Development of Next Generation Heating System For

Scale Free Steel Reheating

 

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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 (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.

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% O_2 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 detailed 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 detailed 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 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^{o}F. preheated air for cold charged steel reheat furnaces 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 the 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 an 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 charged steel for detail design and economic analysis. These applications cover approximately 64% of the steel produced in the 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 the 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^{o}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 the reheating process itself. In the year 2005, the U.S. steel industry used 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 of steel scale – 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 charging of steel with use of an appropriate and economically justifiable heat recovery system such as production of steam and power generation. Phase I economic analysis showed that Phase II be directed to the 64% of the market because of ROI.

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~~ in 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 (ACL-NWO), 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^{o}F. starting from ambient temperature or higher temperature (about 1600^{o}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.

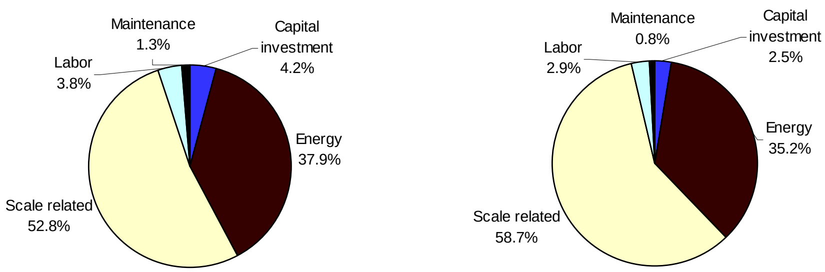


Figure 1: Cost distribution for reheat furnace for thin slabs (left graph) and conventional walking beam reheat furnace (right graph).

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^{o}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 temperatures. 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.

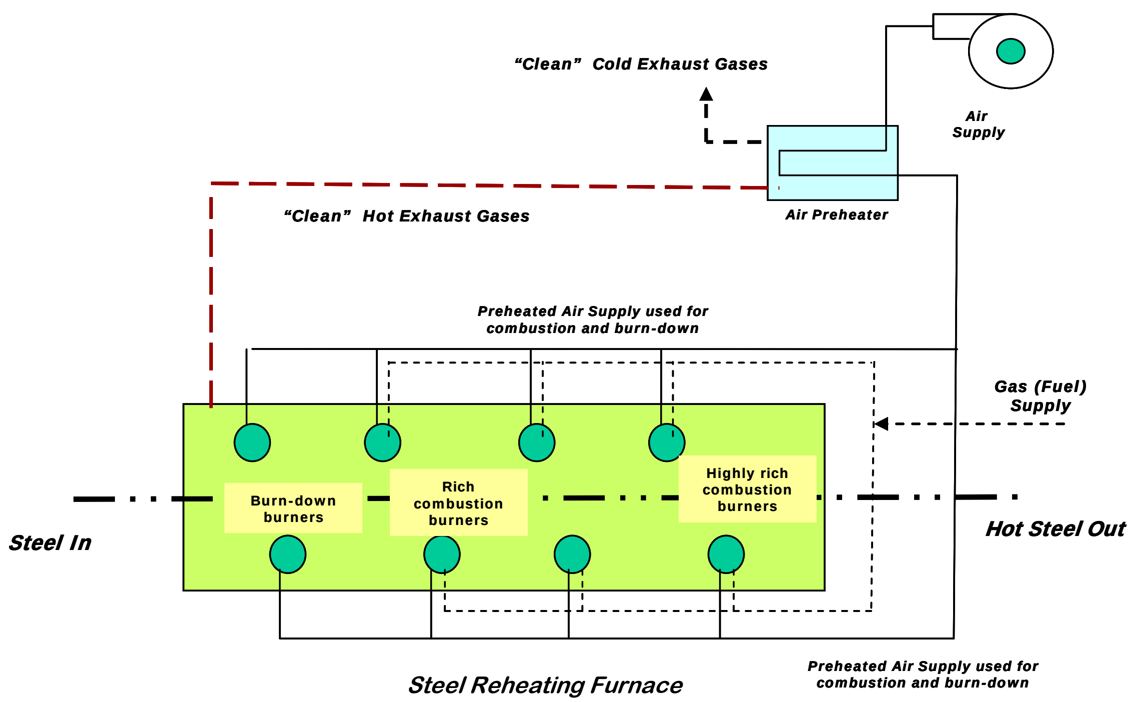


Figure 2: Scale free steel reheating system for furnaces using "cold" charge

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^{o}F. or oxygen enriched air with O_2 content in excess of about 45% to produce the required gas composition (CO/CO_2 and H_2/ H_2O) ratios while maintaining the required "flame" temperature. The combustion products from the soak zone

travel counter current to~~p~~ the flow of steel. The gases are "burned" or reacted by using preheated air to produce more heat and change ratio of CO/CO_2 and H_2/ H_2O 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 H_2 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 (ii) reduction in energy associated with handling and disposal of scale 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 charging of steel. In such cases it is not possible to complete combustion of CO and H_2 in flue gases within the furnace itself. Flue gases discharged from this furnace could contain about 12% CO and 16% H_2 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 H_2 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.

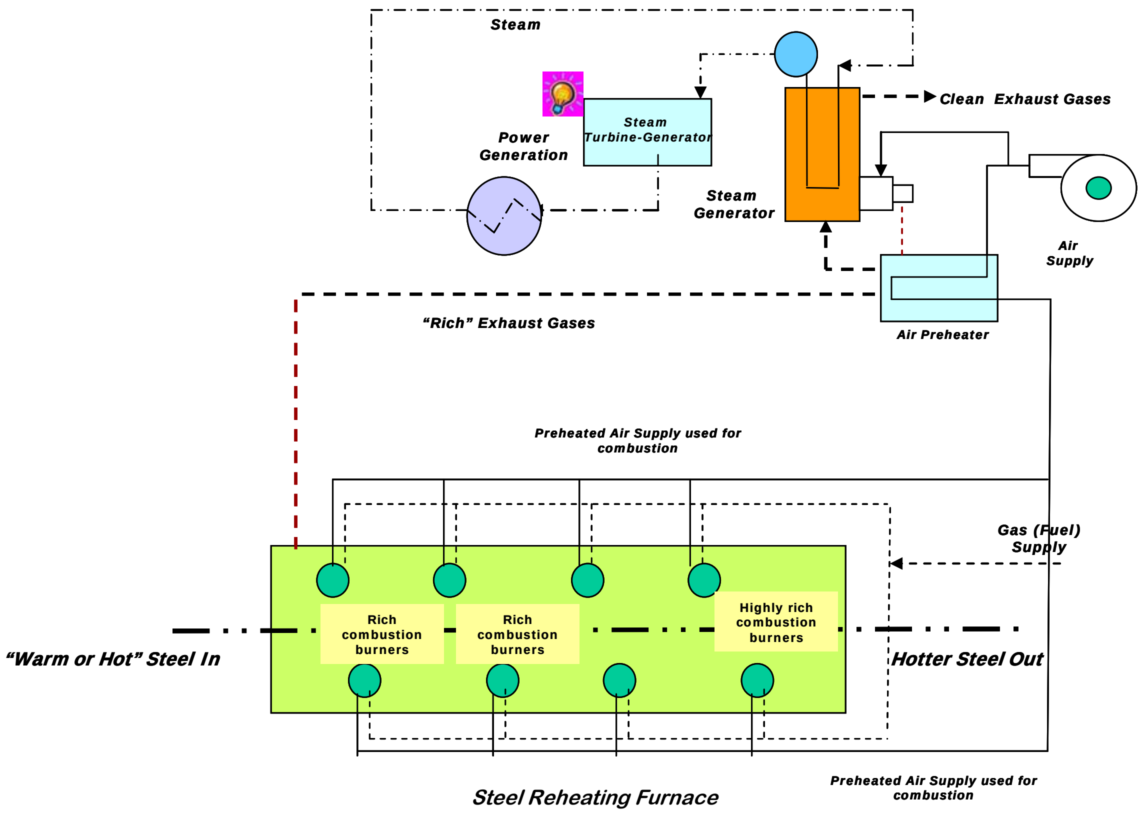


Figure 3: Scale free steel reheating system for furnaces using "hot" charge

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 (1 to 2 years) payback period as it can serve almost 2/3rd 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 private industry contacts and research workers were contacted to investigate work done in the area of preventing scale or oxidation of steel. 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 temperatures (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 describers design and operation of a pilot plant operating at one ton per hour capacity ands used for 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 nineteen-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^{o} 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 values of 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 Selas 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:

$$M = a * \{t * (e^{\wedge(-b/T)})\}^{\wedge 0.5}$$

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 oxidizing heating gases such as O_2, CO_2 and water vapor (H_2O). Oxidation reaction of steel and gases depend on ratio of CO/CO_2 and H_2/ H_2O 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. 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 a strong function of time in the beginning but it levels off (rate goes down) as exposure time is increased.

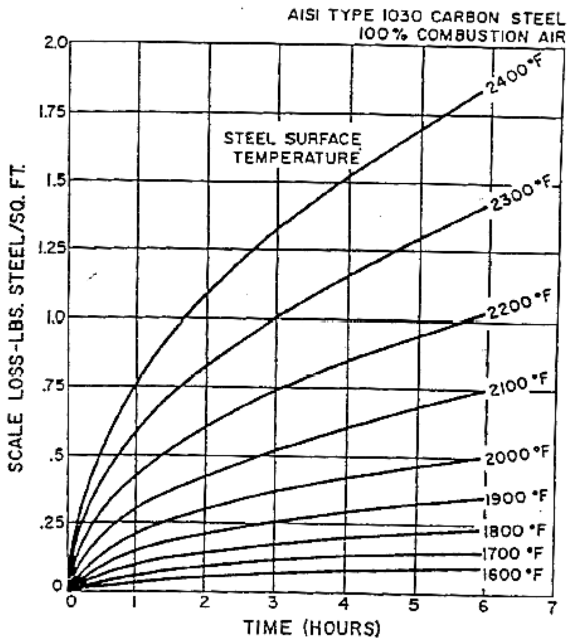


Figure 4: Steel loss by oxidation during heating in products of natural gas

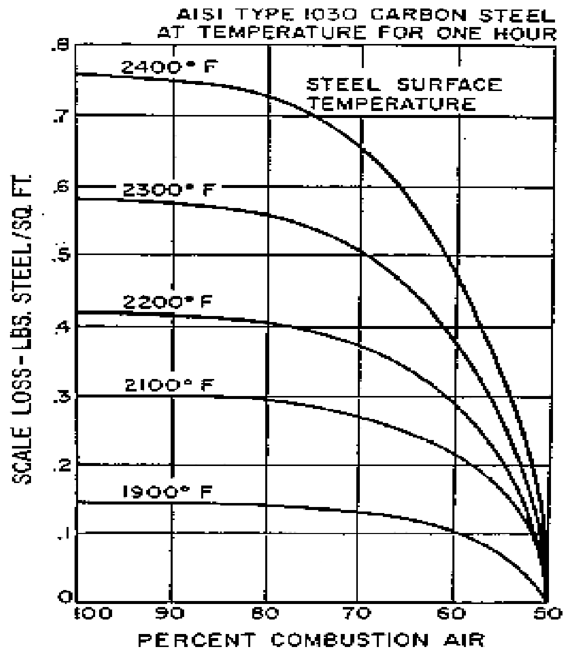


Figure 5: Steel loss by oxidation during heating at

Additional information on the 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 H_2O/ 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 H_2/ H_2O (or H_2O/ 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^{o}F. to 2200^{o}F. Information derived from above ~~can be~~ indicates that it is necessary to maintain CO_2/CO ratio below about 0.3 (or CO/CO_2 ratio above about 3.33) and H_2O/ H_2 ratio below 0.8 (or H_2/ H_2O 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 another section.

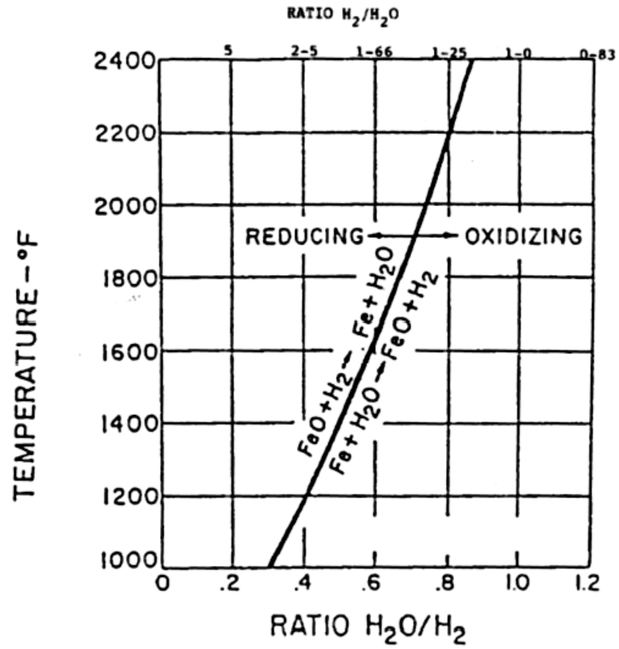


Figure 6: Effect of H2O/H2 ratio on steel oxidation - reduction

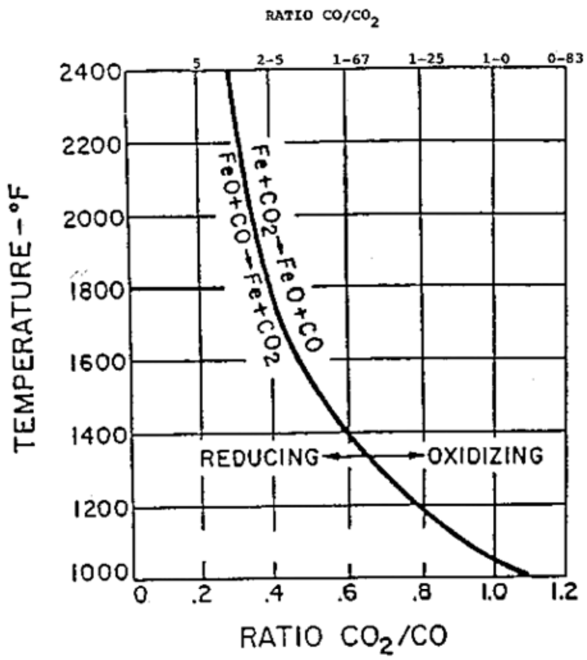


Figure 7: Effect of CO2/CO ratio on steel oxidation - reduction

A furnace system based on above principles was designed and used for heating of steel billets used in 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 ~~is~~ 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, FeO, Fe_2O_3 and Fe_3O_4, each with slightly different Fe content. These oxides are known as Hematite (Fe_2O_3) with 69.9 iron content, Magnetite (Fe_3O_4) 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 Fe_2O_3 and it is reduced to Fe_3O_4 and FeO as the successively formed oxides react with iron (Fe). Additional Fe_2O_3 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.

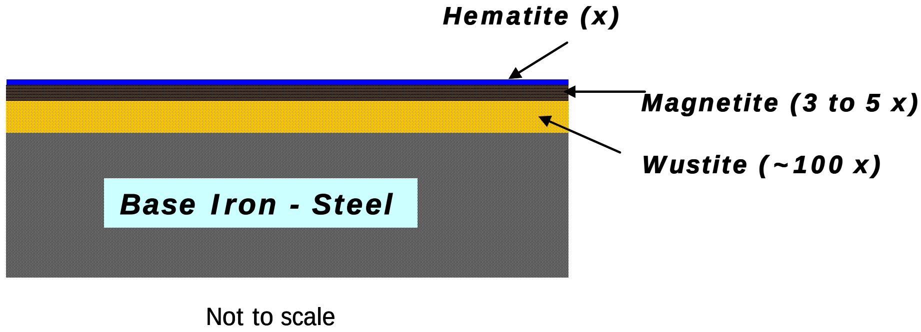


Figure 8: Composition of scale formed on steel surface during reheating

Scale formation for commonly used steel has been studied in detail by Schultz (Ref. 9) during late nineteen 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^{o}F. to 2200^{o}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 CO_2 and H_2O 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 O_2 in scale (Lb. O_2/ft$^{\wedge 2}$) at the end of time t minutes
Wo = Weight of O_2 in scale (Lb. O_2/ ft$^{\wedge 2}$) at the beginning of scale formation
Ro = Initial oxidation rate {Lb. O_2/(ft$^{\wedge 2}$-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 reheat 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 80s. The project was supported by The Gas Research Institute. Several tests were carried out at Inland steel Company 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.

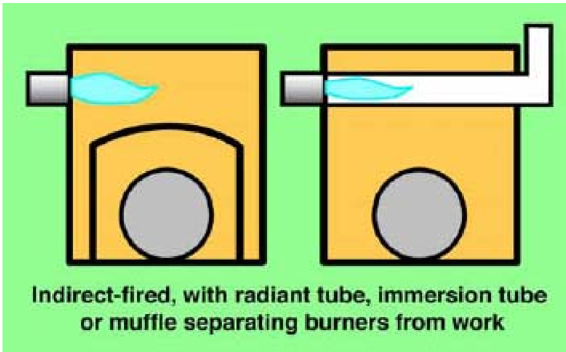


Figure 9. Use of a muffle or radiant tubes for scale free heating of steel

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^{o}F. 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 ft$^{\wedge 2}$. 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.) presents 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. and these 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 the year 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^{o}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 in 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^{o}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/ CO_2 and H_2/ H_2O
- 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 the effect of key combustion parameters that would help us meet the required conditions. Thermal equilibrium analysis was used to study the 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. Composition of the natural gas used for the calculations in terms of % volume fraction for each constituent is given below (Table 1):

Table 1. Composition of natural gas used ~~sued~~ for thermal equilibrium calculations

CH_4	C_2H_6	C_3H_8	C_4H_{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	Cod and 1000 deg. F.	50% to 60%
35% Oxygen in air	Cod and 1000 deg. F	50% to 60%
21% Oxygen in air	1000 deg. F	50% to 70%

The analysis was carried out for an operating temperature of 1200 ^{o}C. or 2192 ^{o}F. that is the closet temperature to operating conditions of soak zone in a reheat furnace. Please note that a 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	H2	H2O	CO	CO2	H2O/H2	CO2/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	H2	H2O	CO	CO2	H2O/H2	CO2/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	H2	H2O	CO	CO2	H2O/H2	CO2/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	H2	H2O	CO	CO2	H2O/H2	CO2/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	H2	H2O	CO	CO2	H2O/H2	CO2/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	H2	H2O	CO	CO2	H2O/H2	CO2/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

Earlier analyses of oxidation of iron in the presence of a mixture of gases containing CO_2, H_2O, CO and H_2 show that it is necessary to have a CO_2/CO ratio of 0.32 and H_2O/ H_2 ratio of 0.8 to avoid oxidation at about 2200^{o}F. temperature at the interface. By assuming interface temperature of 2200^{o}F. we are safe since the gas temperature is always higher than temperature of the material (steel in this case) being heated. Note that ratio of H_2O/ H_2 for 21% oxygen and 1000^{o}F. case for 54% stoichiometric combustion is 0.76, same as in other cases.

Analysis of the results indicate that for all cases it is necessary to have a stoichiometric ratio of oxidant and natural gas at 54% stoichiometry (or richer) to achieve the required values of CO_2/CO and H_2O/ H_2 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% O2 - cold oxidant	21.80	%
45% O2 - cold oxidant	16.22	%
45% O2 - 1000 Deg. F. oxidant	20.55	%
35% O2 - cold oxidant	18.80	%
35% O2 - 1000 Deg. F. oxidant	20.10	%
21% O2 - 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 O_2 content is in the range of 21% to 45%. The results show that preheating 45% or 35% enriched air to 1000^{o}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% O_2 content at 1000^{o}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 a heat recuperator. Oxygen enrichment also requires additional operating cost for oxygen. The following Table 5 gives amount of O_2 required for combustion in terms of cu.ft. of O_2 per cu.ft. of natural gas used in the burner.

Table 5. Cost of oxygen per MM Btu burner input.

O2 in "air"	Oxygen required ft^3/ft^3 of natural gas	O2 cost/MM Btu input
100% O2	1.064	$ 2.25
45% O2	0.718	$ 1.52
35% O2	0.539	$ 1.14
21% O2	0.000	$ -
Note: This is 54% stoichiometric combustion conditions		

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^{o}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/CO_2 and H_2/H_2O ratios at various temperatures has defined the non-oxidizing atmospheres needed for

heating of steel as a function of temperature.

The CO/CO_2 and H_2/H_2O ratios for a conventional heating furnace, where combustion is at or slightly above stoichiometric conditions, are zero since no CO or H_2 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):

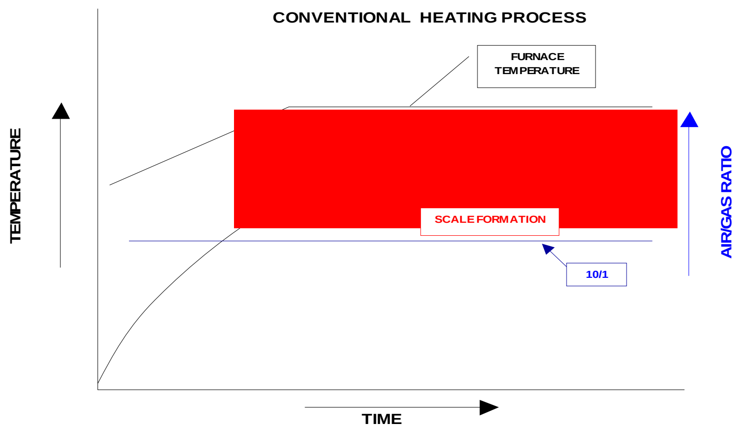


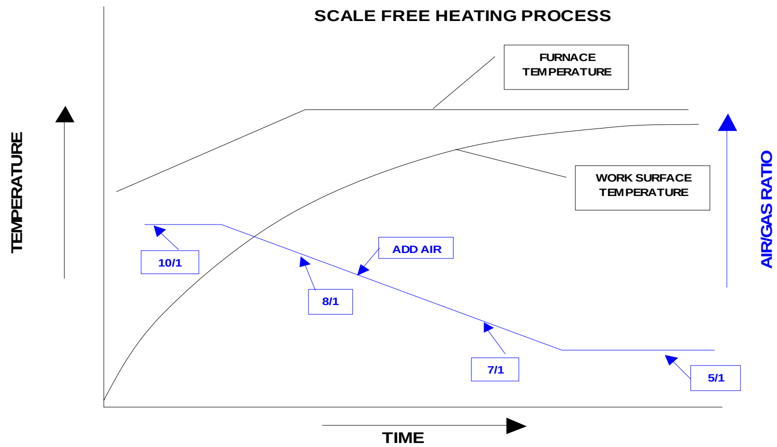
Figure 11. Steel heating in conventional reheating furnaces

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% by weight.

The CO/CO_2 and H_2/H_2O 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/CO_2 and H_2/H_2O 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 H_2) 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.



FFigure 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/CO_2 and H_2/H_2O 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. Therefore, the scale free heating process ends up being more efficient because of this.

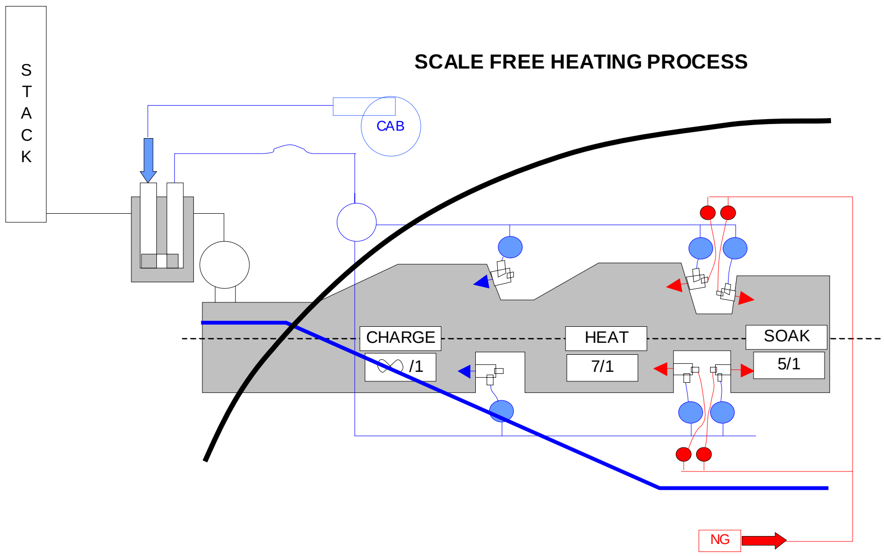


Figure 13. Temperature and combustion conditions for scale free heating – cold charge

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.

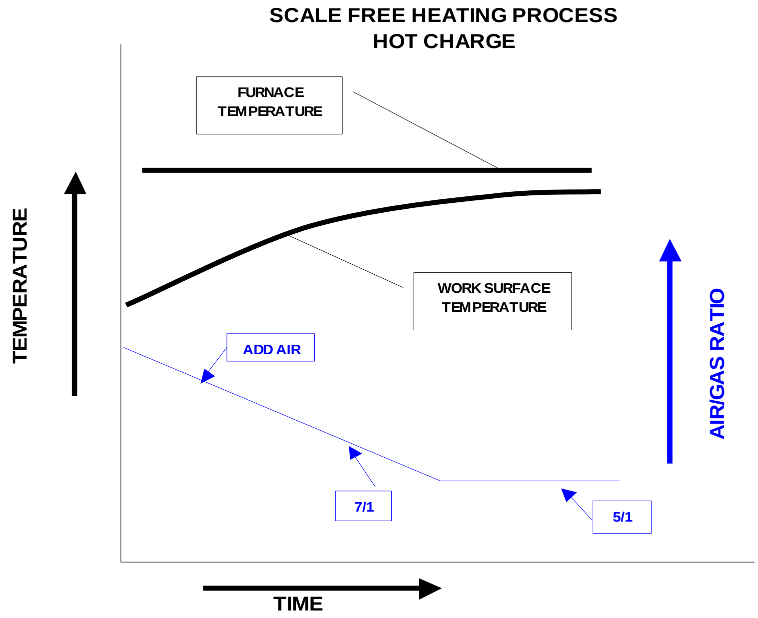


Figure 14. Time-temperature relationship in a hot charged reheating furnace

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.

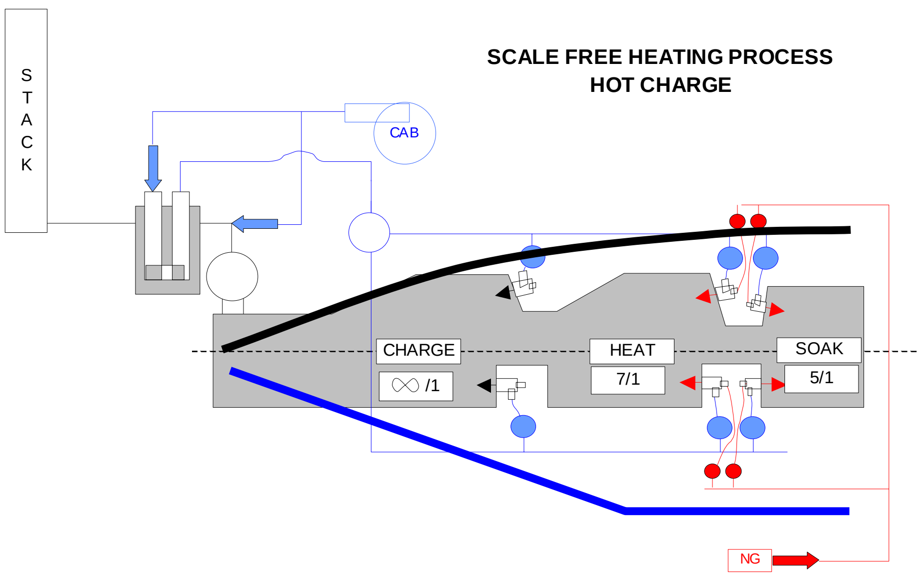


Figure 15. Temperature and combustion conditions for scale free heating – hot charge

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 H_2) 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.

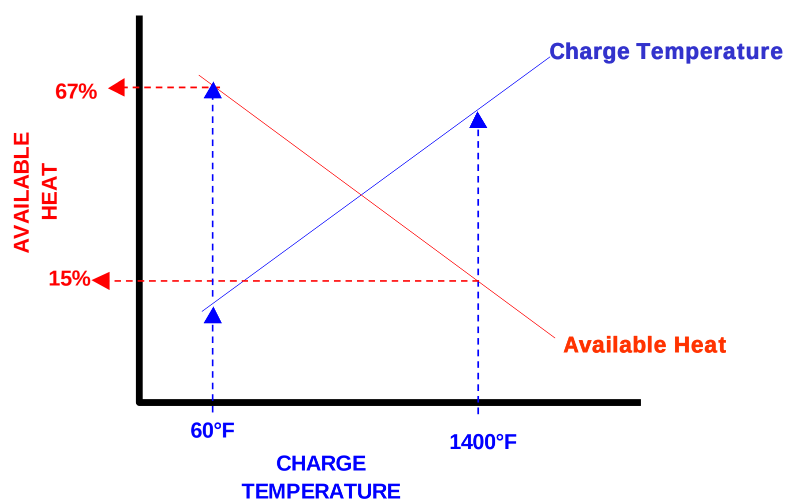


Figure 16. Effect of charge temperature on available heat for scale free reheating

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^{o}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.

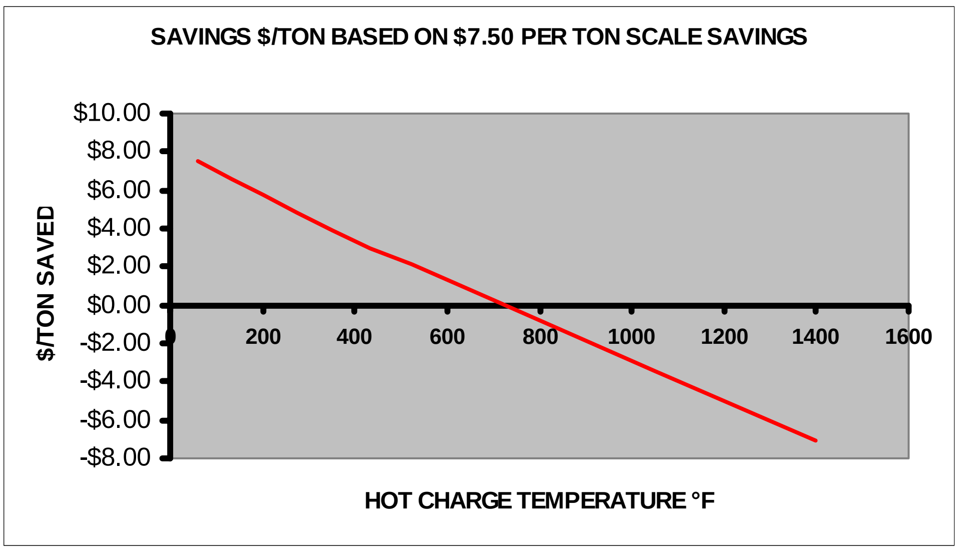


Figure 17. Effect of charge temperature on savings from scale elimination

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 then 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 of 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 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.

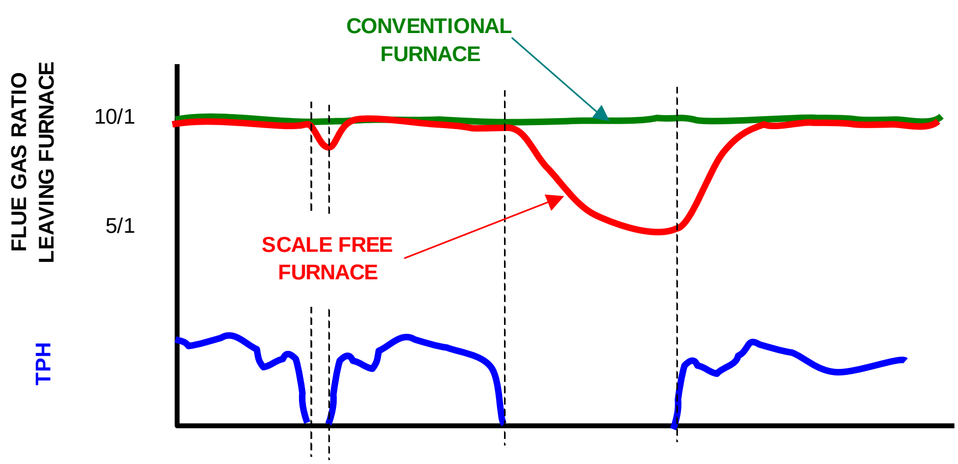


Figure 18. Effect of delays during operation of a scale free heating furnace

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^{o}F. to 2200^{o}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 H_2 in the soak section. Depending on the steel charging temperature the temperature profile of steel could vary from ambient (60^{o}F. to 90^{o}F.) to the discharge temperature. As explained earlier, if the charge temperature is below 600^{o}F. to 700^{o}F. it is possible to burn down the combustibles (CO and H_2) 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^{o}F. in scale free heating furnace, the flue gases are discharged at about 1600^{o}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°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. 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°F. preheated air at flue gas temperature of 1600°F. gives fuel savings of about 26%. In this case the exhaust gas from the recuperator or the heating system represents about 30% of the total heat input in the furnace.

Figure 19. Typical recuperator used for steel reheating

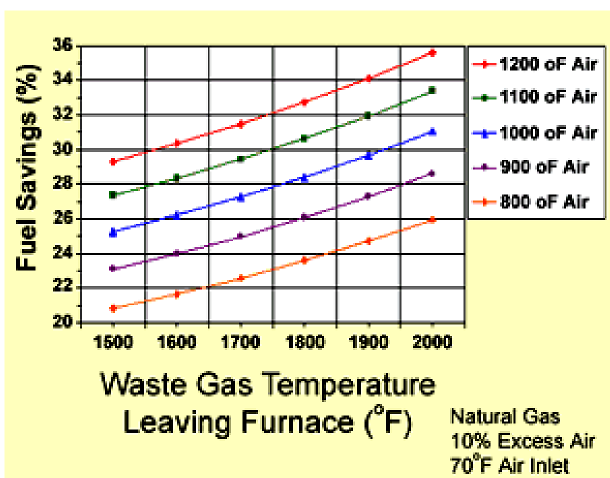


Figure 20. Fuel savings with use of preheated air

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 H_2 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.

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.

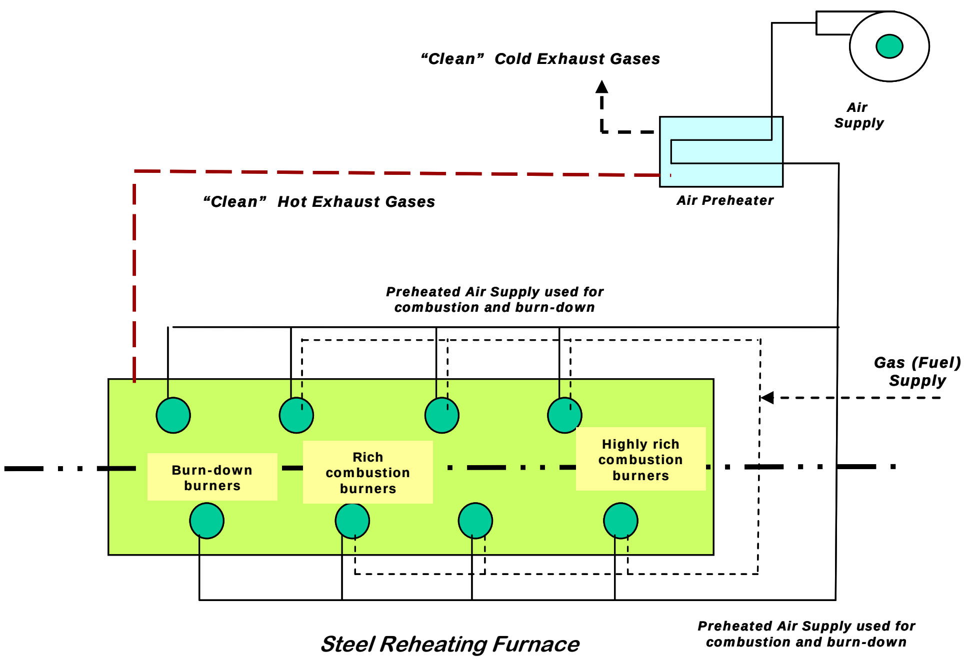


Figure 21. Schematic of the scale free heating system using a recuperator

In cases where the charge is at a higher temperature it is not possible to complete combustion of CO and H_2 in flue gases. In this case flue gases from the furnace could contain about 12% CO and 16% H_2O 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 other 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 H_2 and CO to a distance more than few feet.

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 unacceptable.

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^{o}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 a need for extra steam in the area of a reheat furnace and the only viable option is to use a steam turbine – generator system to generate power.

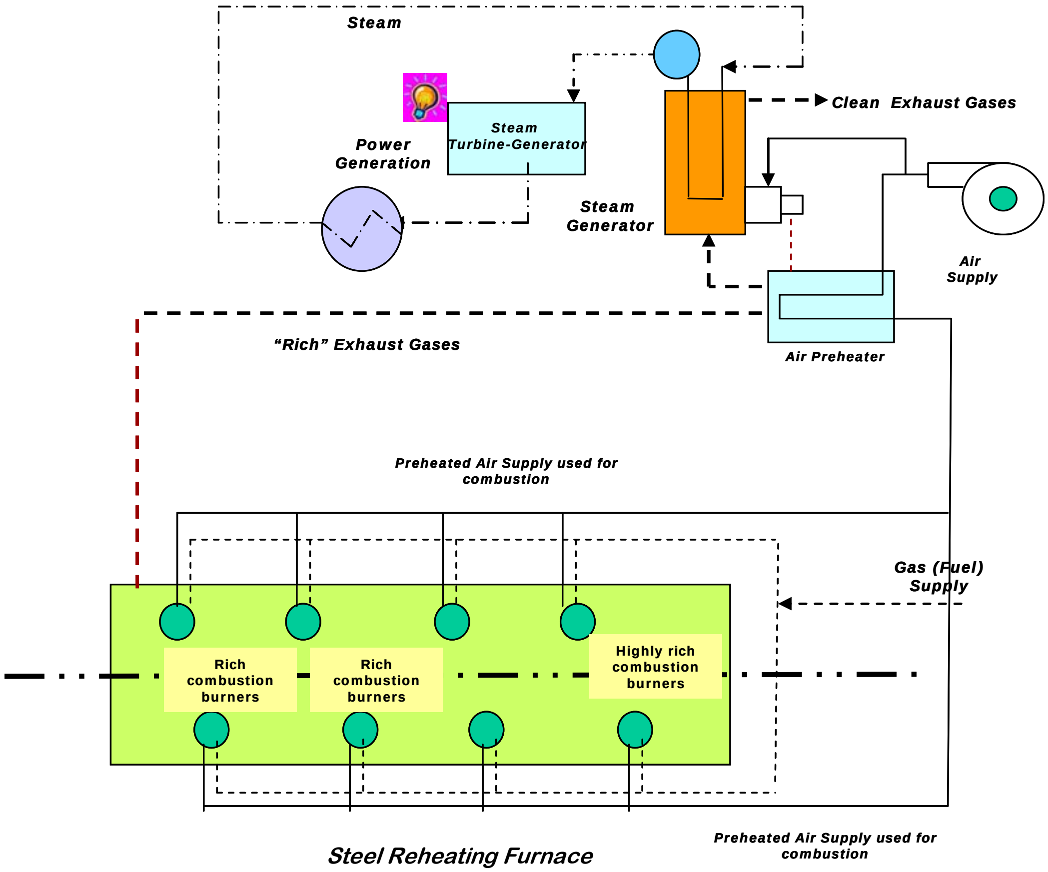


Figure 22. Schematic of the scale free heating system with heat recovery for steam and power generation

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.

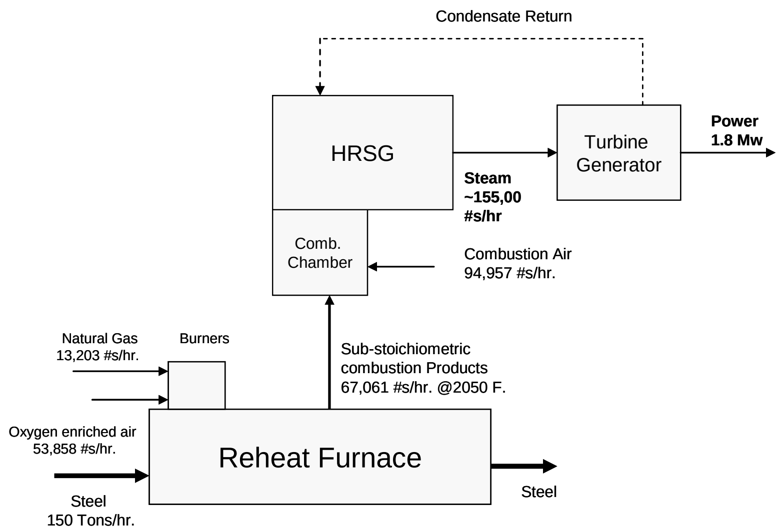


Figure 23. Heat balance for a hot charge scale free reheat system using oxygen enriched air and heat recovery system to generate power

A simple cost-benefit analysis shown in Table 6 shows that pay back period would be in excess of 5 years.

Table 6. Example of cost-benefit analysis for scale free heating system using heat recovery system

Parameters		21% O2, 54% stoichiometric 1000 deg. F. preheat
Production rate	Tons/hr.	150
Heat input to the funace	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/ft3 of n. gas i	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. (Contd.) Example of cost-benefit analysis for scale free heating system using heat recovery system

Parameters		21% O2, 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 per ton of scale	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 plants.

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, energy cost vary significantly in different regions and 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 detailed 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 ACL-NWO, 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 tables and 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 SMA member companies (discussed in a later section), steel mill partner (SDI), furnace supplier (ACL-NWO) 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.

Table 7. Economics for use of scale free heating system in a structural mill walking beam furnace

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

The analysis includes three types of scale free heating systems: Conventional furnace using near stoichiometric combustion burners, SFH with preheated air at 1000^{o}F. and SFH with oxygen enriched air (45% O_2 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 preheated air and oxygen enriched air would result in fuel savings that could be 10% to 15% of the fuel used in conventional furnaces.

In the case shown in Table 7, total annual operating cost for a conventional furnace is $19.02 million, for a preheated air based scale free heating system it is $13.03 million and for oxygen enriched air system based system it is $14.8 million. Further analysis of budget capital cost shows that the relative costs 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 use 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 use a typical value of 70% for hearth coverage.

(iii) Delays (planned and unplanned) that represents planned maintenance delays and unplanned, un anticipated delays during the furnace operation. The model results shown here use 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.

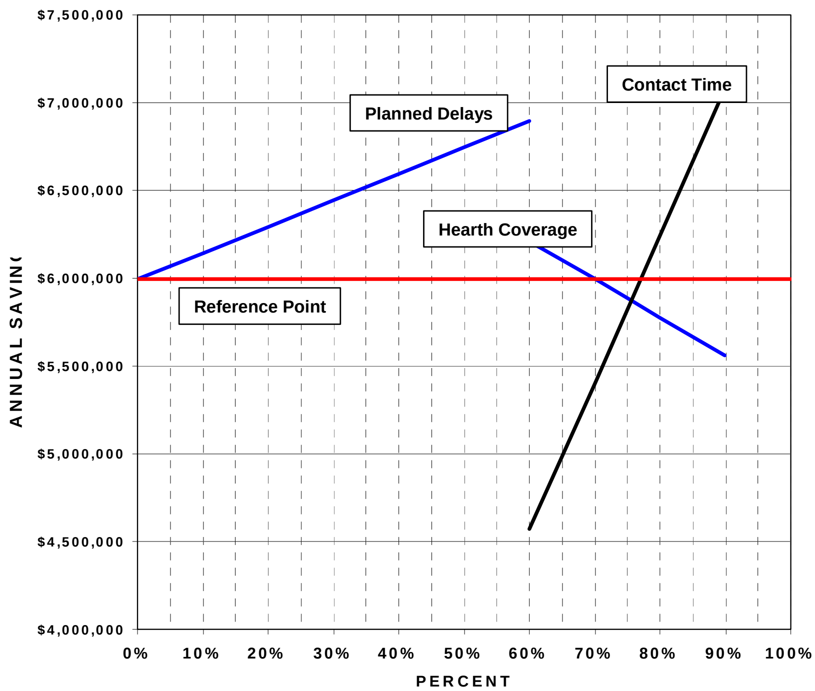


Figure 24. Effect of several operating parameters on savings with use of scale free heating

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. 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~~ analysis. It should only be used as a first indicator of possible financial benefits of the preheated air system.

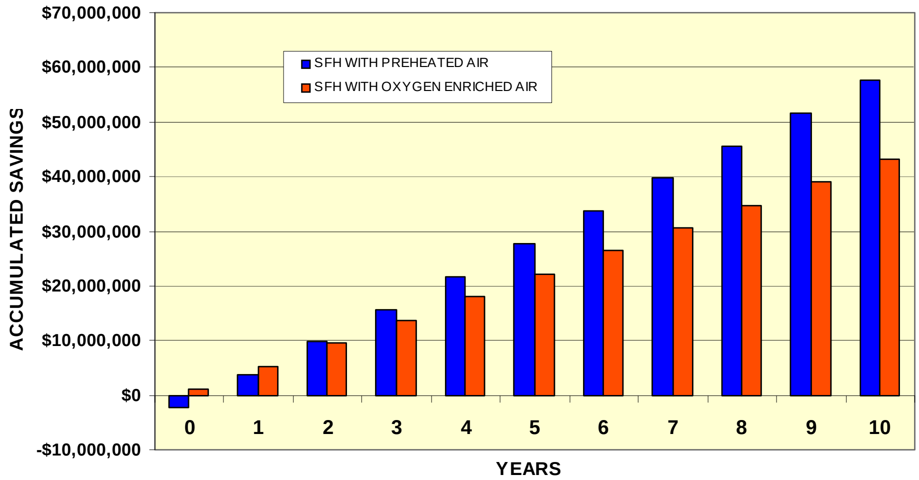


Figure 25. Simple cash flow representation for scale free heating using preheated air and oxygen enriched air

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, the 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 tables. The simple "cash-flow" analysis for each of these cases show that, in each case, the 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.

Table 11. Estimate of potential annual dollar savings for the U.S. steel industry

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

Using the annual production numbers derived from market studies by the furnace company ACL-NWO 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. 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 Versus 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 H_2. 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.

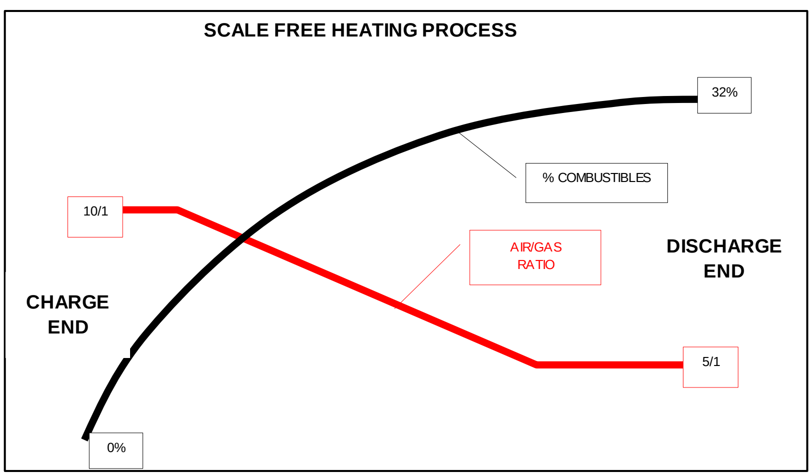


Figure 26. Air-fuel ratio variation from charge end to discharge end in a scale free heating furnace.

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.

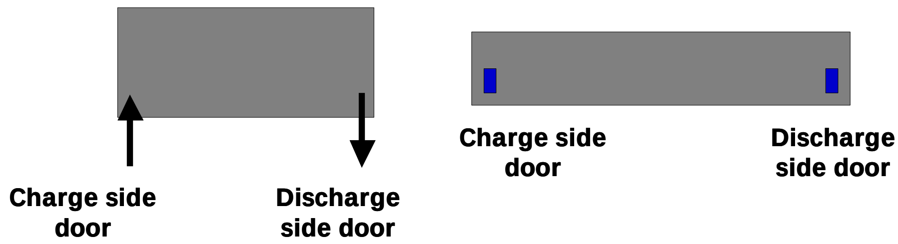


Figure 27. Side charge and discharge arrangement for a reheat furnace.

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.

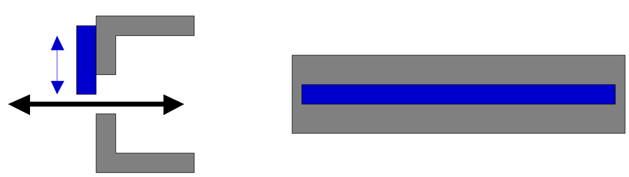


Figure 28. End charge and discharge arrangement for a reheat furnace.

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 affect 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 affect 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.

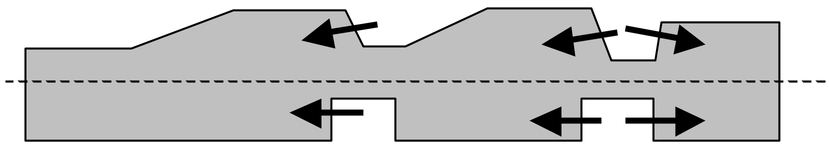
SFH Versus Burner Type:

A couple of conclusions arrived at in the preceding sections of this Report has 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 affects 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 range of 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 in 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 NOx, 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^{o}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 NOx burners presented an opportunity to revisit the feasibility of scale free heating. An ultra low NOx burner is required to operate in a minimum of two modes. At low temperatures (typically below 1700^{o}F.) the burners operate in a normal mode. Above 1700^{o}F. it is necessary for the burners to operate in an enhanced combustion mode capable of producing ultra low NOx. This operational capability is achieved by incorporating elements of 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 NOx 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 have indicated that it is not possible to apply the SFH to all sectors with equally attractive payback periods. This analysis shows that 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 the remaining 35% market that uses hot charge steel is greater than 5 years at the utility costs used in the analysis.

As a part of the market assessment activity, ACL-NWO has investigated the type of furnaces and important process parameters required to perform economic analysis for application of the SFH.

This analysis has 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.

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.

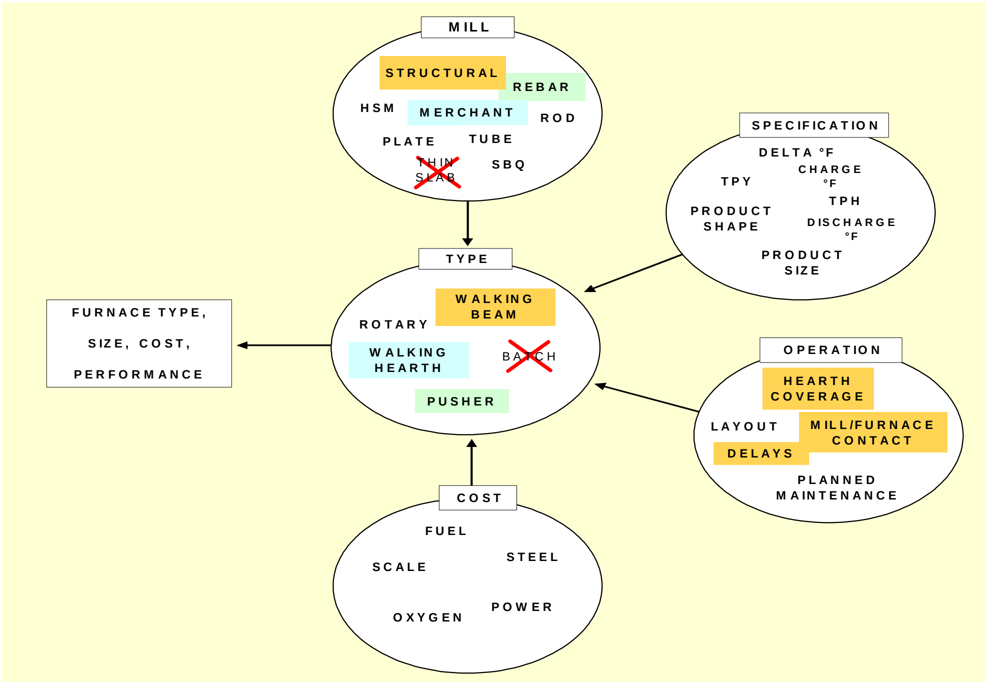


Figure 29. Relationship between various steel reheat furnace parameters

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 flat 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 40 MM tons/yr steel charged at ambient temperature. The SFH can be applied to 40 MM tons/year steel reheating using available heat recovery technology to preheat combustion air up to 1000^{o}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.

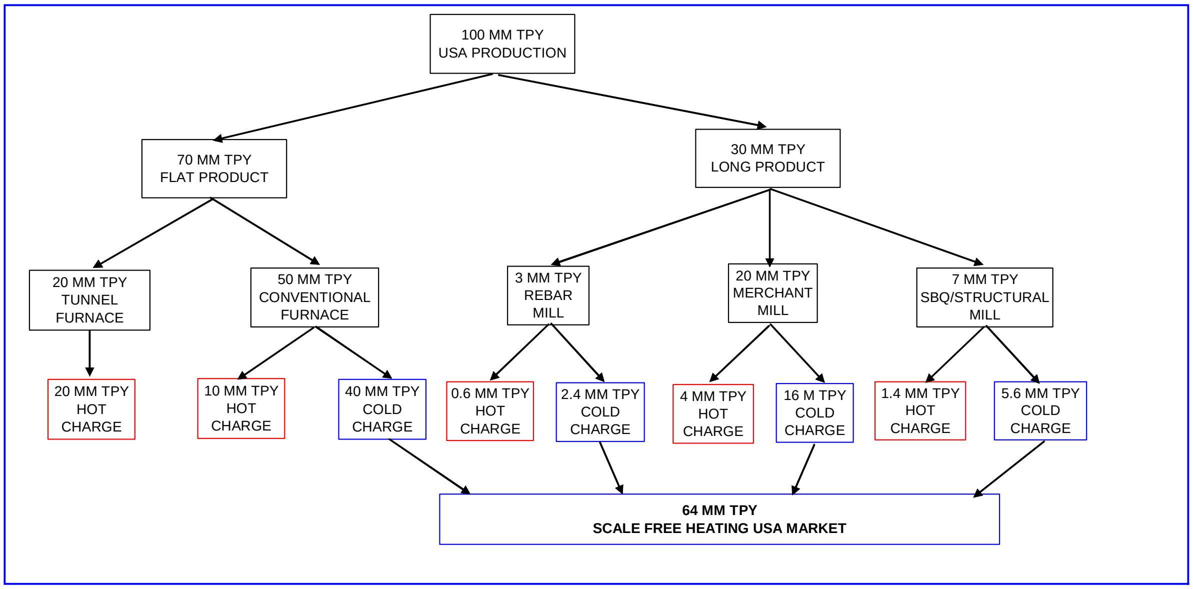


Figure 30. Distribution of U.S. steel production

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, Steel 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.

Table 13. A copy of the questions sent to the SMA members.

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?

Additional input from the steel companies was collected during Plant Operations Division meeting of SMA 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, summary of the conf. call and response of the attendees are 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 "slit" 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 - $8/million BTU	12.15
	What is your cost of power, ($/kWh)? Please consider all costs for actual electricity, demand charges and other charges if any and give average based on total cost.	$.07 in 2005		10 cents	currently~ $0.04	$0.040/kwH	$0.045/kWh	0.055	$.075/kWh	0.038
	What is your cost of oxygen, ($/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.	$.13 per cubic meter		47 cents	currently ~ $0.14	$0.002/scf	Not Available	.23/ccf		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 requrements	

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 are 52% to 58% of the cost of reheating, representing the highest cost of the 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 the application of this technology would result in a 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 the 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, for the remaining market. The analysis shows payback periods exceeding 5 years for this market segment. The estimates assume that application of scale free technology for 35% 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. These 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 (TBtu) 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	
Year →	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total for 10 years
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 revemue 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 revemue 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 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 revemue 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 the 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 price) 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 compared 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 CO_2 and NOx 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. Summary of CO_2 and NOx Emissions.

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		
CO2	MM Tons	17.81
NOx	Tons	10,465

Note: CO_2 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 NOx 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
NOx 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.

a. 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.
b. 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 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 the 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, and ultimately 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) Demonstration 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 stoichiometric conditions while offering the required turn down to run the furnace in either scale free or conventional mode.

(ii) Availability and testing of a burner system that can operate with oxygen enriched air while meeting the performance requirements as mentioned for preheated air.

(iii) Furnace design and operation to avoid leakage of CO and H_2 from the furnace,

(iv) Furnace control to maintain the required burner operation at all firing rates during varying furnace loading rate or operations.

(v) 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.

(vi) Scale free heating tests on a pilot scale furnace using commonly used steel employing process parameters defined in Phase I. It is anticipated that the test matrix would include at least the following parameters:
   - Grade or composition of steel
   - Steel sample time-temperature history
   - Furnace atmosphere composition – H_2 and CO percentages
   - Initial and final steel sample temperature
   - Simulation of delays and warm charge

(vii) 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

(viii) 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 the scope of work for the current phase of the program.

(i) Theoretical analysis and literature search have 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 the forging industry. The literature search also showed that in some cases 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 for scale free heating with preheated air is available 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 the 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 the 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 from SMA members 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 the 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 estimates, based on gradual adaptation of this technology by the U.S. industry over the 10 years after field demonstration of the technology, amount to about 1,500 TBtu during 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 detailed 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) along with a few changes in furnace design and combustion system.

A detailed 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 markets. 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 less than 1 year while payback period for retrofit applications would depend on type of furnaces used and its current condition.

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 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 applications. 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 accommodate 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 (ACL - NWO) 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 the commercialization partner for the project.

Consultations with a major supplier of combustion system to the steel industry (Bloom Engineering) have confirmed that it is possible to provide 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 continue the program by funding Phase II of the program. Phase I economic analysis showed that Phase II be directed to the 64% of the market because of ROI**.** 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 in the 64% market identified in Phase I. This includes testing of critical components and verification of their performance to assure that these 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 systems 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	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 CO_2 emissions and improved product quality. Specifics of these benefits are discussed below and described in detail throughout the report, particularly in the section "Benefits of Scale Free Reheating System", Page 53, of the report.
2. Technical Merit	Scale formation during steel reheating has been a major problem for the steel industry since the very beginning of the modern steel industry world wide. Scale related costs represent more than 50% of the cost of steel reheating. Attempts to achieve scale free heating by using alternate methods such as use of induction heating for large steel mill applications have not been successful, 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, but 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. As discussed in detail in two sections ("Economics", Page 36 and "Benefits of Scale Free Reheating Systems", Page 53) of 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 with increase in product yield by 1% to 2% while reducing energy intensity (Btu/lb.) for steel reheating.

3. Market Potential	A detail market study, discussed in the section "Market Assessment", Page 47, of this report 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 the other 35% additional market. Application of the scale free technology to the other 35% of the market would depend on economic justification of heat recovery system and energy costs at a specific plant. At the current steel industry production rate the system can be applied to reheat 64 MM tons/year steel in the 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 (Page 47) of this report. 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 less than 2 years while payback period for retrofit applications would depend on type of furnaces used and its current condition. The payback period is estimated based on simple cash flow.
4. Risks	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. 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 demonstrated 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. Future market risks include acceptance of the system by the steel industry. A close collaboration with a major steel industry organization, SMA, and its members would help the team to assure that the program tasks would be carried out to address needs of the industry and the program results would meet the industry requirements.

5. Competitive Advantage	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. 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 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 sections “Benefits”, “Market Assessment”, and “Benefits of Scale Free Reheating System” of this report.
6. Technical Project Scope	A technical project scope for Phase II of the project has been developed. It will be submitted to the DOE project office for considerations to support Phase II activities of the project. A summary of the issues 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 ACL-NWO*

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 ACL-NWO, 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., ACL-NWO, 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 NOx, Dr. Thekdi noted that NOx formation is being divided into three distinct stages, yielding roughly .06-.07 lb of NOx 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.