the Energy to Lead

FINAL REPORT

GTI PROJECT NUMBER 61145 (15323)

Development and Demonstration of a High Efficiency, Rapid Heating, Low NOx Alternative to Conventional Heating of Round Steel Shapes, Steel Substrate (Strip) and Coil Box Transfer Bars

Report Issued:
January 2010

Prepared For:
U.S. Department of Energy

Award No.:
DE-FC36-01ID14043

GTI Project Manager:
Mr. Harry Kurek
Senior Engineer
847-768-0527
harry.kurek@gastechnology.org

GTI Principle Investigator:
Dr. John Wagner
Senior Engineer
847-768-0506
john.wagner@gastechnology.org

Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

DOE Notice

Document Availability

Reports are available free via the U.S. Department of Energy (DOE) Information Bridge:

Web Site http://www.osti.gov/bridge

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange (ETDE) representatives, and Informational Nuclear Information System (INIS) representatives from the following source:

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Tel: (865) 576-8401
Fax: (865) 576-5728
E-mail: reports@osti.gov
Web Site: http://www.osti.gov/contact.html

Acknowledgment

This report is based upon work supported by the U. S. Department of Energy under Award No. DE-FC36-01ID14043.

Disclaimer

Legal Notice

This information was prepared by Gas Technology Institute ("GTI") for the U.S. Department of Energy ("DOE").

Neither GTI, the members of GTI, the Sponsor(s), nor any person acting on behalf of any of them:

a. Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights. Inasmuch as this project is experimental in nature, the technical information, results, or conclusions cannot be predicted. Conclusions and analysis of results by GTI represent GTI's opinion based on inferences from measurements and empirical relationships, which inferences and assumptions are not infallible, and with respect to which competent specialists may differ.

b. Assumes any liability with respect to the use of, or for any and all damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; any other use of, or reliance on, this report by any third party is at the third party's sole risk.

c. The results within this report relate only to the items tested.

Report Details

Project Title:	Development and Demonstration of a High Efficiency, Rapid Heating, Low NOx Alternative to Conventional Heating of Round Steel Shapes, Steel Substrate (Strip) and Coil Box Transfer Bars
Covering Period:	September 28, 2001 through September 30, 2009
Date of Report:	January 29, 2010
Recipient:	Gas Technology Institute 1700 S. Mount Prospect Rd. Des Plaines, IL 60018
Award Number:	DE-FC36-01ID14043
Subcontractors:	Fluent, Inc.; North American Construction Services (NACS); Regional Ural Department of Academy of Engineering Sciences (RUD AES)
Other Partners:	Republic Engineered Products, The Timken Company, ArcelorMittal-Burns Harbor (formerly Bethlehem Steel Corporation), Bricmont Incorporated, North American Manufacturing Company, Gas Research Institute, GTI's Sustaining Membership Program
Contact(s):	John C. Wagner (GTI Principal Investigator) Phone: 847/768-0506; Fax: 847/768-0600 E-mail: john.wagner@gastechnology.org Harry S. Kurek (GTI Project Manager) Phone: 847/768-0527; Fax: 847/768-0600 E-mail: harry.kurek@gastechnology.org
Project Team:	DOE Project Manager: Debo Aichbhaumik DOE Contracting Officer: Michael Schledorn

Table of Contents

Page

List of Figures

Page

List Table of Tables

Page

Background

U.S. steel plants, like other heavy industrial facilities, are facing both increased regulatory pressures to reduce NOx emissions and competitive pressures to reduce operating costs, both of which are expected to increase in the future. In order to remain competitive and continue to provide employment for the U.S. labor force, these industries must therefore control emissions while minimizing operating costs. Direct Flame Impingement Technology (DFI) is a viable solution that, when commercialized, will reduce the emissions of NOx, carbon monoxide and carbon dioxide while simultaneously increasing furnace productivity and energy efficiency. DFI will help the U.S. meet its environmental obligations economically without loss of U.S. jobs.

Direct Flame Impingement involves the use of an array of very high-velocity flame jets impinging on a work piece to rapidly heat the work piece (see Figure 1). The predominant mode of heat transfer is convection. Because of the locally high rate of heat transfer at the surface of the work piece, the refractory walls and exhaust gases of a DFI furnace are significantly cooler than in conventional radiant heating furnaces, resulting in high thermal efficiency and low NOx emissions. A DFI furnace is composed of a successive arrangement of heating modules (see Figure 2) through or by which the work piece is conveyed, and can be configured for square, round, flat, and curved metal shapes (e.g., billets, tubes, flat bars, and coiled bars) in single- or multi-stranded applications.

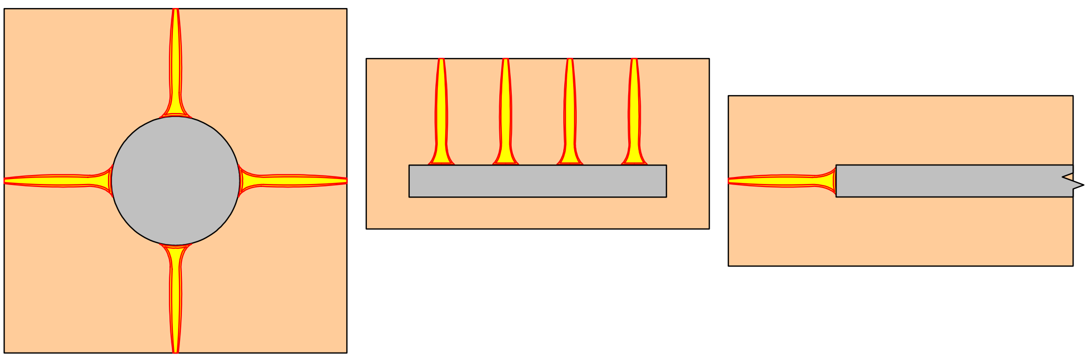


Figure 1. DFI Approaches for Round, Flat, and Edge Heating

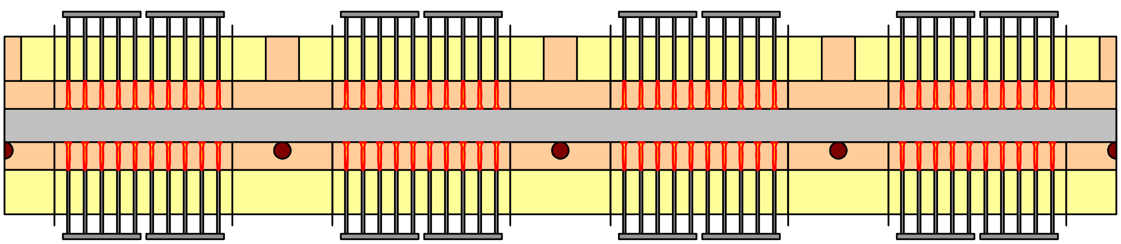


Figure 2. Cross-Section of a Furnace with Four DFI Heating Modules

Project Summary

Objectives and Approach

The objectives of this project were to (1) optimize parameters such as Direct Flame Impingement (DFI) nozzle diameters, spacing, distances between nozzles and product surface, and the firing rate per unit area of the metal surface to achieve a temperature uniformity of ±5 °F for strip and ±25 °F for rounds/squares while maintaining the necessary metallurgical properties; (2) to improve the furnace efficiency (by up to 20% over the base); (3) dramatically increase the potential for productivity (by up to 13% over the base); (4) substantially decrease the NO_x emissions (by up to 75% over the base).

This project consisted of three tasks:

Task 1. System Design Definition

This task involved developing and running CFD models for the DFI process and developing a design for a laboratory DFI furnace.

Task 2. Bench-Scale DFI Furnace Evaluation

This task involved fabricating a laboratory DFI furnace and conducting tests with heating round and flat loads in this furnace.

Task 3. Field Demonstration of a DFI Furnace

This task involved selecting a host site and designing, fabricating, and conducting tests with a DFI field system.

Accomplishments

CFD modeling and the subsequent physical testing of Direct Flame Impingement at GTI's laboratory, which validated the modeling, showed a potential increase in thermal efficiency in the range of 10 to 40 percentage points over that of the traditional radiative form of reheating ferrous and non-ferrous stock. GTI's calculations have shown that DFI heating has the potential to improve the overall thermal efficiency of key applications and niche applications that would lead to reduced processing costs (fuel consumption or electrical usage); no degradation of product quality; and emissions reductions (NO_x, CO_2) that that are the consequence of the heating process itself (lower overall or average flame temperature) and additionally that resulting from reduced fuel or electrical consumption.

A number of applications were reviewed and analyzed for a potential field trial of DFI, including slab preheating and post-heating, tube end heating, bloom heating, rail post-heating, billet preheating, and bundle end annealing. A substantial database has been established particularly for double-sided or single-sided heating of steel slabs; circumferential heating of round or square steel billets; and for several niche applications including induction furnace replacement with an equivalent DFI furnace. Included in the database are various preliminary shapes and sizes of furnaces; limited estimated capital costs; and emission reductions that would be achievable. In an other-funded project, a standard series of DFI furnace packages was proposed for joint-development with a furnace manufacturer to promote/propose DFI technology for the ferrous metals market as opportunities were identified. Applications included replacement of induction heating furnaces for two product shapes: Round Products for billets from 3 inches to 12 inches in diameter; and Flat Products for strip and skelp from 3.75 inches wide to 12.75 inches wide and 2 inches to 6 inches.

The bundle end heater application at Republic Engineered Products (REP) was ultimately selected for the field trial. The application involved the heating of ends of bundles of rods for the purpose of annealing (stress-relieving) the ends of the rods after cold shearing. REP had been using an inefficient system of using overhead cranes to place about a dozen bundles at a time on each of two skid tables and torches mounted on four portable carts to manually heat the ends of bundles. A system was designed by Bricmont, Inc. that consisted of two moving DFI heaters and two fixed DFI heaters to automatically heat the ends of the bundles as they moved through two transfer lines. Because the application involved heating the ends of the bundles in the open air instead of an enclosed furnace, commercial nozzles were incorporated into the design instead of the custom made, extremely high velocity nozzles used in the GTI laboratory furnace. The system was fabricated, installed, and integrated into REP's mill. During commissioning, the system proved unable to cope with varying bundle geometries when placing the bundles in front of the DFI heaters, and there was a concern that the heaters could damage the transfer lines themselves when heating the bundles.

A new system of portable heating carts was designed, using the DFI heaters from the automated system. The new system was fabricated and installed at REP's mill. During commissioning, the new system proved unable to heat the ends of the bundles at a rate that would keep up with production, as well as being difficult to maneuver. A determination was made that a minimum of a 74% increase in heating rate was needed, consequently one of the portable DFI heater carts was sent to GTI for modification and testing. An extensive campaign was carried out which led to an increase of about 66% in the heating rate. The project team felt that this would not be sufficient to guarantee a successful field trial, and that coupled with unsolved maneuverability issues led to a decision to not continue with the field trial. The efforts during the cart modification and testing did lead to a more comprehensive understanding of the effects of DFI furnace parameters, which should lead to improved applications of DFI in ferrous and non-ferrous industries.

Future Direction and Recommendations

The success of the laboratory testing, in this project for ferrous metals and in a related non-DOE project for non-ferrous metals, and the results of the field trial as well as the analysis of potential applications will focus future efforts on applications where product is moved through an enclosed furnace. A modular design approach, with designs established for fixed ranges of product shapes and sizes has already been discussed with potential furnace manufacturers. Product preheating for increased production and induction furnace replacement are envisioned as applications with the most promise.

Work Performed

Task 1. System Design Definition – completed April 18, 2003.

This task included developing and validating CFD models for the DFI process; developing a design for a laboratory DFI furnace and generating fabrication drawings; developing a set of matrices comparing the performance of DFI to conventional technologies; hosting a two-week visit by RUD AES to assist GTI with CFD model validation, laboratory DFI furnace design, and providing input to the comparison matrix.

Task 2. Bench-Scale DFI Furnace Evaluation – completed April 4, 2005.

This task included having the laboratory DFI furnace fabricated by NACS; installing and instrumenting the laboratory DFI furnace; hosting a five-week visit by RUD AES to assist GTI in startup and initial operation of the laboratory DFI furnace; conducting tests with the laboratory DFI furnace with various sized water-cooled round and flat loads (calorimeters) and instrumented steel pipe, round tube, round bar, and flat plate loads; conducting tests with different sized nozzles; refining the design of a set of self-recuperated nozzles and fabricating a set of nozzles and test chamber; co-designing and fabricating a load-moving mechanism;

Task 3. Field Demonstration of a DFI Furnace – completed September 30, 2009.

This task included meeting with one potential field site (ISG-Cleveland); developing a steel slab heating model to determine the effects of possible applications at this site; initiating a feasibility study by NAMCO at the ISG site to determine the best application for DFI at the site; developing a preliminary design concept for a field unit for the ISG site; securing a new manufacturing partner, Bricmont, Inc.; meeting with a second potential field site (Timken-Gambrinus); developing a steel tube and bar heating model to analyze the effects of three possible applications at the Timken site; investigating five alternate sites (Mittal Steel-Inland, Nucor Steel-Seattle, Chicago Heights Steel, CaluMetals, and Republic Engineered Products-Lackawanna); analyzing applications at three of these sites (Mittal Steel, Nucor Steel, and Republic Engineered Products); signing a Field Test Agreement with Republic Engineered Products-Lackawanna; executing purchase orders with Bricmont for the engineering and fabrication of the DFI field system; developing a design for the field system; conducting baseline testing; reviewing the design of the DFI field system with REP; proving the DFI field system flow skid assembly and burner assembly at the fabrication shops, shipping the DFI field system to REP; installing the DFI field system at REP; preliminarily commissioning the system at REP; revising the installation of the DFI field system; conducting a second round of commissioning; modifying the installation of the DFI field system; conducting a third round of commissioning; recognizing the issues precluding operation of the system in a production mode; determining a preferred strategy (portable DFI heaters) to address or circumvent these issues; securing additional funding for conversion of the DFI field system to portable heaters; fabricating a test cart to gauge handling parameters; developing and approving a final design of the portable DFI heaters; removing the necessary equipment from REP to perform the conversion; and assembling the portable heater cart at Bricmont's fabricator; assembling and shop testing the portable heater carts at Bricmont's fabricator; commissioning one of the heaters at REP; testing an alternate burner for DFI performance; delivering one of the portable DFI heater carts to GTI; developing a plan for modification and testing of the DFI heater cart; finalizing the details for modification and testing of the DFI heater cart; procuring the necessary components for the modifications; initializing the setup for the testing; pursuing additional funding for this work; testing and modifying the DFI heater cart at GTI; and analyzing the results of the modifications.

Results and Discussions

Task 1. System Design Definition

Modeling

A RFP (Request for Proposal) for modeling was developed by GTI with contributions by RUD AES and submitted to Fluent, Inc. Fluent submitted a proposal to GTI, and after a couple review and refinement iterations, a final proposal to develop four models was received and approved by GTI and a Service Order was signed with Fluent. The four models include a 2-dimensional axisymmetric single jet model (Model 1), a 3-dimensional single jet model (Model 7), a 3-dimensional model with a single row of jets (Model 5), and a 3-dimensional model with multiple row of jets (Model 6). Each of these models apply to a single section (or portion thereof) of a DFI furnace. Running the models with different inputs and boundary conditions will simulate different sections along the length of the DFI furnace so that post-processing can be used to develop results for the entire length of the furnace. Among the four models are models applicable to flat and/or curved and/or round shaped loads.

Models are highly dependent on geometry. Fluent's approach is to construct a model generating program called a template which will develop a model (any of the four above) for a user specified set of furnace parameters such as distance from nozzle to load being heated, nozzle-to-nozzle spacing, and number of nozzles in a section. This approach eliminates most of the repetitious grid generating steps that the user would have to perform if the user were to generate models from scratch for each different set of geometrical or furnace parameters.

Fluent completed development of the four models by the end of 2002. GTI supplied Fluent with two sets of geometrical and operating conditions for each model so that Fluent (and GTI and RUD AES) could verify the operation of the models before the template is constructed for each model.

Single-jet and multiple-jet CFD models of the Direct Flame Impingement (DFI) process were created by Fluent, Inc., installed on GTI's dual-processor workstation computer, and validated by RUD AES during their visit to GTI in December 2002. RUD AES also performed a literature review during their visit to GTI to gather data for further modeling and post-processing efforts.

A three-dimensional CFD model, based on the previous validated modeling efforts and on the specifics of the laboratory DFI furnace design (see section below), was then created by Fluent and installed on GTI's dual processor workstation computer. This model allows for the adjustment of key DFI parameters so that an optimized design could be developed for the field test unit. Over 40 runs of the model were made with different firing rates (nozzle velocities), product temperatures, nozzle sizes, combustion air temperatures, air-fuel ratios, product temperatures, product sizes, and number of nozzles. Each run of the model takes from 4 to 40 hours to complete. The range of parameters tested was consistent with those developed for the laboratory DFI furnace test plan. A summary of test results is shown in Table 1 and Figure 3 through Figure 7.

Following the CFD modeling effort, a code was developed for the analysis of the transient conduction heat transfer inside the product. The development of code required the conversion of the heat flux output from the Fluent model of the DFI furnace into a form usable for the code. This code determines heat up time, total fuel usage, and temperature uniformity inside the load for various input parameters (firing rate, feed rate, spin rate) for a DFI furnace composed of sections identical to the GTI laboratory DFI furnace. The code was used later to determine overall furnace configuration and furnace efficiency for a field unit.

Table 1. CFD Modeling Results Summary

Thermal efficiency at high to low firing rate
• 61-76% for cold load (90 °F)
• 43-49% for hot load (2240 °F)
Average heat transfer to load in heating section at mid firing rate
• 100,000 Btu/hr.ft^2 for cold load
• 69,000 Btu/hr.ft^2 for hot load
Refractory temperature at mid firing rate
• 1,820 °F for cold load
• 2,525 °F for hot load

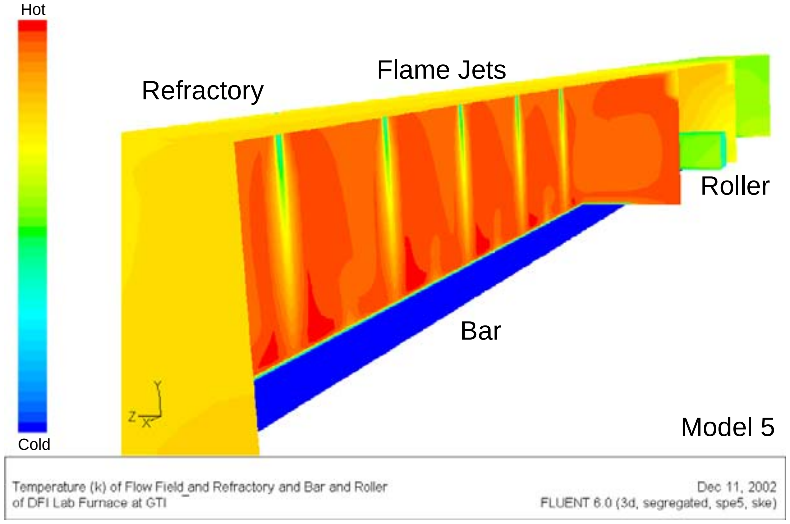


Figure 3. Temperatures Along Flame Jet Centerline for a Flat Load

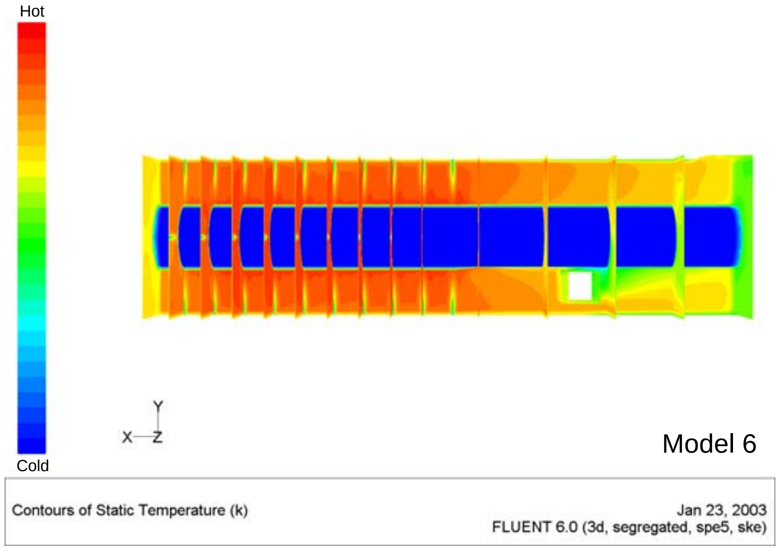


Figure 4. Temperatures Along Flame Jet Centerlines for a Round Load

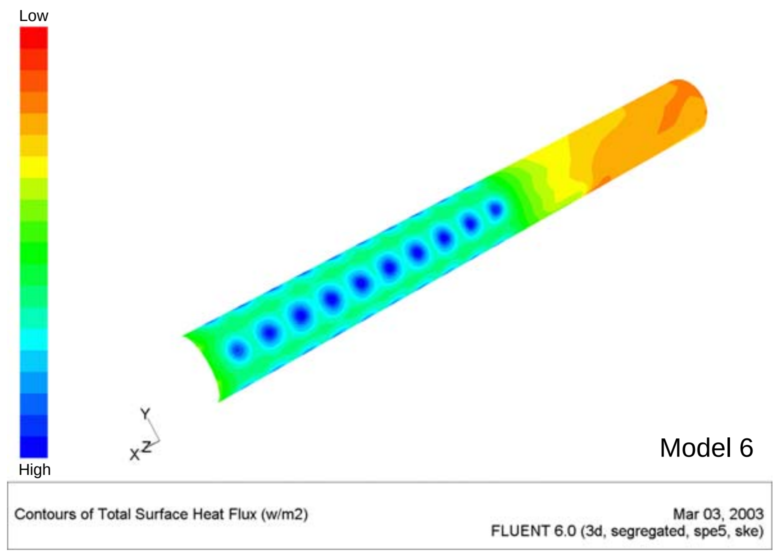


Figure 5. Surface Heat Flux for a Round Load

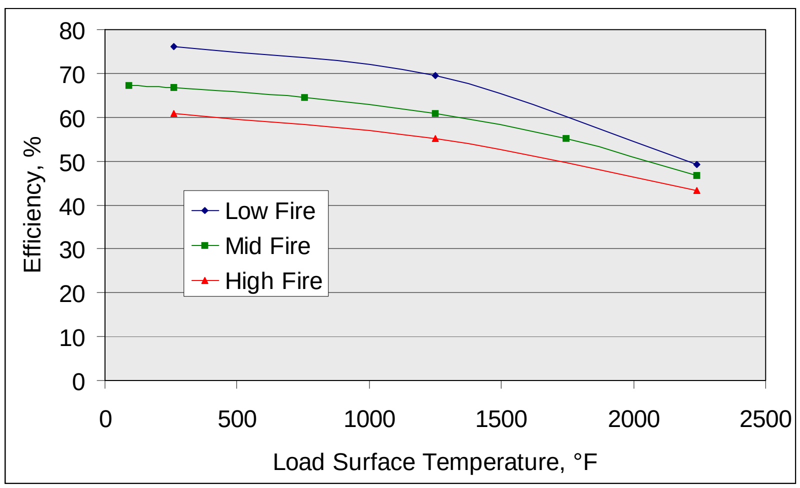


Figure 6. Furnace Efficiency for a Round Load

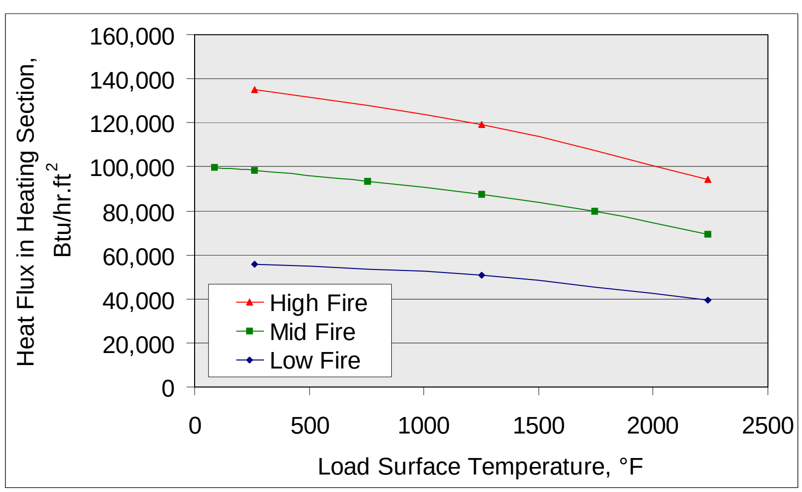


Figure 7. Average Heat Flux in Heating Section for a Round Load

Two cases have been run for the transient conduction heat transfer analysis of a solid round bar (see Figure 8 and Figure 9). The first case is for heating the load up to a certain surface temperature and then soaking the load with no additional heat input until a temperature difference (surface to center) of less than 5 °F exists. The second case is for heating the load up to a certain surface temperature and then applying a gradually decreasing amount of heat input so that the center temperature catches up to the surface temperature (again within 5 °F) while the surface temperature is held constant. In both cases, the amount of heat input in each section of the furnace that the load passes through is the same until the surface temperature reaches its final value.

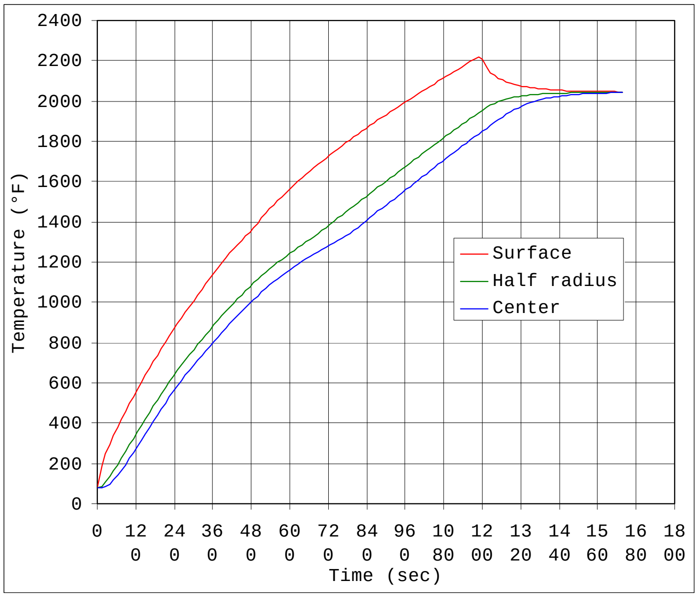


Figure 8. Surface and Internal Temperatures for a Solid Round Bar (Heating to Maximum Surface Temperature and then Soaking)

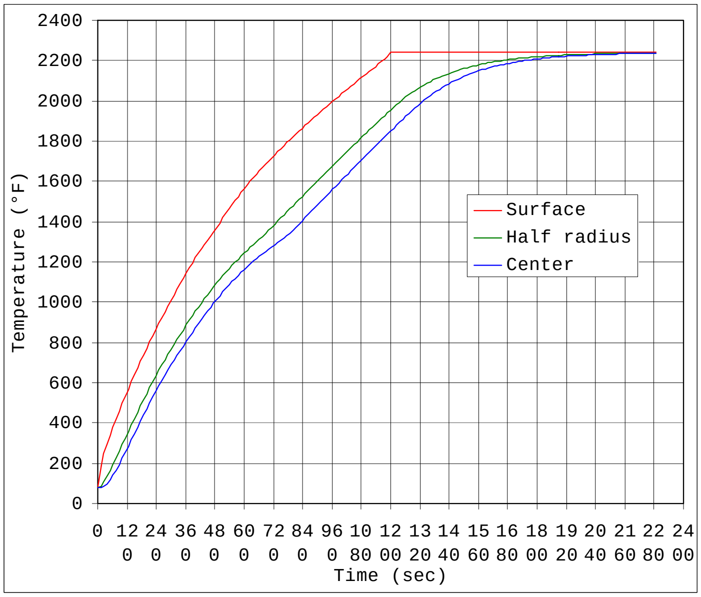


Figure 9. Surface and Internal Temperatures for a Solid Round Bar (Heating to Maximum Surface Temperature and then Modulating)

Additional runs of the Fluent model for the DFI furnace were made to gather enough information to determine a functional relationship between heat flux and firing rate. This functional relationship was added to the functional relations already determined between heat flux and load surface temperature. Subsequent efforts (ran later in parallel with lab furnace testing) analyzed the effect of varying the heat input to different sections of the furnace. In addition, the transient conduction heat transfer analysis code was modified so it could evaluate round tubes as well as solid round bars.

Comparative Analysis

Application data was gathered with the assistance of our industrial partners for the purpose of generating a comparative matrix of DFI technology versus conventional technology for the three main applications of rounds, strips, and coil box transfer bars. Further input on the performance of conventional furnaces was received from our manufacturing partners in order to help complete the development of a comparison matrix contrasting the performance of DFI furnace to that of typical conventional furnaces. RUD AES provided input on the performance of the DFI furnace for the comparison matrix, and gathered literature for review for additional input into the comparison matrix, during their visit to GTI in December 2002. Table 2 through Table 4 show comparisons for round shapes, flat shapes, and coil box transfer bars.

Table 2. Performance Comparison for Billet Reheating

Specifications	Base	DFI
Furnace Type(s)	Billet Reheater	
Product Description (shapes, materials, and grade(s))	Billets	
Product Size (diameter, wall thickness (for tubes)), inches	3.5-6"	
Specific Fuel Consumption, MMBtu per charged ton	3.5-5.5	0.5-1.2
Number of burners, radiant tubes, or nozzles	58	750-1500 nozzles
Capital Costs, $/ft2 of hearth	TBD	lower
Operating Costs, $/hr	TBD	lower
Average Air Preheat, ºF	N/A	1200-1300
Average Combustion Efficiency, (Available Heat/Heat Input), %	25-35	65-75
Average Heat Flux Rate to product, Btu/ft2/hr	TBD	110,000
Temperature uniformity of product, surface to center, ± ºF	30	10-30
Scale Loss, % of tons charged	1.5-2.0	0.5-0.7
Emissions: NOx, ppmv; CO, ppmv	TBD	5-30; 50-100

Table 3. Performance Comparison for Strip Annealing/Galvanizing

Specifications	Base	DFI
Furnace Type(s)	CAL/CGL Direct Fired Furnace	Direct multi flame impingement onto strip surface (one side)
Product Description (shapes, materials, and grade(s))	Strips	
Product size (width, thickness), inches	Strip width to 72”	
Specific fuel consumption, MMBtu per charged ton	1	0.5-0.9
Number of burners, radiant tubes, or nozzles	200-300	750-1500 nozzles
Capital Costs, $/ft2 of hearth	TBD	lower
Operating Costs (average), $/hr	~150 for fuel	~120 for fuel
Average Air Preheat, ºF	750	1200-1300
Average Combustion Efficiency, (Available Heat/Heat In), %	35-40	67-77
Average Heat Flux Rate, Btu/ft2/hr	TBD	110,000
Temp. uniformity along width and length, ± ºF	Width: 40	Width: 5-20, Length: 10-20
Emissions: NOx, ppmv; CO, ppmv	NOx: 100 to 700; CO: < 200	NOx: 5-30; CO: 50-100

Table 4. Performance Comparison for Coil Box Transfer Bar

Specifications	Base	DFI
Furnace Type(s)	Coil Box Furnace	Direct multi flames Impingement onto coil bar surface
Product Description (shapes, materials, and grade(s))	Coiled Transfer Bar	
Product size (width, thickness, coiled diameter), inches	1000 PIW; 30 inch eye; avg. width=60"	
Specific fuel consumption, MMBtu per charged ton	TBD	TBD
Number of burners, radiant tubes, or nozzles	22	120-360 nozzles
Capital Costs, $/ft2 of hearth	TBD	lower
Operating Costs, $/hr	TBD	TBD
Average Air Preheat, ºF	Ambient	1200-1300
Average Combustion Efficiency, (Available Heat/Heat In), %	Est. as < 50	50-55
Average Heat Flux Rate, Btu/ft2/hr	TBD	95,000
Emissions: NOx, ppmv; CO, ppmv	>30-50; >5-10	30-50; 5-10

Laboratory DFI Furnace Design

A preliminary laboratory DFI furnace design was developed by GTI (see Figure 10) based on sketches and parameters supplied by RUD AES. A set of comprehensive drawings were then made by GTI and submitted to NACS, who produced detailed fabrication drawings. After review of the drawings by GTI, a quotation for fabrication of the furnace was received from NACS. After performance calculations were made by RUD AES, and after RUD AES reviewed the drawings during their visit to GTI in December 2002, a set of revisions to the drawings was sent to NACS. After receiving a revised quotation for the laboratory DFI furnace from NACS, a purchase order for the furnace was placed with NACS in February 2003.

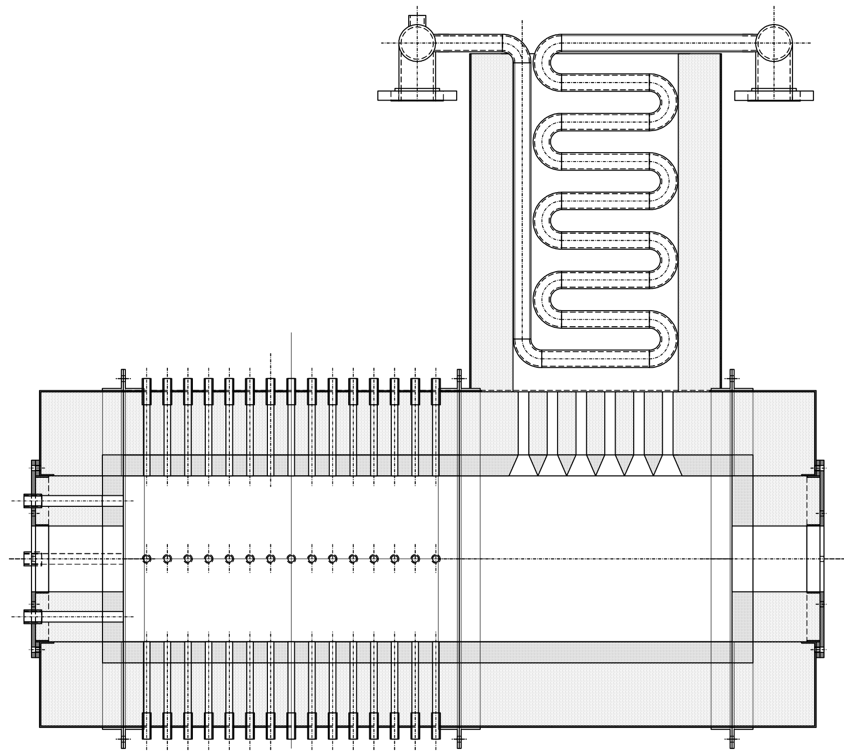


Figure 10. Preliminary Laboratory DFI Furnace Design (Configured for Round Loads)

The laboratory DFI furnace design encompasses the following features:

- Single furnace structure for all three applications -- rounds, flats, and (simulated) coils
- Basic dimensions determined from earlier CFD modeling and based on application product sizes
- Number, size, and spacing of nozzles derived from current CFD modeling at GTI
- Nozzles made from standard pipe with machined tips
- Recuperator and refractory-lined roller included to enhance efficiency
- Adjustable roller height

Configuration of the laboratory DFI furnace for round shapes is shown in Figure 11 and for flat shapes is shown in Figure 12.

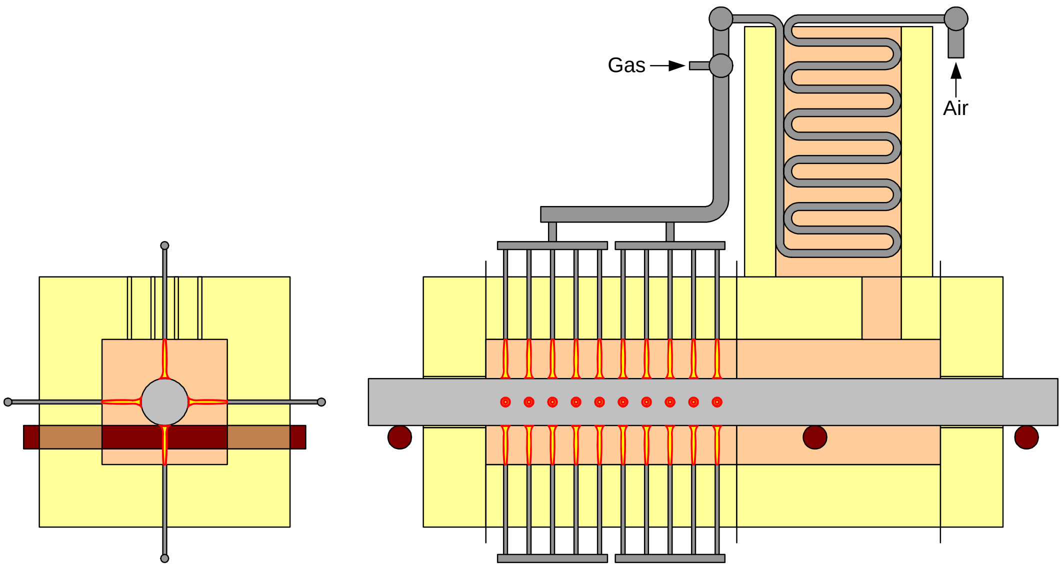


Figure 11. Laboratory DFI Furnace Configuration for Round Loads

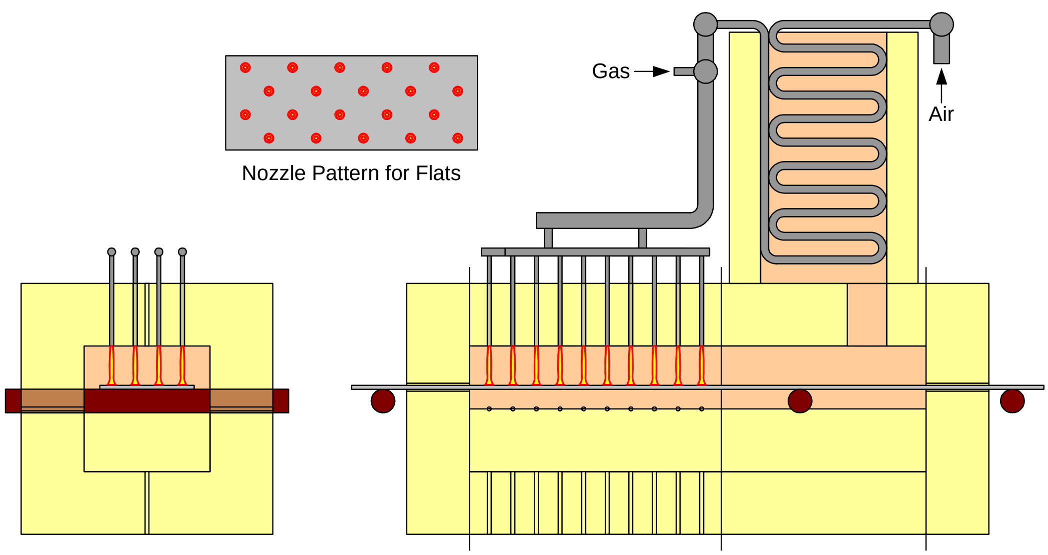


Figure 12. Laboratory DFI Furnace Configuration for Flat Loads

Task 2. Bench-Scale DFI Furnace Evaluation

Laboratory DFI Furnace Fabrication

North American Construction Services worked on fabrication of the laboratory DFI furnace from March to July 2003. It was delivered to GTI on July 16, 2003. A photograph of the furnace as delivered is shown in Figure 13. The furnace was subsequently moved to its designated location inside the GTI Combustion Lab.

Figure 13. Laboratory DFI Furnace as Delivered

Laboratory DFI Furnace Installation

A high-pressure blower to supply the combustion air to the furnace was ordered in June 2003, delivered in August 2003, and placed in its proper location.

An electrical control system for the laboratory DFI furnace was designed by GTI and fabricated by an outside contractor. The main electrical panel of the control system and a variable frequency drive for the blower were mounted on the wall near the furnace.

In October 2003, gas, air, and water piping were run to the laboratory DFI furnace. A gas safety train (flow meter, shut-off valve, pressure switches, control valve, and pilot subsystem) was assembled and installed on the furnace. Wiring was run from the control panel to the gas safety train. A 6" diameter calorimeter (sized to simulate the largest diameter load) was fabricated. Insulation was installed around the preheated combustion air and air-gas mixture piping. An electric air preheater was added upstream of the recuperator so that the combustion air temperature could be set independently of furnace operation and the effects on furnace efficiency and on NOx emissions can be observed as a function of air temperature. Figure 14 shows the laboratory DFI furnace with the round calorimeter installed and the insulated air-gas mixture piping.

Figure 14. Laboratory DFI Furnace Installed at GTI (with Round Calorimeter Inserted)

Laboratory DFI Furnace Shakedown

The RUD AES team visited GTI for five weeks from mid October to mid November 2003. During their visit, they assisted GTI in the initial startup of the laboratory DFI furnace. Figure 15 shows the four rows of flame jets, edge on, firing toward the center of the furnace (without the calorimeter installed). RUD AES also assisted with the curing (binder burnout) of the refractories, the selection and calibration of the instrumentation, and initial tests with the calorimeter load. RUD AES calculated furnace efficiencies and a heat balance. A report was received from RUD AES on their findings during their technical visit. A analysis of the data collected during RUD AES's visit showed a maximum heat flux to the simulated load of 152,000 Btu/hr·ft2 (478,000 W/m2), a peak thermal efficiency of 67.5%, and NOx emissions averaging about 21 ppm.

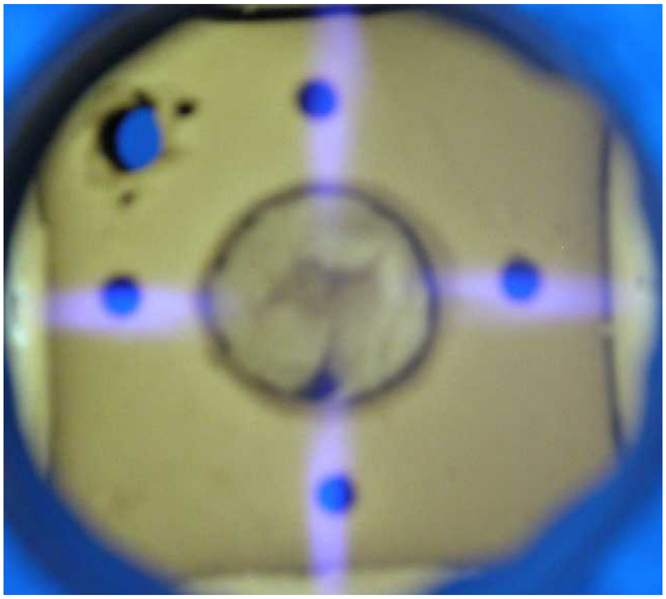


Figure 15. Flame Jets Firing Toward Center of the Laboratory DFI Furnace

Subsequent to RUD AES's visit, the installation of the instrumentation on the laboratory DFI furnace was completed. Thermocouple wiring was run to the laboratory DFI furnace from the control panel. The final set of thermocouples was received and installed on the laboratory DFI furnace. The hardware portion of a data acquisition system was installed in the furnace control panel. All signal lines (thermocouple, flow, and status) were connected to the data acquisition system. The software for the data acquisition system was configured.

Laboratory DFI Furnace Testing

In December 2003, Timken supplied GTI with a set of steel tubes and bars for use in testing of the first application (round shapes) in the laboratory DFI furnace.

Round Calorimetric Testing

In January 2004, testing commenced with the original 6" diameter calorimeter load according to a test matrix prepared in conjunction with the furnace modeling conducted earlier. Selected results are shown in Figure 16 through Figure 19.

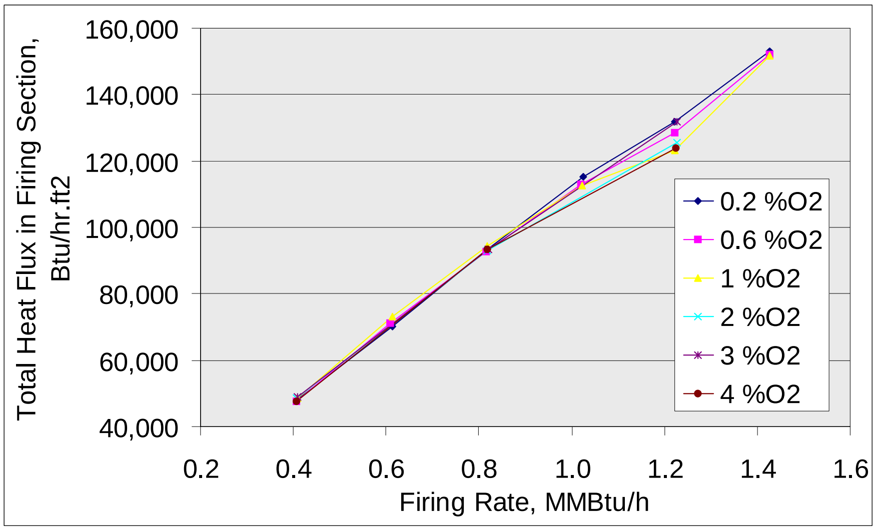


Figure 16. Total Heat Flux in Heating Section for a Round Load

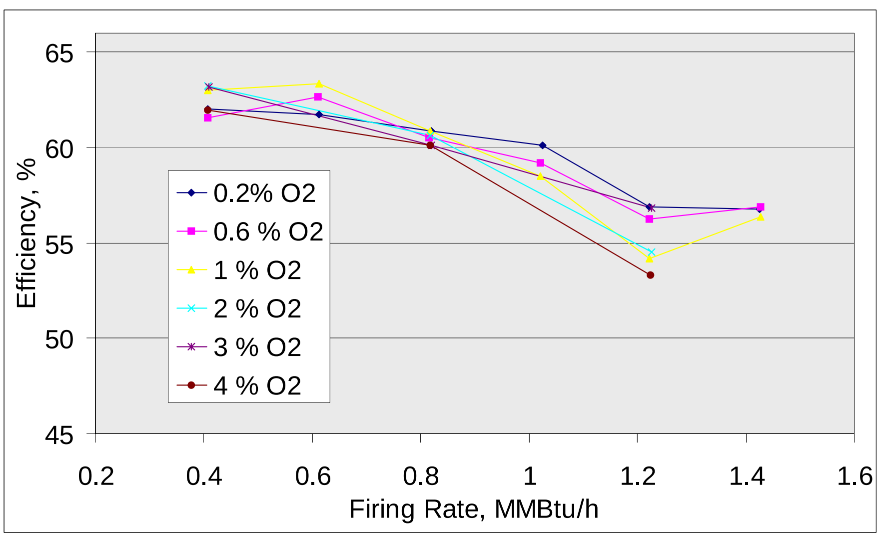


Figure 17. Furnace Efficiency for a Round Load

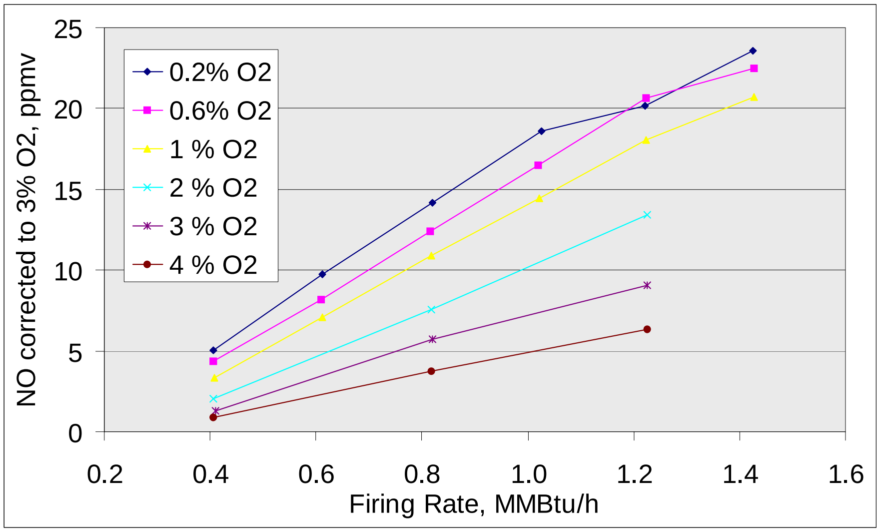


Figure 18. NOx Emissions for a Round Load

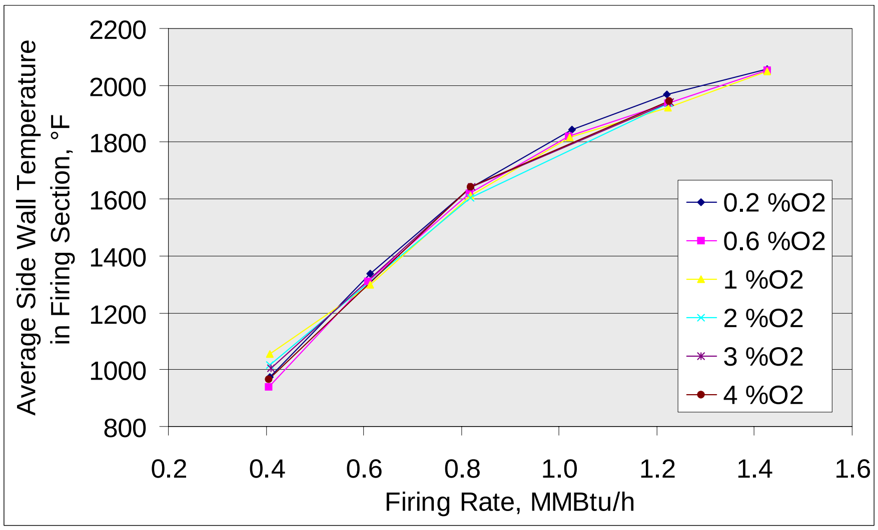


Figure 19. Refractory Wall Temperatures for a Round Load

The calorimeter used in the above tests was sized for simulating a 6" diameter load, and required a higher water flow rate than expected to avoid internal boiling. A new calorimeter design was developed to prevent this problem. Calorimeters of this new design were fabricated with 3", 4", 5" and 6" diameters. While it was expected that these new calorimetric loads would be less prone to internal boiling than the original 6" diameter calorimeter load, the new calorimetric loads had problems with the water flow short circuiting within the devices, allowing less than a desired amount of water to flow in the device under the flame jets. Because of this effect, testing with these calorimeters was somewhat limited in scope, covering mainly the lower end of range of firing rates.

Testing was also conducted with an approximately 2" diameter water cooled probe acting as a calorimetric load. This probe did not exhibit the water short circuiting problem of the previous calorimeters, but its small size only permitted testing at the lower end of range of firing rates. A 6" diameter version and a 4" diameter version of this probe were designed, fabricated, and successfully tested.

New sets of burner nozzles, with diameters both 16% smaller and 20% larger than the present set, were fabricated and tested on the laboratory DFI furnace. The set of larger-diameter burner nozzles have significantly less pressure requirements for the same flow as the original nozzles. Test were conducted with the originally 6" diameter water-cooled load (calorimeter), the newly designed 6" and 4" diameter calorimeters (which proved to not have the water short circuiting problem of the earlier designs), and with an instrumented steel pipe (more on this testing below). Tests were also conducted with the instrumented steel pipe with a water-cooled calorimeter placed inside pipe but not touching the pipe. The purpose of the last tests was to measure furnace performance with the load at an elevated temperature in near steady state conditions.

Tests on the laboratory DFI furnace were completed in July 2004 with sets of larger- and smaller-diameter burner nozzles Because of the reduced opening, the smaller-diameter nozzles exhibited a higher pressure drop than the original nozzles for the same firing rate. This meant that the highest firing rates tested with the original and larger nozzles could not be tested with the smaller nozzles due to the pressure available from the combustion air blower. The smaller nozzles also exhibited some combustion instability at the lowest firing rates, which further limited the amount of tests with these nozzles.

The results of the testing with the original (middle-diameter) and larger-diameter nozzles were analyzed for heat transfer rates, emissions, and furnace temperatures. Based on the analysis, the middle-diameter nozzle set was selected for tests with the steel loads provided by Timken. The larger-diameter nozzle set was very close in performance to the middle-diameter, so the optimal diameter may be in between the middle and larger sets.

Round Steel Load Testing

Prior to testing with the steel loads provided by Timken, testing was initiated in April 2004 with an instrumented steel pipe as the load to measure heat transfer and heat up rates. Sixteen thermocouples were inserted into 1/16" diameter holes on the outer surface 1/8" deep and peened into place. The result of one test, at the mid firing rate (0.8 MMBtu/h), is shown in Figure 20. The pipe was heated to an average surface temperature of 2240 °F in 10 minutes. At a firing rate of 0.4 MMBtu/h, the heat up time was 18 minutes, while at a firing rate of 1.2 MMBtu/h, the heat up time was 7 minutes.

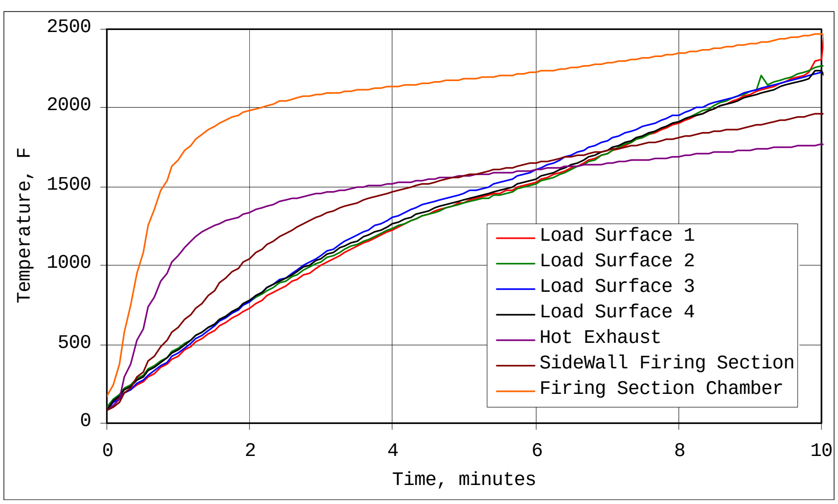


Figure 20. Heating of a Thick-Walled Steel Pipe

Each of the load surface temperatures in Figure 20 is the average of 4 thermocouples, for a total of 16 thermocouples, as shown in Figure 21, which represents a flattened view of the pipe surface. All of the thermocouples were placed halfway between locations, either longitudinally or circumferentially, where the flame jets impinge upon the pipe.

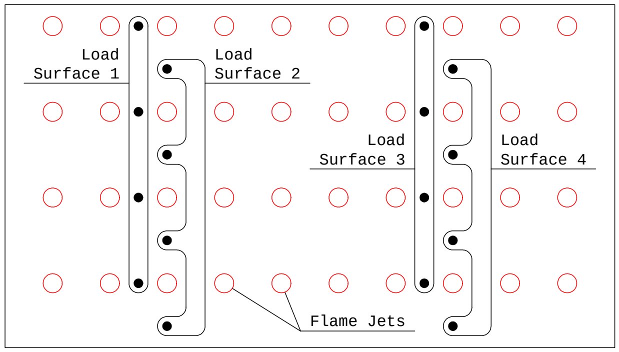


Figure 21. Thermocouple Groupings on the Steel Pipe Surface

Testing in the laboratory DFI furnace with the steel loads provided by Timken was completed in October 2004. Six loads (4", 5" and 6" diameter thick walled tubes and solid round bars) were tested with the middle-diameter nozzles installed in the furnace. The 4" and 6" diameter tubes were also heated with a water cooled load inside, but not touching, the tube. Each load piece was instrumented with thermocouples embedded in the surface at various depths at two locations along the length of the piece. The 5" diameter tube was heated only once and allowed to cool naturally so that its surface properties could be preserved for future analysis. The other loads were heated at two different firing rates to measure heat up rates and then forced cooled after each heat up. The approximate heat up times in minutes to about 2150 °F surface temperature are shown in Table 5.

Table 5. Time In Minutes To Heat Tubes and Round Bars to 2150 °F Surface Temperature

Load \ Firing Rate	0.8 MMBtu/h	1.2 MMBtu/h
4" diameter tube	13	9
4" diameter tube with internal load	14	10
4" diameter solid round bar	14	11
5" diameter tube*	N/A	10
5" diameter solid round bar	20	14
6" diameter tube	17	12
6" diameter tube with internal load	21	13
6" diameter solid round bar	22	17

* The 5" diameter tube was heated only once and allowed to cool naturally so that its surface properties could be preserved for future analysis.

Flat Calorimetric Testing

The laboratory DFI furnace was then reconfigured for testing flat loads (see Figure 22). A set of 20 nozzles, in 4 staggered rows of 5 nozzles each, is installed in the roof of the furnace. The nozzle size is the same as that used (i.e., the middle-diameter) for the final round load configuration. Two end plugs with rectangular openings, including one with the pilot burners, were inserted into the ends of the furnace to replace the end plus with round openings. These nozzle sets and the end plugs were included with the furnace as delivered. A flat, water-cooled load (calorimeter) was designed, fabricated, and installed in the furnace. Additional end plugs, with different locations for the rectangular openings were fabricated so that the distance from the nozzles tips to the load could be varied more. The new end plugs allowed testing with an over 2:1 range in the distance from the nozzle tips to the load. Steel sheets and plates of various thicknesses were procured for testing in the furnace, as well as thermocouples to instruments these loads.

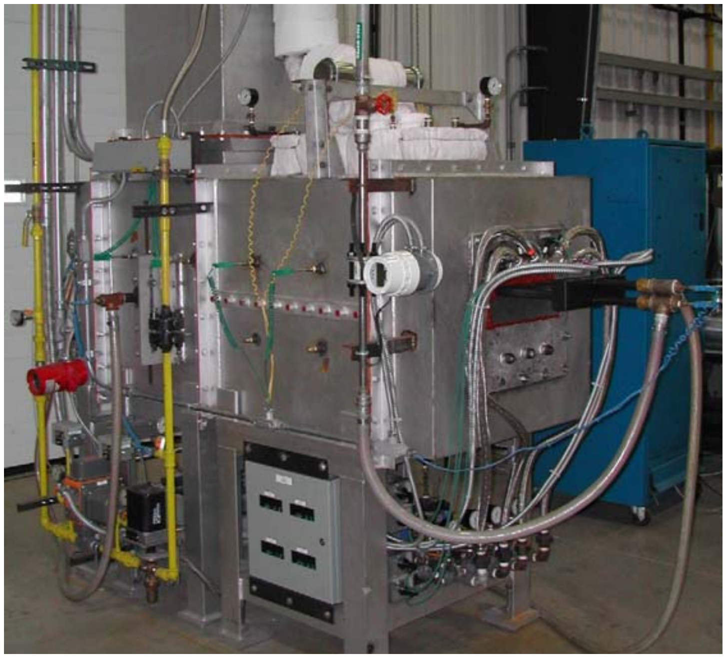


Figure 22. GTI's Laboratory DFI Furnace Reconfigured for Testing Flat Loads (with Flat Calorimeter Inserted)

During testing, space under the load was filled with refractory blocks (delivered with the furnace) and/or blanket insulation, depending on distance from the original floor of the furnace to the load, to simulate a hearth surface under the load. The tests were conducted to determine the effects of firing rate and distance from nozzle tip to load. Analysis of data collected during the testing with the flat calorimeter load in the laboratory DFI furnace showed thermal efficiencies in the range of 59% to 64%, with higher efficiency when the load was closer to the nozzles.

Flat Steel Load Testing

Testing was initiated with flat steel plates in January 2005. A 1" thick plate was instrumented with thermocouples at various depths at two locations along the length of the plate. It was heated at two different firing rates at several distances between the nozzle tips and the plate. At the lower firing rate, it took about 20 minutes to reach a bulk temperature of about 2140 °F, while at the higher firing rate, it took about 15 minutes to reach the same bulk temperature. The two firing rates used have the same heat input per nozzle as is being considered for a field unit.

Tests were then conducted with instrumented 1/2", 1/4", and 1/8" thick steel plates at the same two firing rates, but at a single distance from the nozzles. The approximate heat up times in minutes to about 2140 °F temperature are shown in Table 6, which includes the data from the 1" thick plate for comparison.

Tests with Moving Load

A mechanism was designed and fabricated by NACS to move (rotate and horizontally oscillate) a round steel load and move (horizontally oscillate) a flat steel load in the furnace to simulate the load moving through a series of furnace sections as it is heated. The load moving mechanism received from NACS was assembled and wired to the laboratory DFI furnace control cabinet. A pair of variable frequency drives (VFDs) were procured for the three motors (one VFD for the translating motor and one VFD for the pair of rotating motors (one on each end) so they could turn at the same speed) and installed in the control cabinet. A relay was also installed in the control cabinet to govern the automatic reversing of the translating motor.

Table 6. Time In Minutes To Heat Flat Plates to 2140 °F Bulk Temperature

Load	Distance	Firing Rate	
		0.48 MMBtu/h	0.70 MMBtu/h
1" thick plate	12"	22	15
1" thick plate	10"	19	16
1" thick plate	8"	18	14
1" thick plate	6"	20	15
1" thick plate	4-1/2"	19	14
1/2" thick plate	7-1/2"	11	8
1/4" thick plate	7-3/4"	6	5
1/8" thick plate	7-7/8"	4	3

Testing was conducted with a moving flat steel plate in April 2005 using the mechanism fabricated by NACS. A 1" thick plate was instrumented with three thermocouples at various depths at two locations along the length of the plate (six total thermocouples). The plate was heated at two different firing rates at a 7" distance between the nozzle tips and the plate. At the lower firing rate, it took about 21 minutes to reach a bulk temperature of about 2140 °F, while at the higher firing rate, it took about 15 minutes to reach the same bulk temperature. These times are consistent with the previous, non-moving tests. The surface temperature of the plate appeared more uniform in temperature as indicated by the incandescence level along the length of plate. Tests with a round steel bar or tube were not conducted since it was deemed impractical to instrument a continuously rotating load.

Tests with Self-Recuperated DFI Nozzles

In the third quarter of 2004, GTI received a preliminary report from RUD AES on designs and modeling of an internally recuperated DFI nozzle. RUD AES had developed a design for a set of self-recuperated nozzles applicable to continuously moving round and flat loads, and the subject of Patent Application US 2006/01990119 A1. Based on this scheme, GTI developed a modified design applicable to flat stationary loads, such as steel slabs. A laboratory nozzle set and test chamber were designed by GTI for use with GTI's existing flat calorimeter. In January 2005, the laboratory nozzle set and test chamber shell were fabricated locally. The shell was insulated by GTI to complete the chamber.

In May 2005 GTI tested the self-recuperated DFI nozzle set in its laboratory using the small test chamber and the existing flat calorimeter. Air-gas mixture preheat temperatures of almost 1400 °F were achieved. Efficiencies in the range of 63-77% were noted (see Figure 23) with NO_x emissions less than 40 ppm for all cases. This performance exceeded that of the laboratory DFI furnace with its separate recuperator. Heat fluxes were about 20% higher with the self-recuperated DFI nozzles.

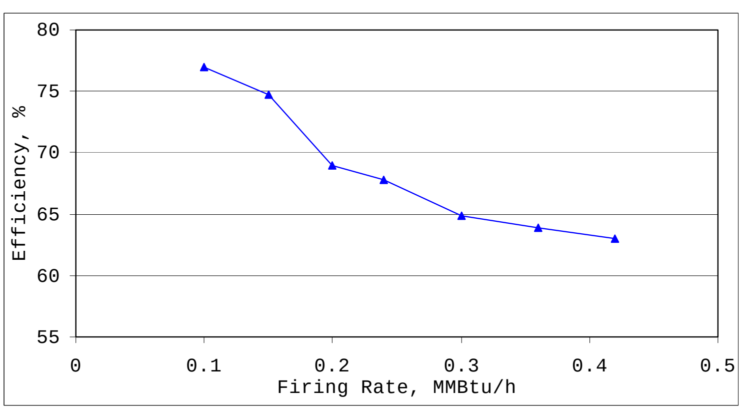


Figure 23. Furnace Efficiency with Self-Recuperated DFI Nozzles

Task 3. Field Demonstration of a DFI Furnace

Field Site Analysis and Selection

International Steel Group (ISG), Cleveland, Ohio

The potential to include a DFI field unit demonstration in conjunction with the 2005 Steel Showcase in Cleveland, Ohio, was discussed with the U.S. DOE. In April 2004, a presentation on DFI was made by GTI and NAMCO to ISG (now part of ArcelorMittal), a steel company in the Cleveland, Ohio, area, for their 84" Hot Strip Mill to act as a potential demonstration site. One potential application discussed was using DFI for a slab preheater to increase the production rate of the reheat furnace. Subsequent to the meeting, a conduction heat transfer model was created to determine the heat up rates for a 9" slab being heated to 400 °F from both sides. Heat flux data was extracted from the Fluent CFD models run earlier by GTI and applied to the heat conduction model for the slab.

Three cases were run with the heat conduction model. In the first case (see Figure 24), the steel was first heated until the average surface temperature reached 400 °F, then the firing rate was modulated (cycled on and off) until the difference between the maximum (surface) temperature and minimum (core) temperature was less than 5 °F. The average surface temperature reached 400 °F in 21.1 seconds. Equilibrium was reached in 1,683 seconds (28.1 min).

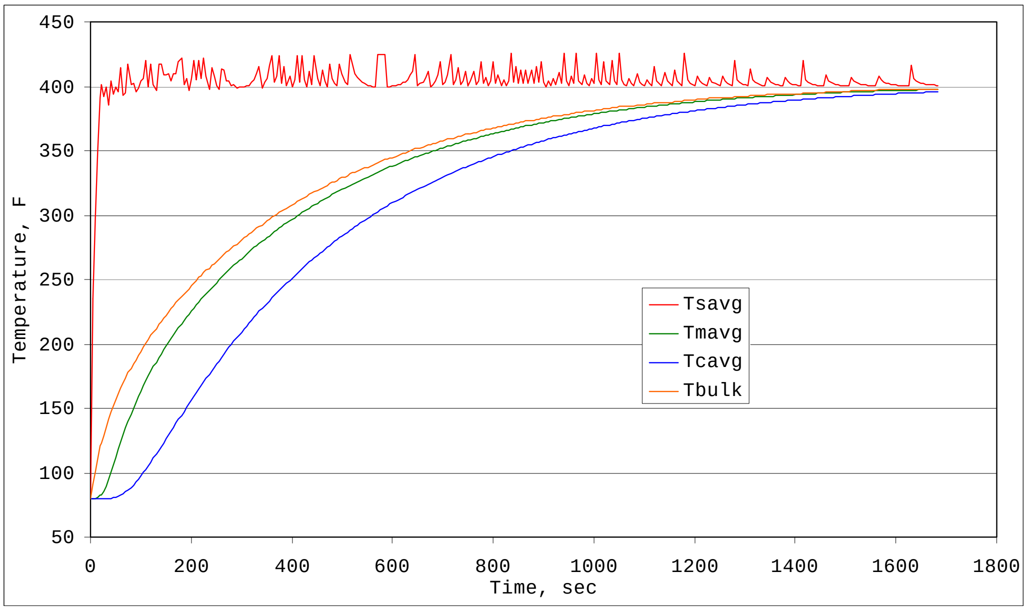


Figure 24. ISG Case 1: Heat Surface to 400 °F and then Modulate until Surface Minus Core Is Less Than 5 °F. (Tsavg = average surface temperature; Tmavg = average midline (quarter thickness) temperature; Tcavg = average core (half thickness) temperature; Tbulk = bulk (volumetric average) temperature)

In the second case (see Figure 25), the slab was heated until the bulk (volumetric average) temperature of the slab reached 400 °F. This was accomplished in 156 seconds (2.60 minutes). The average surface temperature reached 1035 °F, while the average core (centerline) temperature reached 152 °F. The first 21.1 seconds of this second case are identical with the first 21.1 seconds of the first case.

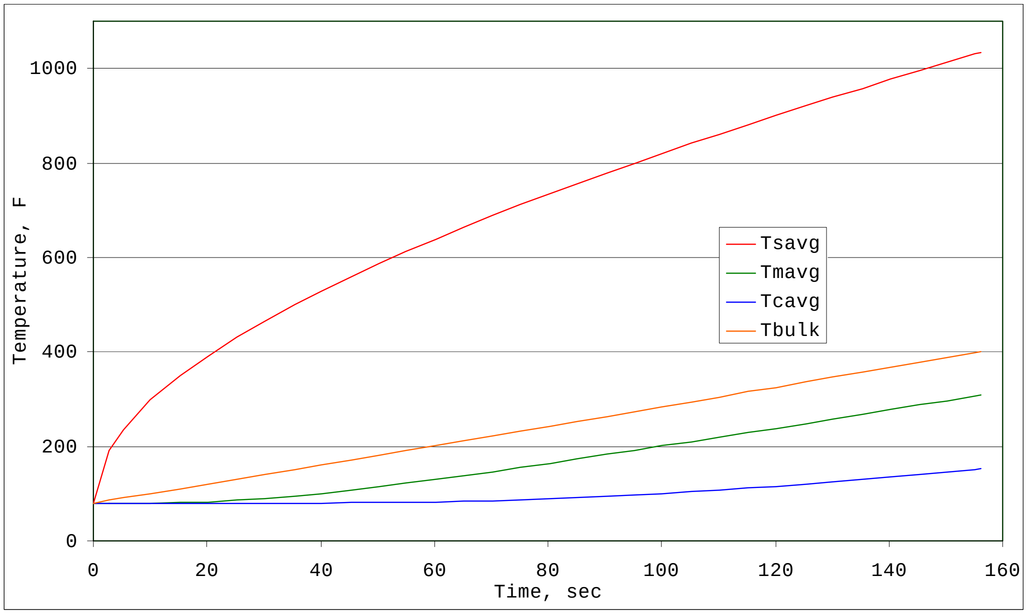


Figure 25. ISG Case 2: Heat slab until bulk temperature reaches 400 °F.

In the third case (see Figure 26), the slab was heated until the bulk (volumetric average) temperature of the slab reached 400 °F, then the heat was removed and the slab was insulated to prevent heat loss until the difference between the maximum (surface) temperature and minimum (core) temperature was less than 5 °F. The final average core temperature was 422 °F. Equilibrium was reached in 722 seconds (12.0 min). The first 156 seconds of this third case are identical with the first 156 seconds of the second case. The difference between the final average core temperature and 400 °F bulk temperature when heating stopped was due to the relationship between the thermal properties of steel and its temperature. The average core temperature reached 400 °F at 461 seconds (7.7 minutes), at which point the average surface temperature was 450 °F, and the bulk temperature was 425 °F.

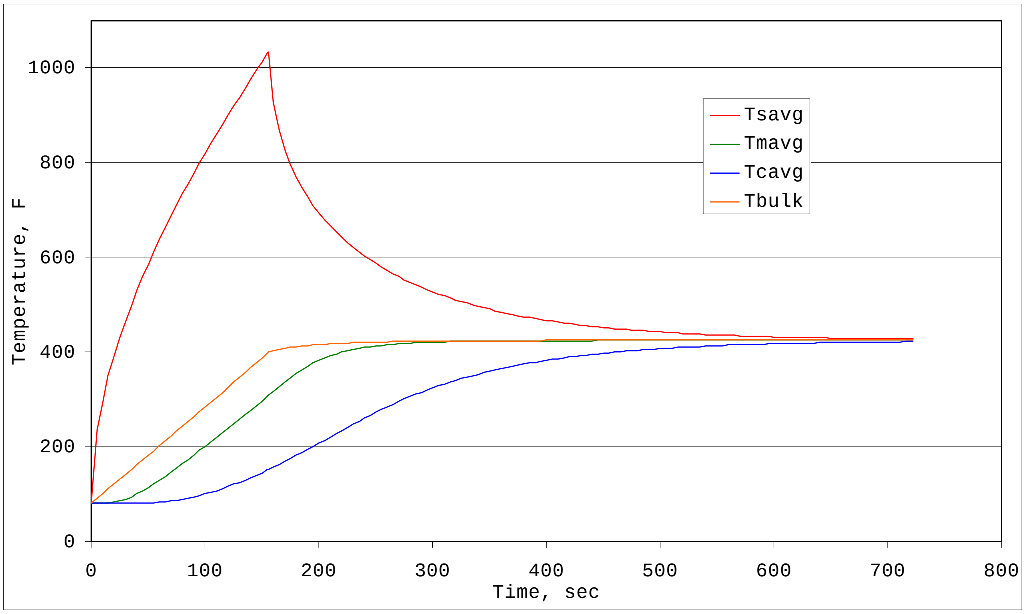


Figure 26. ISG Case 3: Heat Slab Until Bulk Temperature Reaches 400 °F and then Soak until Surface Minus Core Is Less Than 5 °F.

Subsequent to discussing the above evaluations with ISG management it was mutually agreed that a feasibility study to evaluate potential DFI applications at the 84" HSM, subject to approval by ISG, would be the preferable next step

A kick-off meeting was held at ISG in Cleveland, Ohio, on September 20, 2004, for the DFI Applications Feasibility Study, which is being conducted by North American Manufacturing Company (NAMCO). The study will investigate the potential for different DFI applications at ISG's 84" Hot Strip Mill including, but not limited to, a slab preheater, a temperature booster for the discharge end of the reheat furnaces, and a transfer bar edge heater.

The Feasibility Study consisted of four phases:

- Site visit by NAMCO for familiarization, observations, and data collection of slab reheating and hot mill processing
- Study of maximum production operation to define capacities of existing processes
- Construction of slab heating models and heat balances using mill data and DFI modeling data
- Generation of costs-benefits analysis of varied DFI approaches

Following the kick-off meeting, the first phase of the feasibility study was initiated. NAMCO surveyed reheat furnace charge table, discharge door, rolling line to first finishing stand; gathered operating data and drawings; and interviewed the furnace operators. A conference call was held between GTI and NAMCO in October 2004 to discuss the status of the study. By November 2004, the specific applications studied included a slab preheater (three configurations), a temperature booster for the discharge end of the reheat furnaces (leading edge heater), a transfer bar reheater, and a transfer bar edge heater. The slab preheater configurations considered included a charge table module, and inline module, and a stand-alone two-side module.

To support the third phase of the feasibility study, GTI made some calculations using its heat conduction heat transfer model to estimate how well a 9" thick steel slab could be heated from one side with DFI for the slab preheater application. The example in Figure 27 shows that with DFI nozzles firing at full capacity (without air preheat) for 4 minutes, and modulated to maintain an 800 °F surface temperature, a 400 °F bulk temperature in the slab can be reached in 12 minutes.

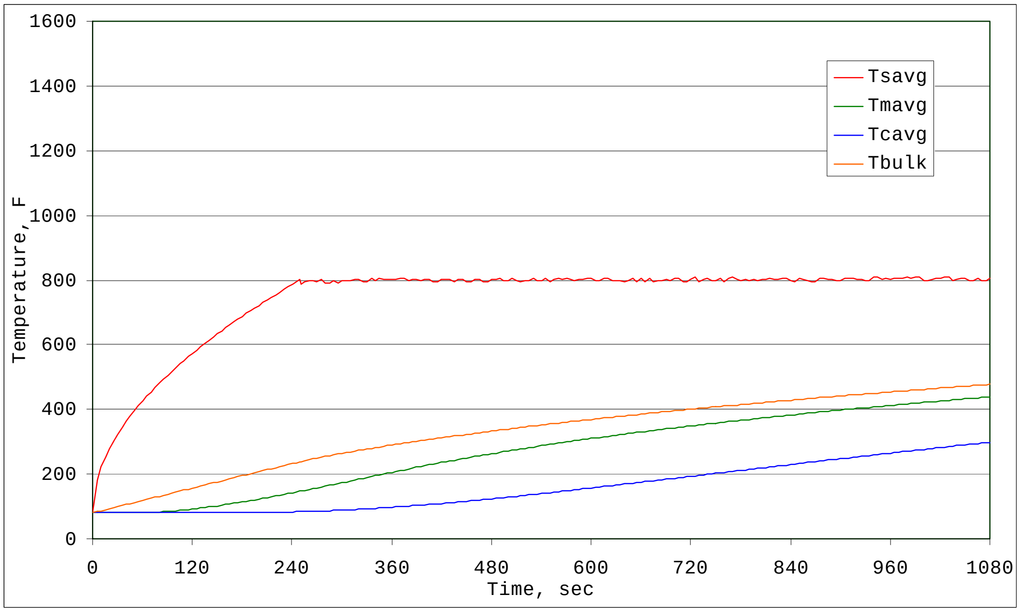


Figure 27. ISG Case 4: One-Sided DFI Heating of a 9" Thick Steel Slab Using Non-Preheated Air with Heated Surface Limited to 800 °F.

A meeting at ISG with NAMCO and GTI was held on November 17, 2004. The results so far of the feasibility study were discussed. Four potential applications of DFI were reviewed. A transfer bar reheating application, which could provide a more consistent and uniform temperature in the slabs entering the finishing stands and could lower heating demand on reheat furnaces, and a transfer bar edge heating application, which could also provide a more consistent and uniform temperature and reduce edge trim losses and increased work roll life, were deemed unsuitable due to limitations of the current runout table (the existing rollers would have to be replaced with high-temperature rollers). The leading edge heating application, which could avoid the rejecting of slabs that cooled off from being held too long at the discharge end of the furnace, showed promise, but was deemed difficult to implement due to the target section of the reheat furnace being a high-maintenance area, due to the distance between the nozzles and the steel slabs, and due to the need to shut down the furnace to install the DFI module.

The slab preheating application showed the most promise. The charge table configuration, which would preheat slabs for all three reheat furnaces, would also require high-temperature rollers, and would require changing the slab handling logistics. In addition, slabs could cool off during delays. The stand-alone two-side configuration, which would also preheat slabs for all three furnaces, would also require changing the slab handling logistics. The inline configuration, which would preheat slabs for one furnace, did not have any of these drawbacks. Also, one of the furnaces was scheduled to have a new water cooled skid system installed that would also extend from the charge door towards the charge table. This furnace would then be most amenable to receive preheated slabs. The opinion of ISG's rolling manager was that this configuration was the most likely application to succeed at the 84" Hot Strip Mill. With this consensus, NAMCO, with GTI's input, began developing a preliminary design of an inline slab preheater.

A meeting at ISG with NAMCO and GTI was held on December 15, 2004. During the meeting, the feasibility study was reviewed, NAMCO presented a preliminary design for the selected DFI in-line slab preheating application and an estimate of the benefits in terms of fuel use and productivity, and GTI presented the overall project timeline and estimated budget. A discussion was held on the utility (natural gas, electricity) requirements and how to bring them to the selected location. ISG requested that an estimate also be generated for DFI in-line slab preheaters for the other two reheat furnace.

Conference calls were subsequently held between NAMCO and GTI to further refine the design for the DFI in-line slab preheater, including the firing rate and air pressure requirements, and to discuss a two-side heating approach, which would put heat more uniformly into the slab and reduce the amount of time required to reach a target bulk temperature. NAMCO obtained additional drawings of the area in front of the furnace where the DFI in-line slab preheater would be installed, and developed a design for two-sided heating based on the available space under the slabs between the skid rails. GTI prepared slab heat-up calculations for the two sided approach, with uniform preheated firing on the top and non-uniform non-preheated firing on the bottom. The example in Figure 28 shows that a 400 °F bulk temperature being reached in 6 minutes.

On December 28, 2004, NAMCO met at ISG with three contractors for the mechanical, structural, and electrical installation of the DFI in-line slab preheater in order to generate budgetary estimates and conclude the DFI applications feasibility study. Several conference calls were held between GTI and NAMCO in January 2005 to further refine the design for the DFI in-line slab preheater, and to discuss equipment and installation costs. A cost estimate was developed for the two-sided DFI slab preheating field unit by NAMCO. Due to the complexity of this approach and the limited access to the space under the slabs being heated, the one-sided approach was revisited and decided upon. GTI prepared slab heat-up calculations for the one-sided approach in order to determine the physical size and connected capacity of a one-sided DFI field unit. One example (see Figure 29) shows that with a lower firing rate to minimize pressure requirements of the combustion air supply system, and with limitations placed on top surface temperature to prevent overheating one side of the slab and therefore limit bowing of the slabs, a 400 °F bulk temperature can be reached in 10.6 minutes. This heat-up time is directly proportional to the proposed width and connected capacity of the field unit.

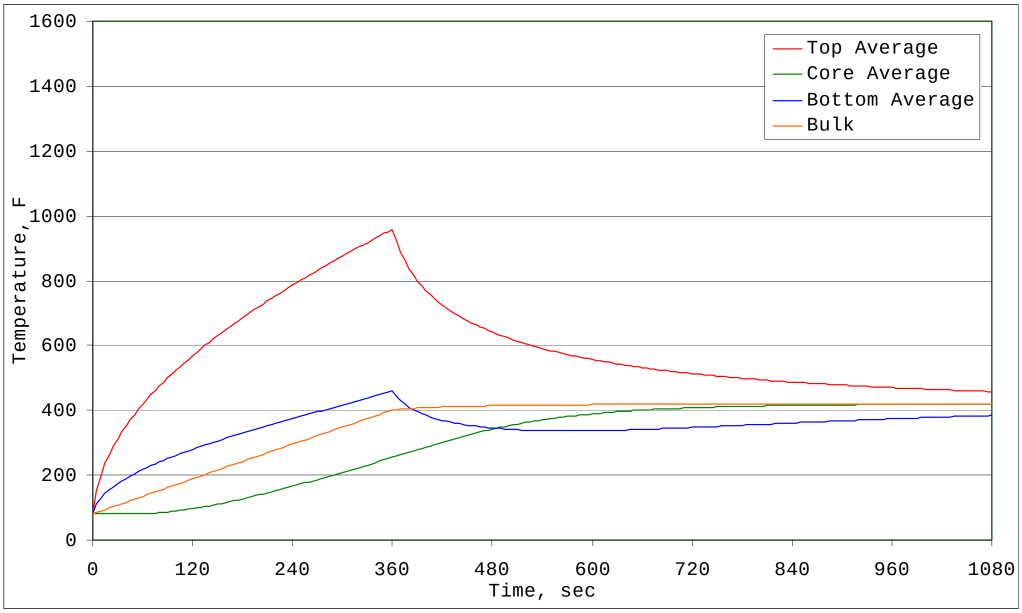


Figure 28. ISG Case 5: Two-Sided DFI Heating of a 9" Thick Steel Slab Using Preheated Top Firing and Non-Preheated Bottom Firing, with Heat Applied Only until the Bulk Temperature Reached 400 °F

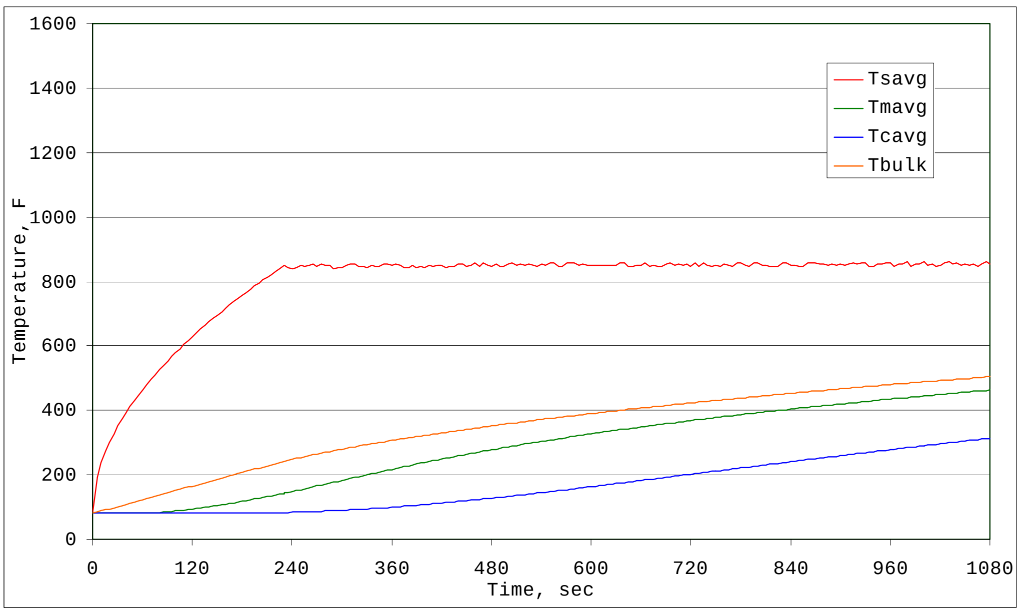


Figure 29. ISG Case 6: One-sided DFI Heating of a 9" Thick Steel Slab with Lower Firing Rate and Top Surface Temperature Limits

NAMCO received pricing estimates from three contractors for the mechanical, structural, and electrical installation of both the two-sided and one-sided DFI in-line slab preheater field units. NAMCO developed a price estimate for the one-sided DFI in-line slab preheater field unit to be applied to the target reheat furnace, and for two additional units for the other two reheat furnaces per ISG's request. The connected capacity of the one-sided DFI in-line slab preheater field unit is about twice that of the two-sided unit connected capacity since the firing rate would have to be modulated to avoid overheating one side of the slab.

The cost estimates of the field units are reflected mostly in the cost of the ancillary equipment (blowers, recuperators) since these are purchased components. The field units have about ten times the capacity and four times the cost as the field unit envisioned in GTI's original proposal to the U.S. DOE., consequently a discussion was held between GTI and the U.S. DOE regarding the budget for the project, and additionally between GTI and NAMCO regarding cost-sharing with respect to the final licensing cost. NAMCO subsequently decided (albeit reluctantly), upon review of the business aspects of entering into a license agreement for DFI technology, that they had to withdraw from the project.

Bricmont, Inc. of Canonsburg, PA was promptly contacted by GTI and agreed to replace NAMCO as the commercialization partner. Bricmont is the world leader in providing compact strip line tunnel furnaces. They saw numerous market opportunities in steel industry for the DFI technology. GTI believed that Bricmont brought superior depth of experience and market capabilities to the team. Upon joining the team, Bricmont began an immediate review of the project test results along with the outcomes of the feasibility study of the 84" HSM DFI applications at ISG, including reassessing one of the previously shelved, but smaller capacity, applications, the soak zone leading edge heater.

The above was reviewed with ISG at ISG on February 23, 2005. They were apprised of NAMCO's withdrawal from the project. ISG cautioned that with the then upcoming acquisition by Mittal Steel in April 2005 that there was not 100% certainty that an application could be supported by ISG. It was agreed that Bricmont would review all the information and advise as to whether they would be willing to proceed with the slab preheater. Within one week, Bricmont decided that due to the complexity of the application and the short duration remaining that they preferred not to pursue this field test. ISG was advised of this decision and thanked for their interest and cooperation.

The Timken Company, North Canton, Ohio

Meetings were arranged between GTI and the Timken Company in North Canton, Ohio and between GTI, Bricmont, and US Steel (USS) Research in Monroeville, Pennsylvania to investigate DFI applications at the Canton, Ohio Plants and the Lorain, Ohio Plants respectively. The renewed interest in Timken as a potential field site was due to the advisement by Larry Boyd (DOE Contractor) that Timken was hosting a showcase of another technology and that a bus trip from Cleveland to Canton was planned for the 2005 Steel Showcase attendees.

On March 1, 2005 GTI and Bricmont met with USS personnel who advised that there appeared to be opportunities at the Lorain No. 4 tube mill and agreed to make the necessary plant contacts to further pursue the matter. It was agreed that to select an application, design, build and install a pilot-scale unit to field test by the end of December 2005 was unlikely but that future applications showed promise.

On the same date, a meeting was held with Timken whereby two applications were identified at two operating plants in Canton, Ohio. One application ("Hotpointing") involved heating the end (2 feet) of a 10" tube to 2200 °F for further processing. Another application was to preheat blooms (22' x 11" x 14.75") prior to charging into a walking beam bloom reheat furnace.

Subsequent to identifying these two potential applications, Bricmont advised GTI that they were interested in joining the project to participate in the designing, engineering and building a DFI module for one of the applications at Timken. Furthermore, Bricmont expressed that they believed there was a high commercial potential for a DFI modular add-on concept to boost the temperature of product reheated in tunnel furnaces that are built and sited for maintaining strip temperature between the caster and the rolling mills. There would be a market for a DFI temperature boosting module or modules on the outlet of these furnaces to elevate the discharge beyond the 1150 °C (2100 °F) that is the highest achievable temperature.

GTI analyzed the Timken bloom preheating application using a modified version of the code used for analyzing the ISG slab preheating application. A four-sided DFI heating approach was considered with temperature gradient limitations specified by Timken. A heat up curve for this application is shown in Figure 30. The analysis of the bloom preheating application was discussed via a teleconference call with Timken and Bricmont on March 9, 2005, which led to the determination that it would to be more appropriately addressed by more conventional means.

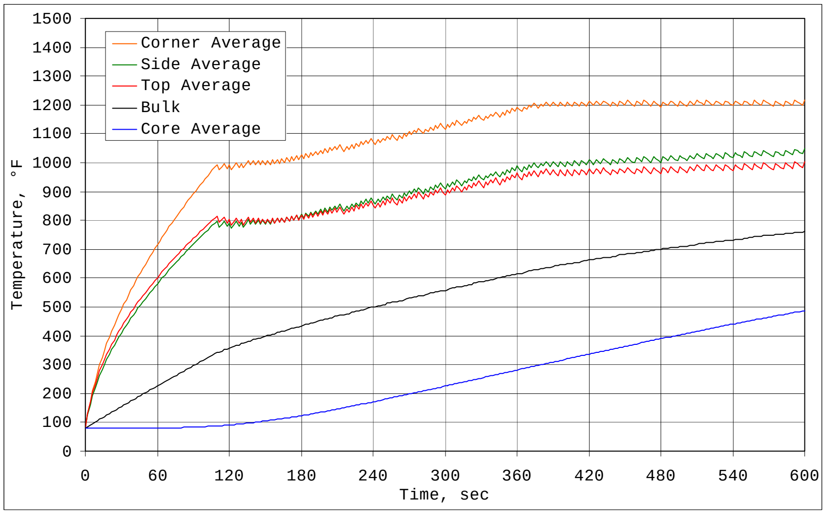
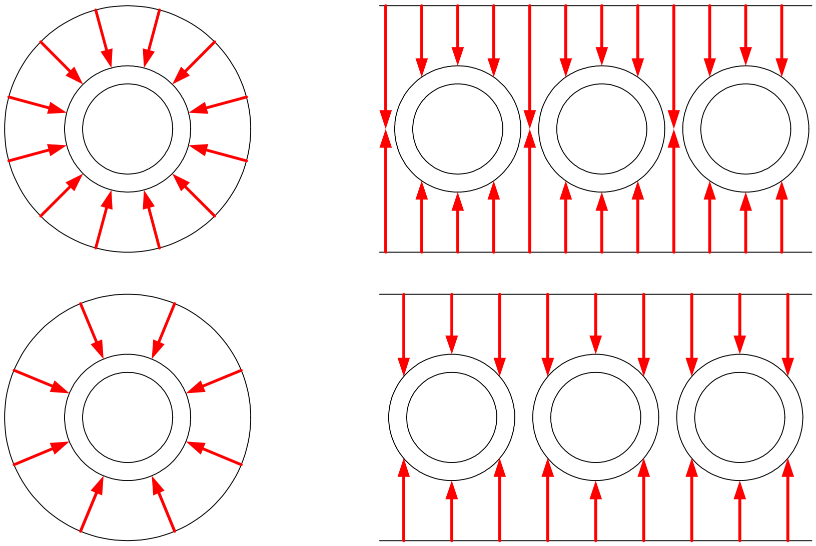


Figure 30. Timken Case 1: Four-Sided DFI Heating of a Bloom with Temperature Gradient Limits

Further information on the Hotpointing application (at Timken's Gambrinus Tube Plant in Canton, Ohio) was assembled by Timken personnel and forwarded to GTI for heat up analysis and to Bricmont for proceeding with a preliminary design and budgetary pricing. The application involves heating the end (2 feet) of a 10" tube to 2200 °F prior to further processing. Two configurations for a DFI furnace were considered (see Figure 31). For the radial configuration, DFI flame jets surround the end of a single tube. A series of three or four heating units would be needed, and the tubes would be inserted and removed from these units every five minutes as the tubes move along an existing material handling system. For the linear configuration, the existing material handling system would roll the tubes by arrays of DFI jets above and below the tubes.



(a) Radial Configurations for Single Tube

(b) Linear Configurations for Multiple Tubes

Figure 31. Approaches for Heating Tube Ends at Timken

The radial configuration required changes to the existing material handling system to insert and remove the tubes from the heating units, so the linear configuration became the focus of further analysis. To account for the rolling of the tubes, GTI's heating model was modified to allow periods of heating and non-heating corresponding to following a point on the circumference of the tube as that point moved under the DFI flame jets and then moved into the gap between tubes.   A heating curve with this effect is shown in Figure 32.

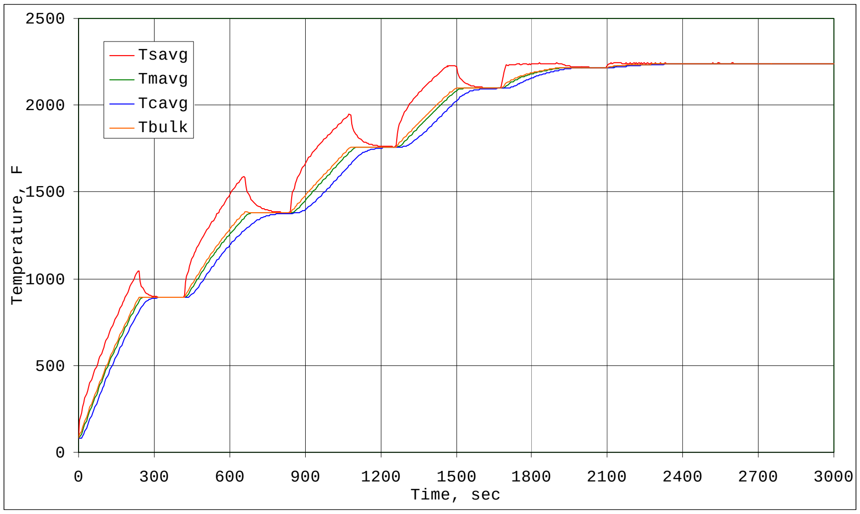


Figure 32. Timken Case 2: Heating of Tube Ends in the Linear Configuration (Tsavg = average outer surface temperature; Tmavg = average midline (half thickness) temperature; Tcavg = average inner surface temperature; Tbulk = bulk (volumetric average) temperature)

Based on the pattern of DFI nozzle spacing derived by GTI's analysis, Bricmont developed a preliminary design for a field unit based on the linear configuration, and estimated the cost to perform the requisite engineering and commissioning, both of which they would cost share. The analyses of both configurations, with and without air preheating options, were submitted to Timken along with Bricmont's preliminary design. Conference calls were held between Timken, Bricmont, and GTI to discuss schedule and installation issues. A Field Test Agreement was drafted and subsequently executed between Timken Project Management and GTI.

Timken's operating management requested a similar analysis of another application at the Gambrinus plant. This application involved the use of DFI for the preheating of tubes and bars in order to increase the production rate of an austenitizing furnace. The amount of space in front of the austenitizing furnace was a constraint placed upon the analysis. GTI devised a two part DFI furnace, with a larger diameter section and a smaller diameter section. Slower moving, larger diameter product would be heated by only the larger diameter section, while faster moving, smaller diameter product would be heated by both sections as the tubes and rods passed through the furnace. Coupling the estimated heating curve of the DFI preheater with that of the austenitizing furnace allowed for the determination of the net production rate increase, which was calculated to be 15-20%, depending on specific product size. An ROI analysis based on estimated capital, installation, operating, and maintenance costs and on a projected revenue increase from the increase production showed a payback of about 6 months.

Due to a full “order book” at Timken the plant operating management at Gambrinus Steel Plant decided to forego a field test of DFI so as not to risk interruption of production via integration of a new technology. This resulted in effectively terminating our field test agreement with Timken and the site would not be available for the DOE Showcase in Cleveland in September 2005.

Mittal Steel, East Chicago, Indiana

GTI continued to work with its commercialization partner (Bricmont, Inc.) and worked with the Steel Manufacturers Association to qualify and install a DFI field test at another site. The first candidate site analyzed during the third quarter of 2005 was Mittal Steel's (formerly Ispat-Inland's, now ArcelorMittal's) facility in East Chicago, Indiana. The application analyzed was the preheating of square steel billets in an inline DFI furnace prior to entering a reheat furnace, which is currently charged with ambient temperature product.

The DFI furnace configuration studied was for heating the billet from two sides or from two sides and the top (see Figure 33). The DFI furnace's length was set at one or two times the length of the billet. The DFI furnace's would be placed over the billets as they were conveyed to the charge table of the reheat furnace. Two values for the spacing of the DFI nozzles along the length of the billet were considered. For cases were DFI nozzles fired from the top, these nozzles were usually offset between the nozzles firing from the sides. Each side would have two rows of nozzles running the length of the furnace, while the top, if used, would have one or two rows of nozzles.

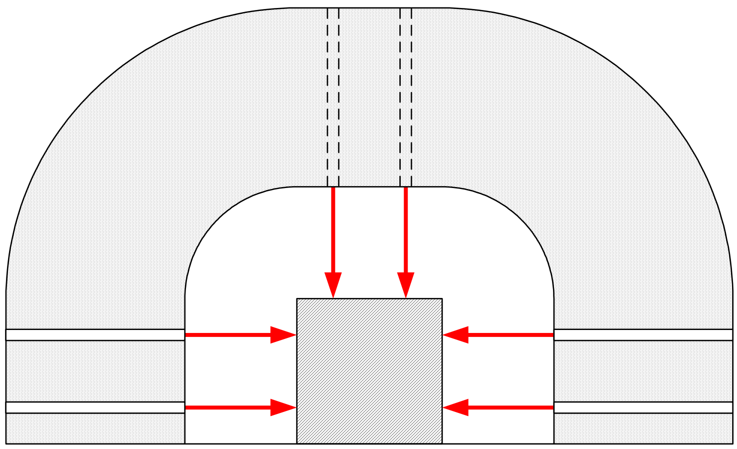


Figure 33. Approach for Heating Billets at Mittal Steel-East Chicago (heating from two sides with two jets each and optionally from the top with one or two jets)

The conduction heat transfer model for DFI heating, was modified and was used for this analysis. The estimated amount of bulk temperature achievable, for simple two and three sided heating approaches are shown in Figure 34.

Nucor Steel, Seattle, Washington

The second candidate site analyzed during the third quarter of 2005 was Nucor Steel's Seattle, Washington facility. The application analyzed was the preheating of square steel billets prior to entering a reheat furnace. A target bulk temperature of 500 °F was desired. Only 44% of their billets were being hot charged. Nucor Steel provided GTI with drawings of the charge area in front of the reheat furnace to facilitate the analysis.

Two heating approaches (see Figure 35) were considered. In the first approach, billets were heated only from the top. In the second approach, billets were heated from the top and bottom. In either approach, the DFI preheater was envisioned for modularity to be constructed of sections, with each section being the width of one billet. Some sections would be fired, and some would not. Each fired section would have two rows of DFI nozzles running along the length of the billet.

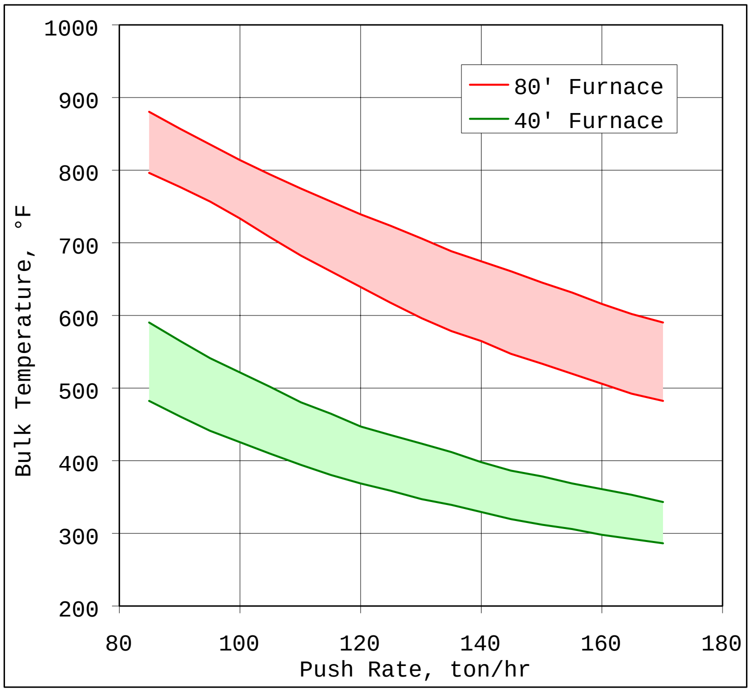


Figure 34. Mittal Steel-East Chicago: Heating of Billets with Two-Sided (lower lines) and Three-Sided (upper lines) Approaches

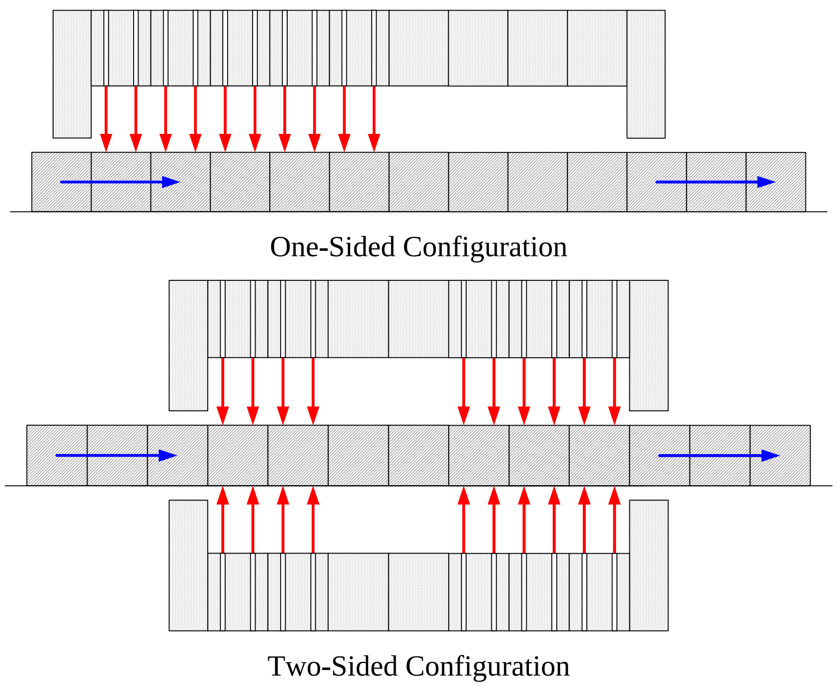


Figure 35. Approaches for Heating Billets at Nucor-Seattle

GTI's conduction heat transfer model was again used for the analysis. For the one-sided approach, different firing rates and nozzle spacings were studied. Modulation of the firing rate was applied if the maximum surface temperature reached 1400 °F. For one-sided heating, the billet will have a tendency to bow or arch toward the side being heated due to the greater expansion of the surface to which heat is applied. The parameter of interest here is the gap under the center of the billet if the ends of the billet are sitting on a flat surface. The gap is proportional to the average temperature gradient across the height of the billet and to the square of the length of the billet. So that the billets do not submarine under one another or pop out of the line as they are pushed into the reheat furnace, a minimum of 50% overlap between successive billets was maintained. Modulation of the firing rate was applied to limit the rate of increase in the gap as the billet was heated. Figure 36 shows the best results in terms of bulk temperature increase given the constraints on available space and bowing.

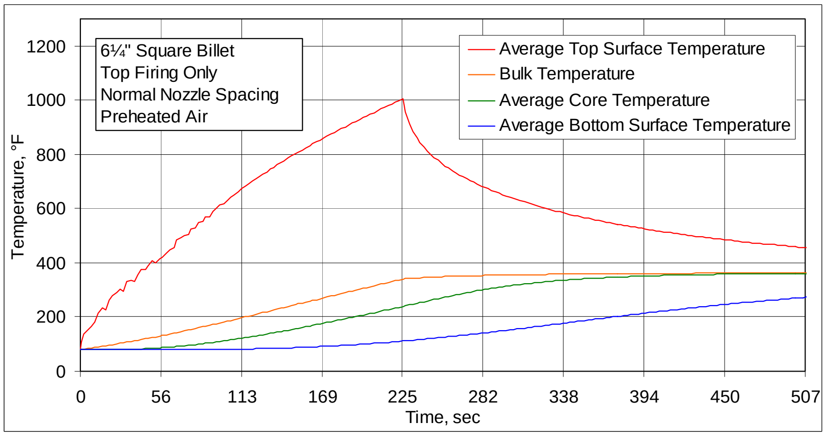


Figure 36. Nucor-Seattle Case 1: Heating of Billets with One-Sided Approach

For two-sided heating, the analysis approach involved fixing the nozzle spacing at the same density as the best case from the one-side heating analysis and varying the firing rate and number of fired sections. Up to ten sections could be utilized for heating as opposed to four for the one-sided heating approach. Because of space constraints, two or three unfired sections were placed in the middle of the fired sections, and the first fired section was placed further downstream than in the one-sided approach, and, unlike the one-sided heating approach, no sections were utilized at the end for equilibrating the temperature in the billet.

Bulk temperatures of 430 °F to 700 °F were achieved depending on firing rate and number of fired sections. No modulation of firing rate was needed for any of the above cases. One heating curve is shown in Figure 37. The ability to preheat the billets to 700 °F as opposed to 500 °F would allow for increasing the production rate of the reheat furnace. A 10% increases in production rate could be sustained by the DFI preheater, with a bulk temperature of 590 °F.

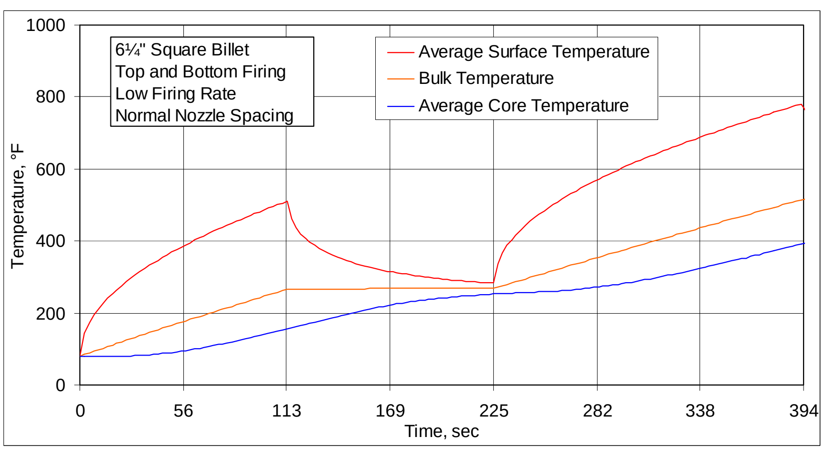


Figure 37. Nucor-Seattle Case 2: Heating of Billets with Two-Sided Approach

Chicago Heights, Illinois Mills

A meeting at GTI's local gas utility, Nicor Gas in Naperville, Illinois on August 24, 2005, led to contacts and subsequent visits to two local steel companies, Chicago Heights Steel and CaluMetals, both in Chicago Heights, Illinois. Both of these sites were visited by GTI and Nicor Gas on August 31, 2005.

Chicago Heights Steel reheats used railroad track, splits the rail into three pieces, and rolls each piece into different structural products. This site was interested in improving the efficiency of their operations. It was suggested that DFI could be used to preheat the rail before the reheat furnace, or could be used to post-heat the rail if the discharge temperature of the reheat furnace is reduced. Due to the limited available space and the wide variety of rail sizes, further action on this application was not considered.

CaluMetals reheats steel billets and rolls them into structural products. The site is also interested in improving the efficiency of their operations. Additionally, the site was interested in rolling higher-temperature grades. It was suggested that the discharge temperature of reheat furnace be reduced, and the difference (and more) could be made up with a DFI booster furnace on discharge side. Drawings and current operational data were requested by GTI, but no further action was considered.

Republic Engineered Products, Lackawanna, New York

The last candidate site analyzed during the third quarter of 2005 was Republic Engineered Products' 13" Bar Mill in Lackawanna, New York. The application analyzed was the heating of ends of bundles of rods for the purpose of annealing (stress-relieving) the ends of the rods after cold shearing. For the analysis, a DFI furnace was configured to fire directly on the end of the bundle, with a small portion of the exhaust gases flowing through the gaps between the rods in the bundle (see Figure 38). Based on preliminary information, the target temperature was 1100 °F at 2" depth into the end of the rods after 4 minutes of heating.

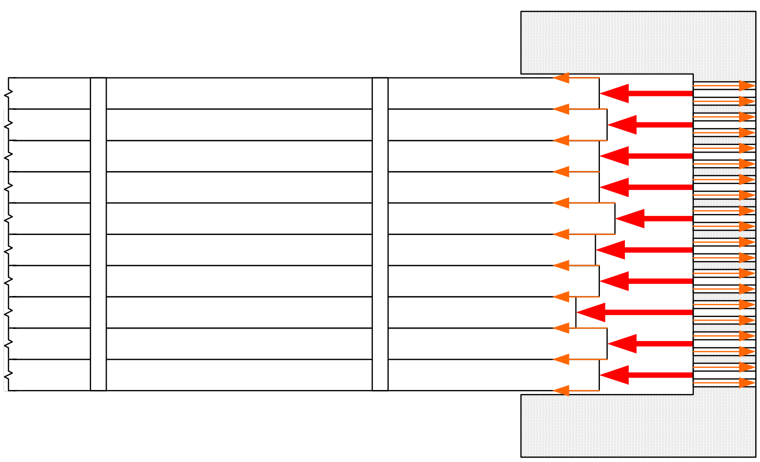


Figure 38. Approach for Heating Bundle Ends at REP

GTI's conduction heat transfer model for DFI heating was modified and used for the analysis. Three values for the spacing of the DFI nozzles were selected. The initial temperature of the bundle was set at 200 °F. The combustion air was assumed to be preheated. The estimated temperature achievable at 1", 2", and 3" depths after 4 minutes of heating, is shown in Figure 39. An average temperature in the first 2" depth of 1100 °F was achieved for the two densest nozzle spacings.

On September 9, 2005, a meeting was held at Republic Engineered Products to discuss and view the application and review the results of the preliminary analysis. Representatives of National Fuel, the local natural gas utility, were in attendance and a representative of Bricmont, Inc. participated via conference call. The Bricmont representative subsequently visited the site on September 23, 2005.

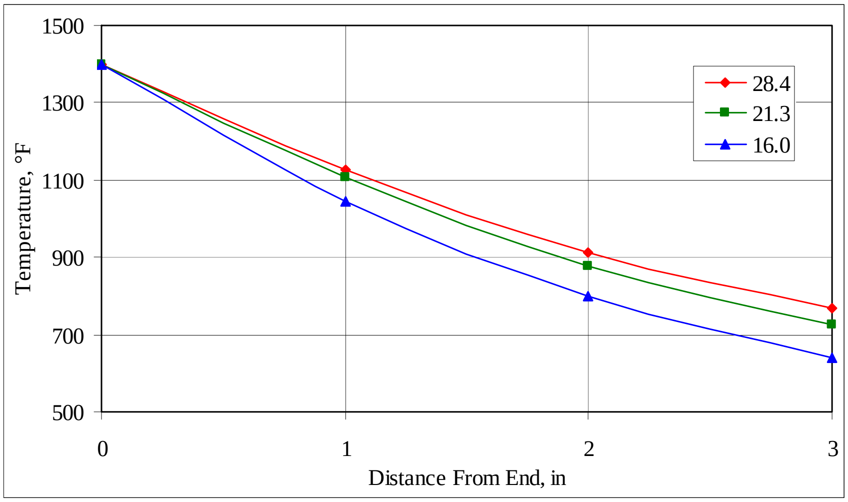


Figure 39. REP Case 1: Heating of Bundle Ends for 4 Minutes with Three Different Nozzle Spacings

Based on information gathered during the site visits, a revised analysis of the application was performed. The target temperature was 1010 °F at the surface after 2 minutes of heating. Four values for the spacing of the DFI nozzles were selected. The initial temperature of the bundle was set at 80 °F or 200 °F. The combustion air was assumed to be not preheated. The estimated temperature achievable at the surface (0" depth) and at 1", 2", and 3" depths (distances from end surface) after 1.5 to 2.5 minutes of heating, is shown in Figure 40 for the higher of the two initial temperatures. An average surface temperature of 1010 °F or greater was achieved for the two densest nozzle spacings for both initial temperatures. A reduction of fuel usage was estimated to be 50% to 60% over the current practice, which is to use skid mounted torches after the bundles have been moved by crane from the bundle chain tables to adjustable stands. Four torches are used, one for each end of the bundles from two shearing lines.

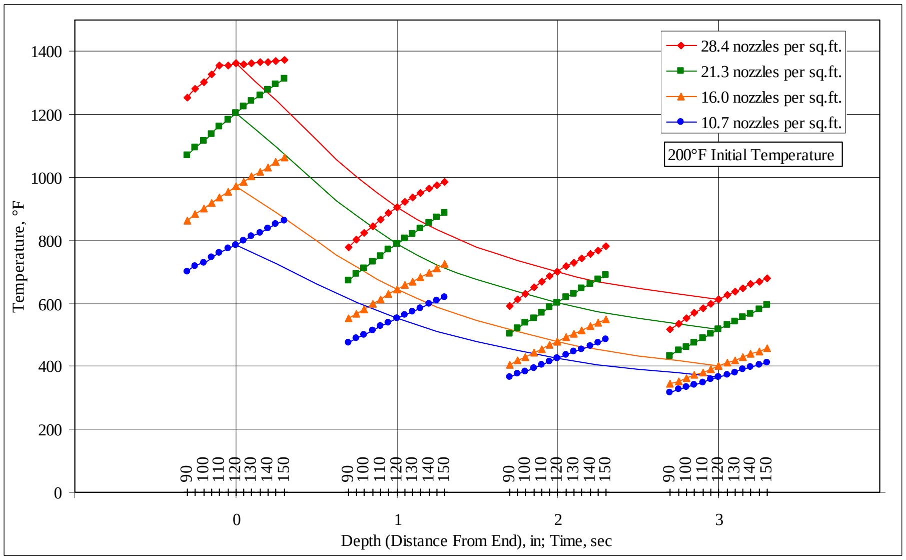


Figure 40. REP Case 2: Heating of Bundle Ends for 1.5-2.5 Minutes with Four Different Nozzle Spacings

It was determined that a DFI heater could heat the end of the bundle to an end surface temperature of 1010 °F in 123 seconds. Four DFI heaters would be needed, one for each end of the bundles from the two lines. Bricmont with Republic Engineer Products analyzed the current product flow and timing, and devised a scheme for the placement and operation of DFI heaters that eliminates the need for transferring of the bundles from the bundle transfer tables to the adjustable stands. On each line the bundles would move toward each other as usual from the roll tables onto the transfer tables. The bundles would move until reaching new disappearing stops near the pulpit that sits between the transfer tables. The new stops would then retract to be replaced by DFI heaters, which would heat the ends (the heads) of the bundles that were previously against the new stops. The transfer tables would then be reversed until the bundles reach existing disappearing stops. The existing stops would then retract and the bundles would then be indexed laterally onto the chain tables and in front of fixed DFI heaters, which would heat the ends (the tails) of the bundles that were previously against the existing stops. After heating, the bundles would be further indexed along the chain tables to be picked up by the crane.

Compared to the current heating system, the DFI application was estimated to reduce fuel consumption by up to 80% or approximately 100 Billion Btu per year

Conference calls were held with REP on November 9, 2005, and November 16, 2005, to discuss the details of the "DFI Automated Bundle End Annealer" system proposal prepared by Bricmont and an ROI analysis prepared by GTI. REP informed GTI that this project would be included in the capital funds requests for energy savings projects. REP would be performing the installation of the DFI field system with these funds if approved.

In mid December 2005, GTI received a verbal approval of the DFI project by the president of REP. A formal Field Test Agreement was negotiated and signed by December 30, 2005.

Field System Design

Purchases orders were executed with Bricmont, Inc. for the engineering and fabrication of the DFI field system in January 2006. A site visit was made by Bricmont in early February 2006. Based on the space available, Bricmont developed a preliminary design (see Figure 41) for the DFI field system that does not rely on the installation of new disappearing stops. Existing fix stops and an existing disappearing stop would be utilized to even out the ends of the bundles by bumping the bundles into these stops. The stops would also serve to position the bundles at the DFI heaters. One pair of DFI heaters would drop down from above the roll tables, while another pair of DFI heaters would be fixed in place alongside the chain tables.

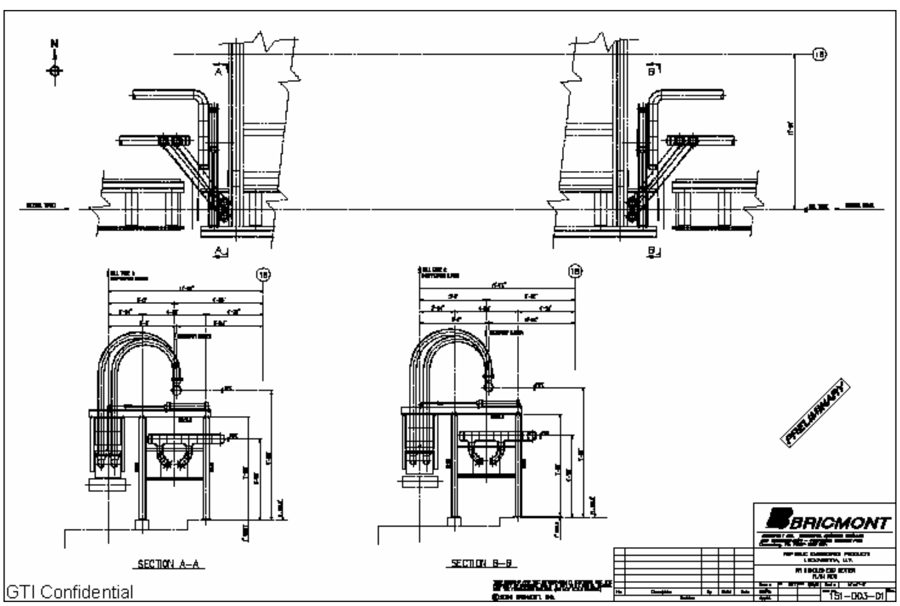


Figure 41. Preliminary Design for DFI Installation at REP with Two Moving Heaters and Two Stationary Heaters

To accommodate the revised system design, variable frequency drives were installed on the motors on the roll tables and transfer tables. REP cost shared the installation of the drives and half of the cost of the drives themselves.

A site visit was made on April 25, 2006, by Bricmont and GTI to review space constraints around the target area for the DFI heaters and to review the existing control system and discuss interfacing it with the DFI heaters control system. A preliminary drawing of the arrangement for the DFI field system was presented to REP during this visit. A follow up visit was made by Bricmont on June 29, 2006, to clarify items regarding the I/O interface.

Since the bundles are not of uniform size, flames from some of the nozzles in the DFI heaters may not impinge upon rods in the bundles, which is different from an application involving a fixed-sized load in an enclosed furnace. GTI, with Bricmont's guidance, investigated the stability of the DFI flames when fired in open air with no load or enclosure present. The custom machined nozzles used in the laboratory DFI furnace would not hold the flame in these conditions, so a different nozzle type was sought. A commercially available nozzle with a functional modification was found to meet the requirements of the application and was incorporated into the design of the field system.

Bricmont developed engineering drawings and the control system and integration strategy for the DFI field system. Gas train components for the system were purchased by Bricmont. A set of drawings of the mechanical components of the system and an updated schedule were issued by Bricmont on August 1, 2006. GTI reviewed the drawings and sent revisionary comments to Bricmont. Bricmont requested and received bids from fabricators for the field system, selected a fabricator and let a purchase order for the fabrication of the mechanical components of the field system. A revised set of drawings of the mechanical components of the system, as well as a set of drawings of the piping arrangement, were issued by Bricmont and reviewed by GTI.

Baseline Testing

Flow meters for the measurement of fuel and air usage rates during baseline testing were procured by GTI. Spool pieces for insertion of the flow meters into the gas and air lines were fabricated by GTI, and then shipped to REP with the flow meters. REP installed the flow meters prior to GTI's visit. Baseline testing of the existing system at REP was conducted August 21-25, 2006. Fuel and air usage was measured, along with heating time, bundle size, rod size, and steel grade, for over 50 sets of bundles, with each set having up to 12 bundles. The gas consumption rate was somewhat higher than had been observed in September 2005, but heating times were shorter. Air consumption was lower than expected relative to gas consumption though. Observations were also made for almost every bundle heated on the uniformity of the placement of the individual rods in the bundle. Bricmont made a site visit on August 23, 2006 to observe the measurement procedures of the fuel consumption of the current process. The flow meters were left installed at REP at the conclusion of baseline testing so gas consumption could be monitored by REP over a full cycle of rod sizes.

Field System Fabrication

Bricmont completed engineering drawings and the control system and integration strategy for the DFI field system, and sent them for construction in the beginning of October 2006. GTI continued to provide feedback to Bricmont on details of the design drawings. The flow skid design was issued for construction to General Fabricating Services in Carnegie, PA; the burner stand design was issued for construction to United Fabricating Inc. in Claysville, PA. Both drawings and the electrical design were submitted to REP, which began preparations for the DFI field system installation. GTI visited both fabrication sites on November 9, 2006 to witness a checkout of the flow skid and controls and to observe the motion of the movable burner. The photographs below show one of the burner stands (see Figure 42), the flow skid (see Figure 43), and one of the control panels (see Figure 44). REP requested and received further information about pre-installation wiring.

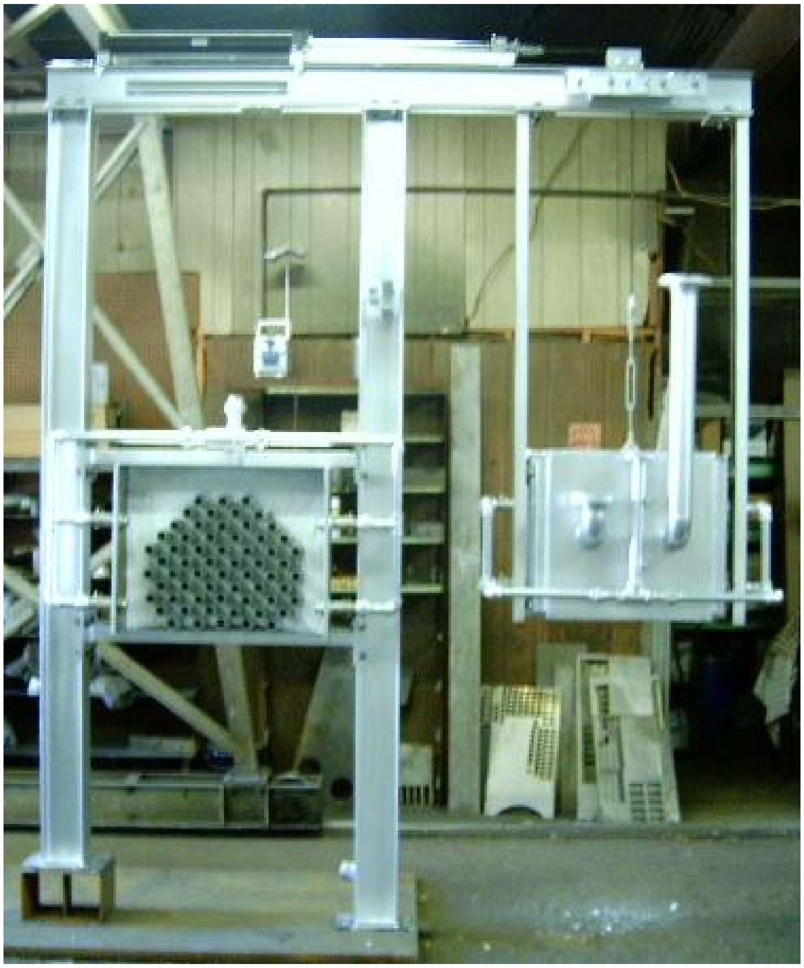


Figure 42. Burner Stand Test Assembly at Fabrication Shop

Figure 43. Flow Skid at Fabrication Shop

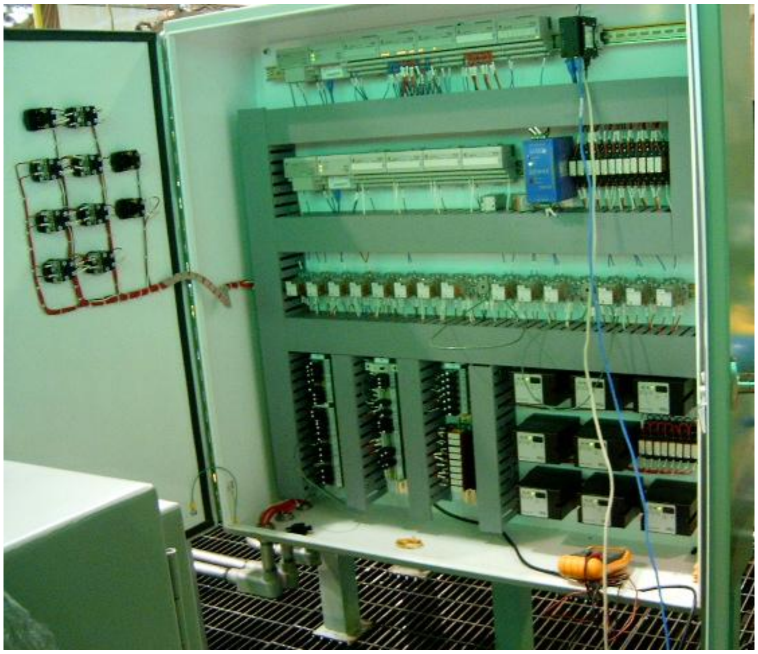


Figure 44. Control Panel for Flow Skid at Fabrication Shop

Field System Installation

All components of the DFI field system were delivered to REP By November 21, 2006, with the exception of a few electrical components. The mechanical installation was performed while mill continued operating with the existing torch heaters. REP installed the burner stands at their designated positions, placed the flow skid (see Figure 45) between the transfer tables near the control pulpit, located the one burner control panel near its respective burner stand (see Figure 45), located the one system control panel (see Figure 46) in the mill's computer room, and located the HMI (human-machine interface) display (see Figure 46) and a few new pushbuttons and switches in the control pulpit. The system control panel contained a PLC and two I/O racks. A third control panel, which was on the flow skid, contained another two I/O racks for the PLC. The control panel on the flow skid also controlled the other burner stand. The two burner stands, one for each line on either side of the control pulpit, each had a stationary burner to heat one end of a bundle on a transfer table and a movable burner to heat the other end of the bundle on a roll table. The movable burner could be raised to allow a bundle to pass underneath or lowered to heat the end of the bundle.

Figure 45. Flow Skid and Burner Stand Installed at REP

Figure 46. System Control Panel and HMI Display Installed at REP

Piping between the flow skid and the two heater stands was completed by REP contractors in early February 2007. The natural gas and compressed air supply lines at the control pulpit that feed the existing torch heaters were branched to also feed the flow skid. Two of the flow meters used for baseline testing were relocated to the flow skid.

Electrical connections between the flow skid, the two heater stands, the burner control panel, the system control panel, the HMI display, and the various photocells were completed by REP contractors in late February 2007. Work was slowed by a period of severely cold weather. The connections between the system control panel and the roll table and transfer table drive controllers was held off until the weekly outage scheduled during the commissioning time since this involved severing the connections between the existing mill control computer and the drive controllers.

Commissioning Round 1

The commissioning of the DFI field system by Bricmont with GTI began on March 5, 2007. The first day involved the checking out of the piping and electrical connections between the flow skid, the two heater stands, the burner control panel, the system control panel, and the HMI display. The second day involved the checking out of the flow skid operation, adjusting the pressure regulators, setting up the pilots for the burners, and lighting one of the stationary burners.

The third day of commissioning coincided with the mill's weekly outage, which was extended from one to two shifts this one day to allow sufficient time for the electrical switchover. Pushbuttons, switches, and indicator lights on the pulpit console were disconnected from the existing computer connections and then wired to the I/O racks in control panel on the flow skid. The roll table and transfer table drive controllers, some of which had been replaced with new variable frequency drives (inverters), and the limit switches for these tables were disconnected from the existing computer connections and then wired to the I/O racks in system control panel in the computer room. In parallel efforts, the photocells that relay the position of the bundles to the PLC were set up. All of the normal manual operations of the control pulpit for moving the bundles on the roll tables and transfer tables were then checked out with the new PLC in control. Any reversed or transposed electrical connections or drive rotations were identified and corrected. The operators later noted quicker speed-up and slow-down of the roll tables with the new system, which allows finer precision in positioning the bundles. One issue noted was that the existing disappearing stop, which was to be used to even out the ends of bundles from one production line, was not equipped with limit switches.

The fourth day of commissioning involved the adjustment of gas and air flows to tune the two stationary burners. While the burners could be lit, some issues were noted concerning the gas and air pressure regulators on the skid, the interaction of the pilots and the main flames which limited the amount of air for the main flame, and the buoyancy of the main flames, which was also partially due to limited air flow. Also it was found that the movable burners were getting stuck in their tracks due to the binding up of the flexible hoses and conduits, and therefore could not be raised and lowered properly. This issue, coupled with the lack of limit switches on the disappearing stop, prevented any checkout of the automated mode of the PLC program for bundle end heating. Also some shielding was found to be needed to prevent overheating of the photocells and pyrometers on the burner stands.

The fifth day of commissioning involved the test heating of bundle ends and the tuning of the movable burners. Two bundle ends were positioned manually in front of the stationary burners and heated, but the limited air flow meant the heating rate and final temperature were too low. The movable burners were tuned to the same parameters as the stationary burners and test fired. Firing the stationary and movable burner together was possible, but the overall gas and air flow was lower due to sharing common metering orifices. At one point all four burners were successfully firing simultaneously.

It was decided between Bricmont, REP, and GTI that some modifications were needed to the flow skid to address the pressure regulation and pilot/main flow issues, some adjustments to the flexible connections at the movable burners were needed to prevent binding, and some heat shielding was needed around the ancillary equipment on the burner stands. REP agreed to address the latter issue, while Bricmont agreed to address the first two issues. In the meantime, the mill continued to the use the old torch heaters on the bundle ends while using the new PLC system to manually move the bundles.

In April 2007 Bricmont designed modifications to the flow skid to address the pressure regulation and pilot/main flow issues that were noted during the preliminary commissioning of the DFI field system. The changes involved installing separate regulators for the pilot lines and pressure relief valves to eliminate overpressure situations. Bricmont also designed modifications to the flexible connections at the movable burners to prevent the binding issues that were noted during the preliminary commissioning. These changes involved using shorter flexible hoses and rerouting the hoses downward instead of upward from the stand to the burner. Mechanical drawings for the modifications were issued, and the same contractors were retained to perform the rework. The rework was completed in early June 2007. In addition, the disappearing stop on the west line was made operational.

Commissioning Round 2

A second round commissioning of the DFI field system by Bricmont with GTI began on June 11, 2007. The new pilot air and gas regulators were set. The new pressure switches for these lines were set. The electrical system was checked out. The pilots were test fired and adjusted. The West fixed burner was fired at the previous settings, then adjusted to the design settings, and finally with increased air flow. The other three burners were set up the same, and various combinations of 1, 2, 3, and 4 burners were fired simultaneously without issue.

Testing of the automated material handling sequences then continued. It was found however that, despite the modifications made to the piping, the air cylinders for the moving burners were still not capable of pulling up the burners. Bricmont ordered two larger diameter cylinders, but they could not be delivered during this commissioning period, so testing proceeded with the portions of the sequence before and after the motion of the burners. The portions of the sequence that bump the bundles into the fixed stop (east line) or the disappearing stop (west line) was proven. The portions of the sequence that position the bundles in front of the moving DFI heaters was proven after replacement of one photocell and some adjustment of the locations of the photocells.

The next portion of the sequence that was tested was the portion that moves the bundles past the moving DFI heaters and positions the bundles prior to lateral movement to the fixed DFI heaters for heating the other end of the bundle. This sequence was problematic on both lines. For some bundles it worked well, but for other bundles, the bundles stopped prematurely, and the sequence had to be stopped manually before the bundles could move laterally, since they would have hit the DFI heater stands. The sequence relies on photocells to detect that bundles have completely passed by, but the photocells were occasionally falsely indicating the bundles were no longer in front of the photocells when they still were. It appeared that the photocells were fooled by bundles with unusual shapes (e.g., with bars that are skewed with respect to the axis of the bundle) or by the banding straps around the bundles. Both of these seem to cause the beam from the photocells to bounce away at an angle instead of returning to the photocells. A delay was put into the signal from these photocells that would allow a banding strap to pass by while still detecting the end of the bundle. The photocells were moved upstream to allow for the motion of the bundles during this delay period so that the bundles still stop in the desired location. The technique was only partly effective. Adding a double check after the bundles stop to make sure they were truly past the photocells was also only partly effective.

The portion of the sequence that moves the bundles laterally to the fixed DFI heaters was proven after some adjustment of the locations of the photocells.

The west fixed burner was test fired with different bundles in front for 80, 120, 180, and 200 seconds. It appeared that about 3 minutes of heating was needed to reach the desired temperature, which was somewhat longer than predicted. It was concluded at that time that additional combustion air to promote complete combustion before the flames impinge the load and to reduce flame buoyancy would improve the heating rate.

A set of action items was prepared and forwarded to Bricmont and REP.

Commissioning Round 3

A third round of commissioning began in July 2007. New air cylinders were installed on the burner stands. The movable burners could now be raised and lowered automatically. There was a little interference between one of the movable burners and part of the surrounding equipment that caused that burner to not sit flat in the down position. This issue was partially addressed by the mechanical contractor. Heat shields were added between the fixed burners and the side of the chain tables. All four burners were test fired, and the movable burners were raised and lowered with the pilots lit to verify that they stayed lit during the motion.

The aiming of all the photocells and pyrometers was checked and adjusted as needed. The full automated sequence was then tested. The portion of the sequence that bumped the bundle against a stop to align the rods, moved the bundle to the movable burner, lowered the movable burner, fired the movable burner to heat one end of the bundle, and raised the movable burner tested satisfactorily, though the heating rate was slightly less than expected, thought at that time likely due to buoyancy of the flame. There was an issue with potential overheating of the disappearing stop near one of the movable burners.

The portion of the sequence that moves the bundle laterally to the fixed burner and fires the fixed burner to heat the other end of the bundle also tested satisfactorily. There was an issue with potential overheating of the chain table the bundle sits on.

The portion of the sequence between the above two portions, where the bundle moved under and past the movable burner, still had issues with bundle detection. Despite the adjustments made to the aiming of the photocells and to the speed of the roll tables, most of the time the bundles were being stopped too soon when moving under the movable burners, and the automated sequence had to be stopped manually before the system could move the bundles laterally and cause them to hit the vertical guides of the burner stands.

Two meetings were held at REP between REP, Bricmont and GTI to discuss the issues (heating rate, overheating surrounding equipment, and bundle detection) and brainstorm ideas to address the issues. It was thought that the heating rate issue could be addressed by moving some of the burner nozzles, closing off some of the burner nozzles, and fine tuning the gas and air rates. It was concluded by the team that for the DFI technology to be used on a production basis, improvements must be made to the design and installation. Some of the possible strategies are listed below:

1. Devise an engineering solution to improve bundle detection. This would require numerous heat-shielding and water-cooling devices.
2. Replace the bundle detection system with a camera system allowing the operator to visually position the bundles for heating. This would eliminate the bundle detection problem.
3. Devise an elevating mechanism which would raise the bundle end or the whole bundle during heating minimizing heating of the chains and tables. This would require a pneumatic or hydraulic control system and machinery.
4. Abandon the in-line concept and convert the heaters to portable units. This solution could use much of what has been designed and installed, but would require a new design for carriages and combustion control.

GTI remained on site to review locations for new and/or different photocells, assess locations for bundle lifting mechanisms, and examine the design requirements for portable DFI heaters. Meanwhile, the mechanical contractor added brackets to the burner stands and lugs to the movable burners and installed turnbuckles between them to hold up the movable burners for maintenance service or in case of loss of compressed air as the bundles had to be able to pass under the heaters for existing mill operation.

Bricmont developed some cost estimates for the four strategies. The strategies were reviewed with REP, and it was determined and shared with DOE that the portable heater strategy has the best potential for a successful system. Bricmont developed a proposal for this strategy, and GTI estimated the overall cost to the project. The cost far exceeded the remaining budget for the project, so GTI began to seek additional funding from DOE and/or others.

Conversion to a Portable System

GTI's Sustaining Membership Program (SMP), which had previously supported this project, agreed to provide the additional funding necessary to complete the project, starting in December 2007. GTI let a purchase order for Bricmont for redesign and detailed engineering. The new design utilized elements from the existing field system, particularly the DFI heaters themselves and portions of the gas and air supply and mixing subsystems. The design called for the heaters to be mounted on four portable carts, and to be used in much the same way as the existing inefficient torch heaters.

GTI let another purchase order to the mechanical contractor to fabricate one empty cart of the same size and loaded with scrap metal to the same weight as the eventual DFI heater carts. This allowed REP to gauge the effort needed to move the carts around, and help determined details such as the proper type of casters needed for moving the cart over the uneven mill floor.

An amended Field Test Agreement between GTI and Republic Engineered Products was executed.

In the first quarter of 2008, purchase orders were let to REP's mechanical and electrical contractors for installation preparation work. The DFI heater stands were removed from the transfer table and chain table areas in preparation for salvaging the DFI heaters for the carts. The electrical connections for the DFI heater stands were disconnected while leaving the roll, transfer, and chain table control functions intact.

The design for the portable DFI heaters was completed by Bricmont in May 2008. The piping schematic and mechanical layout were reviewed by GTI and REP and subsequently approved following a few minor revisions. Bricmont solicited bids for the assembly and selected a fabricator.

Additional components were removed from the flow skid. These components and the DFI heaters and were shipped to Bricmont's fabricator for assembly into the portable heating carts. On July 30, 2008, a shop test was performed on one of the four heaters and witnessed by REP and GTI personnel. The heater was fired and the flow rates of gas and air were adjusted to match previous conditions. The heater was shut off and restarted to ensure reliable operation. Bricmont subsequently set up the remaining three heaters. The four heaters were then shipped to REP.

Figure 47. Side View of Portable DFI Heating Cart at Fabrication Shop

REP removed the flow skid that had supplied the fixed DFI heater stands to make room for the portable DFI heating carts. Even though the DFI heater stands had been removed earlier, the flow skid had remained in place since it contained I/O for the table controls, but that functionality was moved to a new mill control system installed in July 2008, enabling the removal of the flow skid.

Commissioning of the Portable Carts

On September 10, 2008, during a normal down day, REP replaced one of their existing torch heaters with one of the portable DFI heating carts (see Figure 48). Bricmont and GTI participated in the commissioning of this heater on the 10th and 11th, with GTI conducting some further tests on the 12th. On the 10th, the DFI heating cart was test fired, and the heater was used to anneal two bundle ends. The flame appeared smaller than during the shop test, so the gas and air flows were checked and adjusted as needed, and the heater was used to anneal another two bundle ends. The DFI heating cart did take some effort to move around on the mill floor, and the flame had more buoyancy than desired.

Figure 48. Portable DFI Heating Cart in Operation at REP

On the 11th, this same heater was used to anneal the west ends of a "trial" set of six bundles. The east ends of the bundles were annealed with an existing torch heater for comparison. The heating time was lengthened as each bundle end was heated by the portable DFI heating cart until the color change of the ends of the bars in the bundle matched that of the torch-heated bundled ends. The operators lent guidance as to what different colors the bar ends go through as they are heated. The bundle ends that were insufficiently heated were reheated until they reached the proper color. The six bundles were then removed and replaced with a full production set of twelve bundles. The west ends of these new bundles were each heated by the portable DFI heating cart for the time determined from the previous set, and applied additional time to a few bundles that needed spot reheating on a few bar ends. One bundle of bars had sufficiently uneven (unjustified) ends to prevent complete heating of all bars in that bundle. The overall heating time by the portable DFI heating cart was significantly longer than that by the existing torch heater, but the fuel rate was significantly lower. The twelve bundles were then removed and replaced with another set of twelve bundles. This set had four short and eight long bundles. The west ends of the four short bundles were heated by the portable DFI heating cart. By this point in time, the mill was backing up due to the slower heating rate. Also the end of the fourth short bundle could not be heated completely since the DFI heating cart could not fully get into the corner formed by this bundle and the first longer bundle along the side of it. The remaining bundle ends were heated by the existing torch heater, while operational issues of the DFI heating carts were compiled and discussed.

On the 12th, the gas and air rates for the portable DFI heating cart were raised by 50% over that used on the 11th. The west ends of two bundles were heated by the portable DFI heating cart. The gas rate was then lowered to 25% above that used on the 11th, and the west ends of four bundles were heated by the portable DFI heating cart. The flame was more buoyant at the higher rates, and the heating time per bundle was not significantly reduced.

The main issues noted from the commissioning were:

- The heating time with the DFI heating cart is too slow for production use. This also nullified the effect of the lower fuel usage rate.
- The heating cart did not handle bundles with uneven bars or unevenly placed bundles.
- The heating cart was difficult to move over the rough mill floor.
- The ends of the bars cannot be seen while they are being heated by the heating cart.

GTI requested and REP agreed that one of the DFI heating carts be sent to GTI, for further testing and modification, along with a short bundle of bars. GTI estimated that the heat transfer rate from the flame to the bundle needs to be increased by 74% for the heating time of the DFI heating carts to match that of the existing torch heaters. Modifications under consideration at that time for the DFI heating cart included

- Altering the shape of the heating head, e.g., shorter and wider to put more heat on more of the bundle ends
- Air injection to increase flame combustion rate
- Different nozzles to increase flame velocity
- Fewer pilots to reduce fuel consumption
- Different casters to reduce rolling effort
- View ports through the heating head to see the bundle ends

Alternate Nozzle Test

It was decided to conduct a simple direct flame impingement test using a burner being developed and tested for another application and the water-cooled plate used for the flat calorimetric testing of the laboratory DFI furnace. Figure 49 shows the test setup showing the burner and the water-cooled plate calorimeter at the GTI combustion laboratory. The objective of this test was to summarily test the supposition that this type of burner could replace the nozzles being used in DFI bundle end heating application at REP. While delivering a high rate of heat transfer to the plate, the test did not yield satisfactorily uniform heat transfer results to consider pursuing at that time.

Figure 49. Side View of Setup for Testing Performance of Alternate Burner

Cart Modification-Improvement Plan

The DFI heater cart and two short-length bundles of round bars were delivered to GTI on December 29, 2008. A detailed modification-improvement plan was prepared by GTI to act as a test matrix to test and evaluate changes to the DFI cart design:

0. Baseline measurements – Test current heater as is with the water-cooled plate calorimeter as a load to measure heat transfer rate and observe buoyancy.
1. Load position
   a. The water-cooled plate calorimeter can be raised to simulate lowering the heater to capture more of the flame buoyancy.
   b. Also test distance from the heater to the water-cooled plate calorimeter versus heat transfer.
2. Firing rate.
   a. Increase natural gas and air flow rates by 50% and 100%.
   b. Increase air flow rate by an additional 50% and 100%.
3. Shrouding – Ceramic shroud arrangement to deflect any remaining buoyant flame(s) towards the load.
   a. Fiberboard insulation of 1" or 2" thick with metal backing.
   b. With pilots relocated, side shrouds could be removed to help air entrainment and view of the load.
4. Pilot number & location – Convert to one pilot on each side instead of the current two pilots on each side or the DFI nozzles. The pilots may be interfering with the heat release pattern.
   a. Test with 4, 2 and 0 pilots.
   b. Relocating pilots to top (or bottom) (only 2 or 3 needed). If unit is ultimately made twice as wide, 3 or 4 top mounted pilots would be needed (or 2 side and 2 top pilots).
5. Air injection – Add combustion air ports within the center of the cluster of DFI nozzles to promote immediate release near the bundle end. This modification may require a separate pressure regulator for this flow stream.
   a. Decide on number and location of air ports. Air ports could be concentrated in center or dispersed.
   b. Air ports can be tubing interspersed between the nozzles.

6. Nozzle arrangement – Change the flattened egg shape of the nozzle face (now about 24" wide by 20" high) to a rectangular shape of (ultimately) say 48" wide by 20" high. This will aid in containing the flame front and also enable the heating of two bundle ends simultaneously. A practical height may be closer to 16" than 20" (achievable with top 2 rows removed) since a 6-ton bundle will have a round diameter of 18.17", but will flatten into an ellipse somewhere between 20" by 16.5" and 24" by 13.75", say 22" by 15".
    a. Test with 2 and 3 top rows of nozzles removed.
    b. Test with 2 nozzles installed in lower corners
    c. With top 2 rows removed, test with 2 nozzles added to upper corners.
    d. With pilots relocated, the nozzle face can be rearranged into a rectangular area of 27.5" wide by 17" high with 67 nozzles within same structure. This would however require that the air-gas plenum behind the heater face to be widened about 2" in each horizontal direction, and the mounting tabs and support brackets be moved to accommodate, so this modification is not being pursued at this time.

7. Wheels – Investigate increasing diameter of wheels and converting two of the swivel casters to non-swivel casters.
    a. Check if swivel casters can be locked (pinned) to prevent swiveling.
    b. Non-swivel casters can be at front, back, or one side.

8. Steel load tests – All but the last of the above tests are to be conducted with a water cooled plate calorimeter so that the heat transfer rate can be directly measured and compared. When the final aggregate of modifications is determined, the heating time with the steel load bundle will be measured.

If the modifications were successful, the remaining three DFI carts would need to be modified. GTI assumed that the local contractor for REP would make the modifications on site or locally to REP.

The gas industry partnership Utilization Technology Development Company (UTD) agreed to reallocate a portion of its funding from a non-ferrous DFI project to this project so that a better understanding of the effects of DFI furnace parameters being studied above for ferrous heating would lead to improved applications of DFI in non-ferrous industries.

Cart Modifications and Testing

Piping and structural details were sketched out for the above tests and modifications. Appropriate components were procured for steps 0, 3, 4, 5, and 6. The DFI cart was positioned at a location just outside GTI's Combustion Laboratory, where an existing natural gas supply line is located. A compressed air supply line was added alongside the natural gas line, and hoses were added to the ends of these lines for the cart. An air injection manifold was assembled for step 5.

Work began with step 0 by placing a 12" tall water-cooled plate in front of the burner head (see Figure 50). The plate is the same one that was used in the laboratory DFI furnace at GTI for the flat load calorimetric tests. Instrumentation was added to measure the water temperature in and out of the plate and water flow rate. This allows the heat transfer rate to be determined. Insulation 4 inches thick was added to a 48" wide section of the back of the plate so that only heat impinging the front of the plate is observed. Digital manometers were added to the orifice meters on the main gas and air lines to set their flow rates.

A few baseline tests (step 0) were conducted with the load plate 2" away from the burner head and lined up with the bottom of the burner head. This distance was typical of that used during the field test. Tests with increased air-fuel ratio and increased firing rate were conducted next (step 2) since it was simpler to change these parameters than to adjust the load position. The compressed air capacity of GTI's combustion lab was exceeded on some tests, so the remainder of these tests were deferred until a large compressor could be rented in conjunction with another project at GTI.

Figure 50. Portable DFI Heating Cart Undergoing Improvement Testing at GTI

For step 1, the load was moved further away from the burner head at the normal elevation, and was moved vertically upward at the normal distance. Tests were conducted at the standard firing rate at each load position.

Brackets were added to the sides of the burner head so that channel could be attached to the top of the burner head extending above the load. Fiberboard insulation was inserted between these channels to "shroud" the flame to limit buoyancy (step 3). Tests were conducted at the standard firing rate with boards extending 12" and 24" out from the edge of the burner head, and with a 12" board starting at 2" and 4" away from the burner head, leaving a gap for air entrainment.

Step 4 required permanent modifications to the DFI cart, so work continued with step 5. An air injection (secondary air) manifold was assembled from copper tubing and brass compression fittings, with thick-walled stainless steel tubing used for nozzles. This designed allowed for rearrangement of the manifold and capping off of unneeded nozzles. An unregulated line was added to the air flow piping on the cart to supply the manifold. The manifold was placed behind the DFI nozzles such that there was a secondary air nozzle in between all but the outer most DFI nozzles. Tests were conducted with two different air supply pressures for manifold. Some improvement in heat transfer was seen, but in operation, despite being behind the DFI nozzles, the manifold was subjected to excessive heat. Several of the brass fittings melted, and eventually the copper tubing began to melt.

The DFI cart was piped such that all four pilots on the burner head were operated together. For step 4, the supply piping for the pilots was modified, with a shut-off valve installed upstream of each pilot. The piping changes required that the pilots be retuned (gas and air flow rates adjusted) for different modes of operation. Tests were conducted with two pilots operating and, after ignition of the main DFI nozzles, no pilots operating. Two pilots proved sufficient to ignite the main DFI nozzles, so tests for subsequent steps were conducted with two pilots operating instead of the original four.

For step 6, the arrangement of nozzles was converted from a flattened oval shape to a shorter, rectangular shape, more in line with the load shape. The top two rows of nozzles were removed to shorten the height, and nozzles were added to the corners of the array to create a rectangle. With this array shape, two of the pilots were no longer effectively positioned, so operation with just the two other pilots was appropriately justified. Tests were conducted with the new DFI nozzle array shape with various levels of gas and air to the DFI nozzles, a combination of steps 6 and 2. Heat transfer results were not improved compared to the baseline in step 0 and the firing rate changes in step 2, though less gas was being used due to the overall reduction in the number of nozzles from 62 to 59.

A new secondary air injection manifold was fabricated from stainless steel pipe and nozzles salvaged from the brass and copper manifold. This manifold was installed within the new DFI nozzle array from the previous step. Tests were conducted with three different air supply pressures for manifold and with various levels of gas and air to the DFI nozzles, a combination of steps 5 and 2. Heat transfer results were the best so far and showed a significant improvement, and the flame was less buoyant (more directed toward the load).

Analysis of the data ultimately showed a 66% improvement in the heat transfer rate with the modifications described in the last set of tests compared to baseline tests. This result was slightly less than the 74% goal and not enough to guarantee success in a field trial, consequently steps 7 and 8 were not attempted, and no further tests were planned.

Non-Task Related

The gas industry partnership Utilization Technology Development Company (UTD) provided coordinated funding to extend the DFI technology into non-ferrous applications, including aluminum and copper. GTI anticipated multiple licensees for DFI technology. GTI had multiple companies interested in this technology. Granco-Clark was the commercialization partner for the non-ferrous (Aluminum) project.

Bricmont prepared a 28 page business plan preliminary to negotiating a license for Direct Flame Impingement (contingent on a successful field trial). The sales projections and commercial goals for rapid heating applications are shown in Table 7 and Table 8.

Table 7. Commercial Goals for In-Line Heater Application

IN-LINE ANNEALER			
	2007-2010	2011-2015	2016-2020
No. Units Sold	2	3	4
Sales Value, MM $	1.0	1.5	2.0
MM Tons Steel	1.2	1.8	2.4
New/Retrofit	2/0	3/0	4/0
Competing Technology	Electric	Electric	Electric

Table 8. Commercial Goals for In-Line Temperature Restoration Application

IN-LINE TEMPERATURE RESTORATION			
	2007-2010	2011-2015	2016-2020
No. Units Sold	2	3	6
Sales Value, MM $	1.2	1.8	5.6
MM Tons Steel	1.6	2.4	4.8
New/Retrofit	2	1	2/4
Competing Technology	Electric	Electric	Electric

As a result of a gas industry sponsored Customer Project Development program to help develop more effective ways to utilize natural gas, GTI conducted a site visit at a domestic pipe mill who had expressed an interest in replacing an induction preheater for a gas skelp furnace with a gas-fired DFI skelp preheater. GTI prepared a heating analysis and proposed to the gas industry to develop furnace bid specifications and request bids for construction and installation.

Conclusions and Recommendations

CFD modeling and the subsequent physical testing of Direct Flame Impingement at GTI's laboratory have shown a potential increase in thermal efficiency in the range of **10 to 40 percentage points** over that of the traditional radiative form of reheating ferrous and non-ferrous stock for processing into rounds and flat shapes. The level of improvement within this range is highly contingent on where in the heating process that DFI would be instituted. There are several key applications and a number of niche applications. Examples of key applications would be: employing DFI as a preheater of billets or slabs upstream of an existing typical reheat furnace which would yield one subset of performance metrics; employing DFI as a temperature-boosting technique of billets or slabs downstream of a typical reheat furnace will yield an entirely different subset of performance metrics; thirdly, replacing an induction heating furnace that heats round or square billets with a DFI equipped furnace will result in another unique set of performance metrics; and finally the preheating of strip substrate upstream of the annealing furnace section of hot dip galvanizing lines. Several niche applications with different subsets of performance metrics that include transfer bar edge-heating (e.g., Wierton Steel – other DOE Project); temperature-retention of coiled transfer bars at coil box-equipped mill operations; annealing of bundled bars that have been cold-sheared such as was examined and field tested at Republic Engineered Products.

GTI's calculations have shown that DFI heating has the potential to improve the overall thermal efficiency of key applications and niche applications that would lead to reduced processing costs (fuel consumption or electrical usage); no degradation of product quality; and emissions reductions (NO_x, CO_2) that that are the consequence of the heating process itself (lower overall or average flame temperature) and additionally that resulting from reduced fuel or electrical consumption.

Over the course of this project a substantial database has been established particularly for double-sided and single-sided heating of steel slabs; for the circumferential heating of round or square steel billets; and for several niche applications such as replacement of an induction furnace with an equivalent DFI furnace. The domestic steel companies that of the original project partners, and other companies that required heating of steel for their product lines included: ISG, Nucor, Mittal Steel (now ArcelorMittal), Chicago Heights Steel, and a domestic pipe mill. Included in the database are various preliminary shapes and sizes of furnaces; limited estimated capital costs; and emission reductions that would be achievable. In an other-funded project, a standard series of DFI furnace packages was proposed for joint-development with a furnace manufacturer, ONEX, Inc., to promote/propose DFI technology for the ferrous metals market as opportunities were identified. For example, conceptual designs were carried out for replacement of induction heating furnaces for two product shapes: Round Products for billets from 3 inches to 12 inches in diameter, and Flat Products for strip and skelp from 3.75 inches wide to 12.75 inches wide and 2 inches to 6 inches thick.

Extensive modeling and physical testing of DFI in the non-ferrous UTD funded project in collaboration with Granco Clark, a first tier aluminum extrusion furnace manufacturer, were also carried out that established a database for non-ferrous applications. The efforts during the cart modification testing led to a more comprehensive understanding of the effects of DFI furnace parameters, which should lead to improved applications of DFI in ferrous and non-ferrous industries.

Appendix A – Inventions

A Patent Application (US 2006/01990119 A1) for an Internally Recuperated DFI Nozzle Concept has been filed. GTI is currently continuing to clarify some of the claims to the U.S. Patent and Trademark Office.

Appendix B – Publications/Presentations

A project status meeting was held at the U.S. DOE headquarters in Washington, DC, on March 12, 2003. A representative of North American Manufacturing Company was also in attendance, representatives from the Timken Company and Geneva Steel were present via conference call, and a representative from Bethlehem Steel met later with U.S. DOE. The results of the modeling, laboratory DFI furnace design, technology comparison matrix, and current schedule at that time were presented.

An article titled “Hybrid Systems Make the Most of Both Gas and Electric Energy Sources” was published in the Summer 2003 issue of Gas Technology. The article contained the sidebar “DFI Plus Induction Can Heat Steel Billets More Efficiently.”

A presentation on the DFI project was made at the GTI SMP Fall Meeting on October 22, 2003.

A presentation regarding the DFI project was made to members of the Association of Iron & Steel Technology's Energy and Utilities Operating Committee that visited GTI on June 22, 2004.

A project summary was presented at the Portfolio Review Meeting for the U.S. DOE IOF Steel Planning Unit on September 1, 2004. In early October 2004, GTI submitted a reply to a list of comments from the panel who reviewed the GTI project update presentation.

A project update presentation and a laboratory DFI furnace demonstration was given to the U.S. DOE technical monitor during a visit to GTI on October 18, 2004.

A poster presentation titled “Direct Flame Impingement for the Efficient and Rapid Heating of Metal Shapes” was displayed at the 2004 International Gas Research Conference (IGRC), which was held November 1-4 at the Vancouver Convention and Exhibition Center in Vancouver, B.C., Canada.

A paper titled "Direct Flame Impingement for the Efficient and Rapid Heating of Ferrous and Nonferrous Shapes" was presented at the Process Heating/Reheating session at the Materials Science & Technology 2005 Conference and Exhibition on September 28, 2005, in Pittsburgh, PA.

A paper titled "Mathematical Modeling of Direct Flame Impingement Heat Transfer" is being prepared for the 2006 ASME International Mechanical Engineering Congress and Exposition to be held November 5-10, 2006, in Chicago, Illinois.

A paper titled "Mathematical Modeling of Direct Flame Impingement Heat Transfer" was presented at the 2006 ASME International Mechanical Engineering Congress and Exposition, which was held November 5-10, 2006, in Chicago, Illinois.