
Scale reduction related savings	0.195	MM Btu/ton
Energy reduction-reheating*	12%	
Average energy use for reheating*	1.50	MM Btu/ton
Energy savings - reheating	0.180	MM Btu/ton
Per ton energy reduction - total	0.375	MM Btu/ton

* Energy savings due to higher air preheat temperature and other improvements in furnace design

Steel production using hot charging (2007)	25	MM tons/year
Scale formation (average)	1.0%	% of reheated
Steel in scale formed	0.25	MM tons/year
Energy for scale reduction	13.00	MM Btu/ton
Scale reduction related savings	3.25	TBtu/year
Scale reduction related savings	0.130	MM Btu/ton

Notes:

- It is assumed that application of scale free heating to hot charged furnaces does not reduce energy used for reheating. All energy savings for this case are due to energy savings associated with scale loss elimination only.
- It is assumed that the industry growth rate will be 2% per year and value of steel at reheat stage is \$500 per ton with price increase of 2% per year.

Estimate of the Environmental Benefits

A summary of values for CO₂ and NO_x emissions reduction from energy savings resulting from elimination of scale and correspondingly need for increased steel production plus improved energy efficient design are given in Table 17. The values for emission rates are derived from References 11 and 12.

Table 17.

CO₂ emission		
Electricity	#s/kWh	2.30
Electricity on a MM Btu basis	#s/MM Btu	673.89
Natural gas	#s/MM Btu	113.00
Average for steel production	#s/MM Btu	393.45
Total Emissions Reduction over 10 Years		
CO ₂	MM Tons	17.81
NO _x	Tons	10,465

Note: CO₂ emissions for steel production are based on an average value of 393.5 #s/MM Btu

The following Table 18 gives data used to derive these values.

Table 18. Data used to estimate CO₂ and NO_x emission reduction with use of scale free heating.

Environmental impact	Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total for 10 years
CO₂ reduction *													
Hot charge	MM lbs./year	-	-	-	-	-	195	390	584	779	974	1,363	
Cold/warm charge	MM lbs./year	-	283	566	1,131	2,262	2,828	3,393	4,242	5,090	5,656	5,882	
Total/year	Million Tons/year	-	0.14	0.28	0.57	1.13	1.51	1.89	2.41	2.93	3.31	3.62	17.81
NO_x reduction **													
Rate	lbs./MM Btu	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	
Total/year	Tons/year	-	82	164	328	656	883	1,110	1,418	1,727	1,953	2,144	10,465

The overall benefits associated with successful development and application of this technology can be summarized below.

- It removes the largest cost factor associated with the steel reheating. Scale cost represents 52% to 58% of the reheating cost. It is more than all other costs (labor, amortization, energy, maintenance) combined. This has a potential of reducing value added cost by \$5 to \$10 per ton of steel based on scale loss of 1% to 2% and steel cost of \$500 per ton
- Use of this process and associated equipment result in major energy savings in two areas. One is due to elimination of scale and need to produce an equivalent amount of steel from iron ore or scrap steel. It is between 0.13 to 0.26 MM Btu/ton of steel reheated. Other is due to energy reduction in a reheat furnace due to improved design and operations. This saving is about 0.18 MM Btu/ton for cold or warm charged furnaces.

- c. It increases productivity of the reheating furnaces since it eliminates or greatly reduces the production interruptions associated with time required for scale removal.
- d. It reduces maintenance of the furnace. Presence of scale in furnace and other areas in flue gas exhaust adversely affects life of a number of furnace components (refractory, rolls, burner blocks, recuperators, exhaust fans etc.).
- e. It improves steel surface quality. Presence of scale results in a variety of surface and internal defects in the final product results in costs associated with scale related defects.
- f. It offers possibilities of producing steels for new markets due to improved quality or lower price.

Issues Identified for Further Study

Following issues have been identified for further study after completing Phase I activities. All of these issues would be addressed and resolved during Phase II of the program.

Major technical issues include:

- (i) Design and testing of preheated air burners that can meet operating requirements defined in Phase I. The burners should be capable of operating under sub stoichiometric conditions using preheated air as well as under stoichiometric conditions while offering the required turn down to run the furnace in scale free as well as conventional mode.
- (ii) Availability and design of a burner system that can operate with oxygen enriched air while meeting the performance requirements as mentioned for preheated air.
- (iii) Furnace design to avoid leakage of CO and H₂ from the furnace,
- (iv) Material handling system design at the discharge end to avoid leakage of CO and H₂ from the furnace while maintaining scale free atmosphere that may be affected when the billets or slabs are discharged from the furnace
- (v) Control to maintain the required burner operation at all firing rates during varying furnace loading rate or operations.
- (vi) Furnace and heating system design to maintain required heat transfer or heat flux.
- (vii) Additional issues that may be raised by the steel industry. They may include: upper temperature limit for the steel before scale becomes a problem in the charge zone when the furnace is operated as scale free furnace; effect of delays, planned and unplanned on scale formation; limits on air-fuel ratios on scale formation in different zones of a furnace etc.
- (viii) Scale free heating tests on a pilot scale furnace using commonly used steel using process parameters defined in Phase I. It is anticipated that the tests matrix would include at least the following parameters:
 - Grade or composition of steel
 - Steel sample time-temperature history
 - Furnace atmosphere composition – H₂ and CO percentages
 - Initial and final steel sample temperature
- (ix) Further investigations for waste heat recovery methods that can be used for hot charge applications. Preliminary design - sizing of the system for a typical application
- (x) Analysis of critical safety and environmental issues and definition of instrumentation and controls requirements.

Accomplishments

A summary of accomplishments during Phase I is given below. These accomplishments are in accordance with the project objectives and include all issues mentioned in scope of work for the current phase of the program.

- (i) Theoretical analysis and literature search has confirmed that scale free reheating of steel can be carried out by using rich natural combustion under practical operating conditions. The

search revealed that at least 4 companies had investigated possibilities of scale free reheating of steel using non-oxidizing atmosphere and in two cases the process was applied to smaller furnaces for forging industry. The literature search also showed that these systems were relatively inefficient and perhaps uneconomical to apply for large steel reheating furnaces at current energy prices.

- (ii) Development of a model to define required combustion conditions and available heat that can be used for thermal system design and energy use estimates. This model uses thermal equilibrium calculations.
- (iii) Definition of required furnace operating parameters and investigations in obtaining critical hardware (combustion system – burners) required for preheated air based SFH. A major combustion system supplier has confirmed that the required burner hardware and associated combustion system can be designed and has offered to demonstrate the burner operation under the required conditions.
- (iv) Development of an economic analysis model that can be used to analyze cost – benefit analysis for application of scale free heating using conventional heating methods, preheated air based scale free heating system and oxygen enriched air based scale free heating system. Use of this tool has helped us identify specific market and application areas and prioritization of scale free heating applications in U.S. steel industry.
- (v) Detail technical analysis of the process requirements that concludes that scale free heating can be carried out by at least two different methods. They are: use of preheated air and use of oxygen enriched combustion air.
- (vi) Market assessment in cooperation with steel industry has shown that scale free heating system is applicable to furnaces used for 64% of the steel reheating market. Such applications offer industry acceptable economics (less than 2 years payback period with use of preheated air).
- (vii) Confirmation of problems and economic penalty resulting from scale formation on steel reheating furnaces and their willingness to contribute and collaborate in efforts to eliminate scale problems.
- (viii) Strong support from steel industry through SMA and direct contacts with major U.S. steel companies.

Conclusions

The project team has achieved objectives of Phase I of the scale free steel reheating system development program.

Activities of Phase I of the program has demonstrated that it is possible to develop and apply a scale free reheating process that offers major competitive advantages to the U.S. steel industry while offering significant reduction in energy used by the steel industry.

Application of this technology can eliminate scale formation and increase the yield by 1% to 2% during reheating process used by the U.S. steel industry. It also offers overall reduction in energy use (about 0.375 MM Btu/ton of steel). This includes energy savings associated with the elimination of scale and need to produce this steel as well as reduction in energy used during reheating process.

Adaptation and use of this technology by U.S. steel industry for economically justifiable market sector (64 MM tons/year in 2007) can save 24 TBtu/year or approximately 1.2% of the total energy used (about 2,000 TBtu/year) by the U.S. steel industry. However energy savings estimated based on gradual adaptation of this technology by the U.S. industry over the 10 years after field demonstration of the technology can save about 1,500 TBtu during the this time (10 years).

Application of this process offers increased yield, potential for improved quality, reduction in over all energy use and reduction in cost of steel production while eliminating major issues of furnace maintenance, scale disposal and down-time associated with current steel reheating practices.

A detail analysis of issues related to the scale free reheating process and its technical requirements carried out during Phase I has defined required process parameters and has helped the team to conclude that it is possible to convert an existing furnace from conventional heating to scale free system while maintaining current system of material handling, downstream processing (hot rolling) and a few changes in furnace design and combustion system.

A detail market assessment carried out in cooperation with the U.S. steel industry shows that the project results would be applicable to reheating furnaces used by 64% of the U.S. steel production in the near term with long term potential for additional market. The technology can be used by two major segments of the steel industry: integrated mills; and mini (or market) mills. Application of the technology to other 36% of the market would depend on economics of heat recovery system and energy cost at a specific plant. Average payback period for new furnaces is estimated to be about 2 years while payback period for retrofit applications would depend on type of furnaces used and its current condition.

The scale free reheating requires use of heating system and furnace design features that are different than the conventional system. During Phase I the team members have developed and analyzed preliminary necessary design concepts for the furnace modifications and heating

system that can be used for commonly used reheat furnaces for the steel industry. However it is necessary to finalize the designs for specific application specifications. It is also necessary to test and demonstrate scale free heating process using the process conditions identified during Phase I analysis. The steel industry would want to see demonstration of a functional combustion (burner) system with associated controls and details of a furnace design (or modifications to an existing furnace) that can be sealed properly to eliminate discharge of furnace gases in the atmosphere during the range of operating conditions.

It is necessary to address a number of issues and demonstrate performance of critical components to meet requirements of the steel industry. This includes tests on steel samples, demonstration of performance of critical components and discussion on critical design issues with the potential users.

The furnace supplier company (Alchas Inc.) who is a team member has confirmed that they can provide detail design and its safety analysis for the system during Phase II of the program. They will also be commercialization partner for the project.

Consultations with a major supplier of combustion system to the steel industry has confirmed that it is possible to design and supply the required combustion system to meet requirements of the process. The company has agreed to participate as a team member during Phase II of the program.

Recommendations

Based on results of Phase I of this program and feedback from the steel industry furnace users we recommend that The Department of Energy continuation the program by funding Phase II of the program. The program tasks would be carried out to meet requirements of the following recommendations.

- Conduct scale free heating tests on a pilot scale furnace using commonly reheated steel grades recommended by the steel industry (SMA) using process parameters defined in Phase I. These samples should be tested to verify acceptability of the samples to meet the steel industry needs
- Carry out activities required for preliminary design - sizing of the system for a typical application to make sure that the current furnace size can adequately heat the steel shapes and sizes without adversely affecting the production rates. This includes testing of critical components and verification of their performance to assure that they can meet the process and equipment operating requirements under conditions specified by the steel industry.
- Perform analysis and required tests, if necessary, to address critical safety and environmental issues. Verify that the furnace and heating system meets the specified requirements.
- Continue collaboration with the steel industry to get feed back as well as to identify potential pilot unit installation at the end of Phase II. Seek support from the industry representatives for review of the analysis, recommendation on required revisions, and technical input required on the scale free reheating system design.
- Explore options for waste heat recovery system to identify economically justifiable system that can be used for hot charged reheating furnace.
- Develop a model that can be used to perform detail (site specific) analysis of energy, economic and environmental performance and for evaluation of options.

Go/No-go Decision Criteria

Category	Comments and Guide to Detail Information
1. Strategic Fit	<p>This program meets requirements of ITP mission statement, “Improve energy intensity of the US industrial sector through coordinated program of research and development, validation, and dissemination of energy efficiency technologies and operating practices”. The program is an example of coordinated R&D and its validation by the industry and ITP. Application of the proposed process could save about 24 TBtu/year or 1.2% of the total annual energy used by the U.S. steel industry. The process application would increase steel reheating process yield by 1% to 2%, valued at average annual savings of \$480 million for the U.S. steel industry. Additional benefits include reduction in operating and maintenance cost, NOx and CO2 emissions and improved product quality. Specifics of these benefits are discussed below and described in detail throughout the report.</p>

Technical Merit	<p>Scale formation during steel reheating has not changed since the very beginning of the modern steel industry. The industry has attempted several options to break scale before rolling or forging of steel slabs/billets or slabs. Attempts have been made to achieve scale free heating by using alternate methods such as use of induction and radiant tube furnaces however they been unsuccessful, impractical or uneconomical. Under this program the team has developed and analyzed a method of scale free reheating using heating system that resembles the conventional heating system however allows scale free heating of steel. The system is designed to maintain current furnace structure, material handling system and downstream processing equipment. It requires few changes to the combustion and heat recovery systems that can be installed on a new furnace or as retrofit for an existing furnace.</p> <p>As discussed in this report, the process offers increased yield, potential for improved quality, reduction in over all energy use for the US steel industry and reduction in cost of steel production while eliminating major issues of furnace maintenance, scale disposal and down-time associated with scale removal. Development of this technology will allow the US industry produce consistent and improved steel quality without increasing energy intensity (Btu/lb.) and product yield by 1% to 2.5%.</p>
Market Potential	<p>A detail market study shows that the project results would be applicable to reheating furnaces used by 64% of the U.S steel industry in the near term with long term potential for other 25% additional market. Application of the scale free technology to other 25% of the market would depend on economic justification of heat recovery system and energy cost at a specific plant. At the current steel industry production rate the system can be applied to reheat 64 MM tons/year steel in USA. Actual market penetration would depend on the industry experience. Expected market penetration based on very conservative estimates is discussed in the Market Assessment section of this report.</p> <p>The system can be retrofitted on existing furnaces or can be used for new furnace installations. The technology can be used by two major segments of the steel industry: integrated mills and mini (or market) mills. Average payback period for new furnaces is about 2 years while payback period for retrofit applications would depend on type of furnaces used and its current</p>

	<p>condition. The payback period is estimated based on simple cash flow.</p>
Risks	<p>The scale free reheating requires use of innovative features for design of the heating system and certain features of a furnace. They are quite different than the conventional system and require use of new technology and design approaches. It is necessary to design and test a combustion (burner) system, controls and the furnace components (or modifications to an existing furnace) that assures safe operation with zero discharge of furnace gases in the atmosphere during a range of operating conditions.</p> <p>A major supplier of burners to the steel industry has offered burners and their participation as a team member in the next phase of the program. They are very confident that they can provide a heating system (burners and associated controls) that would be tested and verified to meet the system requirements. An experienced furnace company will carry out detail design and its safety analysis for the system during Phase II of the program.</p> <p>Market risks include acceptance by the steel industry and a site that is willing to build (or modify) a furnace and carry out production tests. A close collaboration with a major steel industry organization, SMA, and its</p>

	members would help the team eliminate (or minimize) risks and to assure that the program tasks would result in acceptable system.
Competitive Advantage	<p>The technology offers competitive advantages over the current steel reheating processes used by the steel industry worldwide. At this time almost 100% of the steel reheating is done in fuel (mostly natural gas in USA) fired furnaces that produce 1% to 2% scale with severe cost penalty in product loss, down time for scale removal and added maintenance due to effects of scale on furnace refractory and other hardware.</p> <p>Application of the scale free technology developed under this program would eliminate these costs, increase production and offer a cost advantage of \$5 to \$10 per ton of steel produced. This cost represents 10% to 20% of the net income per ton of steel shipped for integrated steel producers and a market (mini) mill producers. Use of the scale free reheating technology would help the US steel industry be competitive with the overseas suppliers. Additional details of the savings and other advantages are discussed in section Benefits of Scale Free Heating section of this report.</p>
Technical Project Scope	A technical project scope for Phase II of the project has been developed it will be submitted to the DOE program office for considerations to support Phase II activities of the project. A summary of the issues to that would be addressed during Phase II of the program are discussed in the section "Issues Identified for Further Study " of the report.

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11. *Private communications with SDI personnel and Frank Vereecke of Alchas, Inc.*
12. U.S. Environmental Protection Agency. July 2000. *Carbon Dioxide Emissions from Generation of Electric Power in the United States*.

Appendix 1

Details of SMA Member Collaboration and Contacts

Steel Reheat Project Conference Call Participants

1. Jeff Dyck, Cascade Steel
2. Scott Ertl, Charter Steel
3. Jerald Rains, CMC Steel – AL
4. Dale Schmelzle, CMC Steel - AL
5. Rick Wood, CMC Steel – AL
6. Mike Buckentin or Dennis Malatek, CMC Steel – SC
7. Ty Hall, CMC Steel – TX
8. Alan Jackson, CMC Steel – TX
9. Alan Speir, CMC Steel – TX
10. Joe Busch, Gallatin Steel
11. Denis Desjardin, Gallatin Steel
12. Curtis Durbin, Gallatin Steel
13. Bobby Heinz, Gallatin Steel
14. Todd Minor, Gallatin Steel
15. Mike Sarafolean, Gerdau Ameristeel
16. James Huff, Nucor Birmingham
17. Clark Lenz, Nucor Jackson
18. Nick Tepovich, Nucor Jackson
19. Wade Hedrick, Nucor Texas
20. Chad Utermark, Nucor Texas
21. Joe Golden, Nucor Tuscaloosa
22. Eugene Hunter, Nucor Tuscaloosa
23. Stanley McClellan, Nucor Tuscaloosa
24. Andy Seibert, Nucor Tuscaloosa
25. Jim Crompton, TAMCO
26. Joe Samu, TAMCO

Scale Free Heating Project – Conference Call Notes

August 3, 2006 3:00-4:00pm

On Thursday, August 3, SMA hosted a conference call concerning Dr. Arvind Thekdi's project, Development of Scale Free Heating System for Steel Reheating. Dr. Thekdi first reported to the SMA group at the March 2006 SMA Plant Operations Division meeting in Belterra, IN. The purpose of this call was to provide a brief background on the project, discuss developments and results since March, outline potential next steps, and allow for SMA members to submit questions.

In addition to Dr. Thekdi of E3M, Inc., the call included Debo Aichbhaumik and Simon Friedrich from the Department of Energy (DOE), Frank Vereecke of Alchas, Inc., SMA staff, and approximately 25 representatives from the following SMA member companies: Cascade Steel, Chaparral Steel, Charter Steel, CMC Steel (AL, SC, TX), Gallatin Steel, Gerdau Ameristeel, Nucor (Auburn, Birmingham, Jackson, Seattle, Texas, Tuscaloosa), TAMCO, and V&M Star.

Project Summary

The call began with an introduction of Dr. Thekdi, who then described the background and objectives of the project: developing and testing a scale free heating system that reduces scale formation in the steel reheating process, resulting in a substantial reduction in energy usage, significant yield increases, and improvement in overall steel quality, all of which results in significant cost advantages for the U.S. steel industry. Dr. Thekdi is pleased with the team that has been working on the project, which includes: E3M, Inc., Alchas, Inc., Steel Dynamics, Air Products and Chemical, SMA, and the Forging Industry Association (FIA).

Phase I of the project was scheduled to last roughly 12 months, and should be completed at the end of August. This phase includes an assessment of the economic impact of usage of scale free heating by the domestic steel industry, as well as an economic analysis of the operating and capital costs for a scale free steel reheating system. The intention of the project is to conduct burner testing to adjust the combustion ratios of burners, as scale forms at high temperatures in the presence of carbon dioxide, oxygen, and water vapor.

Along with Frank Vereecke, Dr. Thekdi summarized the preliminary results of Phase I and a market analysis. Scale free heating can be applied to roughly 65 percent of the 100 million tons of domestic steel product, including reheating cold charged products with the most commonly used reheat furnaces (walking beam, walking hearth, pusher and rotary types). Any continuous heating furnace is capable of scale free heating. Application of scale free heating for the 35 percent of the industry that uses tunnel furnaces with hot charged products would require a usage of waste heat and rich combustion products that is not currently economically viable.

Savings are projected at \$4-6 per ton of steel produced, or an anticipated \$354 million per year for the included 65 million tons. This amounts to \$3 million to \$5 million for the typical furnace per year. Bloom Engineering is working on burner designs that would promote energy savings and benefit the industry.

A DOE-appointed review team will make a decision on the continuation of the project at the conclusion of Phase I. This decision will be based upon several factors, including: benefits offered to the steel industry; economic justification for the process application; the continued cooperation of the steel industry; the participation of a furnace supplier and other project partners. The strong participation of SMA member companies in this call will be taken as a sign of continued interest on the part of the industry. Phase II would last approximately two years, and would include the actual research and development of a furnace design model, to run tests and answer questions of the steel industry, regarding safety issues and energy usage. Phase III would then apply more to the actual implementation of the design model.

Question & Answer

SMA members were then given the opportunity to ask Dr. Thekdi and Mr. Vereecke questions on the project.

Responding to a question on the impact on NO_x, Dr. Thekdi noted that NO_x formation is being divided into three distinct stages, yielding roughly .06-.07 lb of NO_x per million BTUs.

A question was asked on the level of CO generation. Dr. Thekdi stated that in order to ensure safety, CO emission must be designed without escape, and that CO must be burned off completely. Furnaces should be run under a slightly negative pressure to maintain a nearly complete containment of CO.

The final question focused on the need for the utilization of deep sniffers in furnaces to verify correct gas mixtures. Existing technologies should be sufficient.

SMA will continue to keep its members updated on the status of Dr. Thekdi's project, and will be glad to filter any questions (please direct those inquiries to Adam Parr – parr@steelnet.org). An update will be provided on this, as well as other DOE projects, at the fall meeting of the Plant Operations Division, which will be held Sept. 30 – Oct. 2, 2006 in Indianapolis, IN.