THERMAL IMAGING CONTROL OF FURNACES AND COMBUSTORS

Final Technical Report

for

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FINAL TECHNICAL REPORT

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EXECUTIVE SUMMARY

The objective of this project is to demonstrate and bring to commercial readiness a near-infrared thermal imaging control system for high temperature furnaces and combustors. The thermal imaging control system, including hardware, signal processing, and control software, is designed to be rugged, self-calibrating, easy to install, and relatively transparent to the furnace operator.

High-temperature, natural gas-fired furnaces, especially those fired with preheated air, produce large quantities of NO_x[1] per ton of material processed. Regulations on emissions from industrial furnaces are becoming increasingly more stringent. In addition, competition is forcing operators to make their furnaces more productive and/or efficient. Switching from preheated air to industrial oxygen can increase efficiency but does not necessarily reduce NO_x due to NO_x formation from nitrogen present in the industrial oxygen, in the natural gas, in the air trapped within the raw materials, and in air that infiltrates into the furnace through cracks or discontinuities in the furnace's shell. Use of cryogenic oxygen (with almost no nitrogen) does help reduce NO_x compared to industrial oxygen (with 5%-10% nitrogen), but this oxygen is significantly more costly.

A three-year project was conducted to develop and demonstrate the thermal imaging system for the control of furnaces and combustors. The approach uses intensity data from two near-infrared wavelengths to calculate a temperature 'map' of the image. Software work continued throughout the project to acquire intensity images, to determine temperature maps, and to determine various values of interest. The values of interest include temperatures of selected points, average temperature of selected areas, historical data, and data storage.

The concept used in this project, to provide improved control to high temperature furnaces using a near-IR thermal imaging control system, was developed by GTI and UIC approximately 5 years ago. At that time, the hardware needed to commercialize the technology was neither reliable nor low enough in cost.

Initial stages of the Thermal Imaging sensor hardware development were conducted by testing on a laboratory electric furnace. Filters in early tests were changed manually. Later, a variable LCD filter was to use to establish the optimum wavelengths for temperature determination. The industrial prototype version utilizes a CCD camera and a mechanical filter wheel assembly. Also, a water-cooled periscope was installed for furnace measurements. The complete system was then tested on a GTI heat treat furnace. A state-of-the-art control system was installed and accepted input for control from the thermal imaging system. A final test is planned on an industrial furnace.

Many improvements have recently been made in the speed and reliability of process computers. Thermal imaging systems, both visible and infrared, have undergone a similar order of magnitude increase in reliability. The thermal imaging control system uses a periscope, the complete thermal imaging system, a process control computer, and a series of software codes

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[1] NO_x is the sum of NO plus NO_2. For most high-temperature combustion processes, NO_x is 90% or more NO. For regulatory purposes, emissions reporting on a weight basis assumes all NO_x to be NO_2.

including digital signal processing, control algorithms, field set point input, and output signals to the main furnace controller. All of the hardware is now in place to commercialize this technology. Now, this project is focusing on combining this available hardware and developing the software to operate the control system.

Several previous efforts have moved in the same direction as the one used in this project. Several companies market thermal imaging systems for high temperature furnaces. Some of these systems include signal-processing software to generate false-color temperature maps of the full furnace. However, none of these systems has been employed to provide thermal field data in real time to assist the main furnace controller. To develop a low-cost instrument, researchers on this project worked with available technology to the full extent possible and focused on developing the needed software and links to interact with a wide range of commercial control systems used on operating furnaces.

The thermal imaging system has been demonstrated on the laboratory and pilot scales. Not only has thermal data for all furnace and load surfaces been collected, but the data was converted by GTI-developed algorithms to an average temperature in OPC format that was used to control a heat treating furnace. Temperatures and temperature maps have been obtained in near-real time for temperatures of 500°C and above. A complete system consisting of a water-cooled periscope, filter wheel with 750 and 800 nm filters, shutter, CCD camera, frame grabber card, and software for analysis and presentation was assembled and implemented. Tests have been conducted on a laboratory electric furnace and a heat treat furnace with two air-gas fired tubes at GTI. A proposal was submitted with partner IEM Corp. to NYSERDA for funding to develop the technology into a working industrial tool. This project was approved by NYSERDA, and work is expected to begin in March or April 2003.

The software needed to collect intensity data, determine temperature maps, and to derive average temperature data for selected points and fields with conversion to input data to a PLC controller (in OPC format) has been improved throughout the project. The C++ code determines the intensity and temperature maps and allows determination of temperatures at selected points or the average temperature in a selected area. The software also allows storage of data and review of historical information. Temperature data from operator selected points or areas is averaged by GTI-developed algorithms and output in industry-standard OPC format for control of furnace inputs such as fuel rate and air to fuel ratio.

An original project strategy was to input the thermal imaging system data into a set of control system algorithms that would give secondary control instructions to burners (air-fuel ratios, etc.) for tuning control. This was intended to not interfere with primary furnace control. Full process control was never the goal of this project. The original strategy was found to be too complex and did not adequately address the capabilities of modern multiple input-multiple output (MIMO) process controllers to operate multiple control loops with a wide range of inputs. The power of the thermal imaging control system under development is to provide 'field' temperature data of furnace walls and loads in essentially real time. These data can be processed by 'thermal imaging control' algorithms to convert data into a format usable by already available PLC control logic control loops. This was accomplished in this project.

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INTRODUCTION

Manufacturing industries consume 15 quadrillion Btu's of primary energy to produce heat and power, or about 75 percent of the total energy consumed by U.S. industry (1988 values). Effective use of all energy resources is a critical issue for many industries, especially the energy-intensive process industries. In these industries, energy is a substantial share of production costs and can limit industrial ability to compete in domestic and global markets. A technology that can improve energy efficiency, while also reducing emissions per unit of energy consumed would be of significant benefit to U.S. industry, particularly the high temperature material processing industries. High temperature materials processing furnaces operated by the steel (heating, melting, forging, brazing, sintering), stone, clay, glass, aluminum, and chemical industries consume more than 4 quadrillion Btus of energy per year. These processes often suffer from low efficiency (10-50 %) and, because of high temperatures involved, produce high levels of NO_x.

High-temperature, natural gas-fired furnaces, especially those fired with preheated air, produce large quantities of NO_x[2] per ton of material processed. Regulations on emissions from industrial furnaces are becoming increasingly more stringent. In addition, competition is forcing operators to make their furnaces more productive and/or efficient. Switching from preheated air to industrial oxygen can increase efficiency but does not necessarily reduce NO_x due to NO_x formation from nitrogen present in the industrial oxygen, in the natural gas, in the air trapped within the raw materials, and in air that infiltrates into the furnace through cracks or discontinuities in the furnace's shell. Use of cryogenic oxygen (with almost no nitrogen) does help reduce NO_x compared to industrial oxygen (with 5%-10% nitrogen), but this oxygen is significantly more costly.

Improved furnace and combustor control offers the potential for significant energy savings and emissions reductions, especially NO_x. These savings can be achieved with on-line sensors monitoring furnace performance. Thermal imaging of the load and inside furnace walls can provide data to optimize combustion system performance under all furnace conditions.

Overall Project Objective

The objective of this project is to demonstrate and bring to commercial readiness a near-infrared thermal imaging control system for high temperature furnaces and combustors. The thermal imaging control system, including hardware, signal processing, and control software, is designed to be rugged, easy to install, and relatively transparent to the furnace operator.

The project is being co-funded by the Gas Research Institute (GRI). GRI has a strong on-going concern with improving industrial process efficiencies and reducing air borne emissions.

Brief Description of Project

The project to develop and demonstrate the near-infrared thermal imaging control system is being co-funded by the Gas Research Institute (GRI). GRI has a strong on-going concern with

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[2] NO_x is the sum of NO plus NO_2. For most high-temperature combustion processes, NO_x is 90% or more NO. For regulatory purposes, emissions reporting on a weight basis assumes all NO_x to be NO_2.

improving industrial process efficiencies and reducing air borne emissions. A three-Phase, 36-month project was proposed, and work was carried out in a thirty-nine months. Work in each Phase included:

- Phase I – Control System Development (12 months) – review of furnace control systems and an industry needs assessment, followed by thermal imaging control system input, control algorithm, and output software development,

- Phase II – Bench-Scale Development (12 months) – assembly of a thermal imaging control system, followed by testing, evaluation, and modification using two GTI laboratory furnaces,

- Phase III – Field Demonstration (12 months) – assembly of field testing thermal imaging systems, followed by testing on host industrial steel and glass melting furnaces.

A strong project team was assembled to bring this technology from concept to readiness for commercialization. This team possesses a unique combination of industrial manufacturing experience, commercial burner and combustion controls manufacturing and installation experience, and research and development experience on both the applied and the theoretical level.

- GTI has many years experience in combustion research and development, industrial testing, and project team management.
- UIC operates the Reaction Flow Laboratory and is a leader in non-intrusive furnace measurements and controls.
- Owens Brockway is a leading manufacturer in the glass industry. Their partnership shows strong industry interest in this technology and will keep the project team focused on the needs of industry.
- Combustion Tec, Inc., a division of Eclipse Combustion, is a leading producer of burners and furnace and combustion control systems.

Rationale for Undertaking the Project

The near-infrared thermal imaging control system provides a refinement in the control used on high-temperature industrial furnaces. This refinement provides a number of performance improvements both in energy use and in air-borne CO, CO_2, and NO_x emissions reduction. Current furnace control systems use 'discrete' control in which point measurement set points are matched by controlling furnace independent inputs. This technique can handle global process control but is not capable of controlling the overall furnace and the hot spots and instabilities that occur during operation. The innovative thermal imaging control system provides 'field' control. Field control works in conjunction with traditional controllers to provide adjustments to mitigate hot spots and instabilities and to optimize combustion performance. Field control consists not of matching set points of a limited number of measurements, but of minimizing the difference between a set of field set points and actual field measurements. This system is ideally suited to tuning the combustion process and improving combustion performance. A number of distinct benefits are realized by operators of high-temperature furnaces. These benefits include:

- decreased energy use by 5 percent,
- reduction in CO and CO_2 production by 5 percent,
- reduction in NO_x production by 30 percent,
- elimination of hot spots and instabilities providing longer furnace life and higher product quality,
- Improvements with no major process or equipment changes and at low cost,
- Near-infrared thermal imaging control system is essentially transparent to the operator,
- Thermal imaging system is self-calibrating and adaptable to many types of furnaces,
- Technology is fail-safe and readily acceptable because system assists, but does not override or replace, existing furnace control.

This technology offers benefits to many different energy-intensive industries. Review of the DOE OIT industries of the future found applications in furnaces operated by 5 of these industries. Team member Owens Brockway Glass Containers (glass) has expressed a strong interest in pursuing development of this technology and demonstrating the wide range of interest in this advanced control system within different industries. Among the many examples of thermal imaging control systems for furnaces and combustors, seven examples have been selected from the furnaces operated by the DOE industries of the future.

The energy savings and reduction in air-borne emissions anticipated with application of near-IR thermal imaging control are based on real industrial experience. Since furnaces are typically controlled by adjusting input parameters to match output set points, no adjustments are made to fine tune the combustion process inside the furnace. The thermal imaging control system minimizes the difference between field temperature set points and a set of up to 1 million temperature readings. Optimizing combustion processes with multiple burners provides heat at desired locations inside the furnace and has been shown to allow a decrease of at least 5 percent in the total fuel usage. Emissions of CO and CO_2 will automatically decrease 5 percent to match the decrease in energy input. NOx is dependent on temperature. Tuning burners has been shown to decrease NO_x emissions by 30 percent. The same level of NO_x decrease is assumed as a reasonable estimate of the NO_x decrease resulting from the elimination of hot spots by the thermal imaging control system.

Figure 1 shows the expected savings in fuel energy and decrease in air-borne emissions with use of the thermal imaging control system. Seven types of high temperature furnaces have been identified in five of the DOE industries of the future. This list is not exhaustive, but is meant to give an indication of the large energy savings and emissions reducing benefits from application of this technology and the flexibility of the technology.

The high temperature materials processing industry consumes 3.5 quadrillion Btu's per year. The seven identified applications areas account for 0.4 quads per year, just over 10 percent of the total. Other applications of thermal imaging control systems have yet to be identified. For the seven identified industrial furnace applications (see Figure 3), with a conservatively estimated market penetration of 20 percent of all U.S. furnaces, a total annual fuel savings of 4×10^{12} Btu per year is anticipated. Along with the savings in fuel for heating, large reductions are realized in air-borne emissions. Total reductions are over 200,000 tons per year of CO_2, over 50 tons per year of CO, and over 3,200 tons per year of NO_x.

Figure 1. ENERGY SAVINGS AND EMISSIONS REDUCTIONS WITH THERMAL IMAGING CONTROL SYSTEM

| Industry | Furnace or Combustor | Production, 10^6 ton/y | Total Fuel, 10^{12} Btu/y | Reductions, 20% of market | | | |
				Fuel, 10^{12} Btu/y	CO_2, Ton/y	CO, ton/y	NO_x, ton/y
Steel	Reheating	90	144	1.44	83,600	13.6	2,160
Steel	Continuous Annealing	22	19.8	0.2	11,600	1	99
Steel	Batch Annealing	8	8	0.08	4,600	0.4	12
Aluminum	Remelting	3.5	7	0.07	4,100	0.2	4
Glass	Melting	30	120	1.2	69,700	22.4	600
Chemicals	Ethylene Cracking	6	50.4	0.5	29,000	1.2	27
Metal Casting	Heat Treating	60	60	0.6	34,800	12	360
	Total		410	4.1	237,400	50.8	3.262

* Energy savings of 5%. Reductions in CO_2, CO, and NO_x emissions of 5, 5, and 30 percent, respectively.

Background

In this project, a near-infrared thermal imaging control system will be developed and demonstrated for high temperature industrial furnaces. In the technology, an advanced thermal imaging system using multiple infrared wavelengths, is combined with a water-cooled periscope probe to obtain fast, accurate, high-temperature mapping of the full field of the combustion space during operation. The field includes all surfaces of the furnaces and combustors and the exterior surfaces of loads. A false-color temperature chart of the full combustion space is developed. The system measures the intensity of 0.5 to 1 million pixels, calculates temperatures, and compares the results with field temperature set points. Control algorithms minimize differences between field temperature set points and measured field temperatures and sends output signals to the main furnace controller to assist with furnace combustion control. A unique feature of this technology is the use of 'field control' instead of traditional 'discrete control' in which the controller works to match set point values of a limited number of measurement devices (flows, temperatures, pressures, etc.). Important benefits of this technology include:

- Increased energy efficiency resulting in fuel savings of up to 5 percent, or 4×10^{12} Btu/year (fuel energy savings based on 20% market penetration for seven identified applications with actual applications and savings expected to be much higher),
- Decreased emissions of CO and CO_2 by up to 5 percent and NO_x by up to 30 percent,
- Longer furnace life because of elimination of refractory hot spots and furnace instabilities,
- Improvements with no major process or equipment changes and at low cost,
- Near-infrared thermal imaging control system is essentially transparent to the operator,
- Thermal imaging system is self-calibrating and adaptable to many types of furnaces,
- Technology is fail-safe and readily acceptable because system assists, but does not override or replace, existing furnace control.

The concept used in this project, to provide improved control to high temperature furnaces using a near-IR thermal imaging control system, was developed by GTI and UIC approximately 5 years ago. At that time, the hardware needed to commercialize the technology was neither reliable not low enough in cost. Many improvements have recently been made in the speed and reliability of process computers. Thermal imaging systems, both visible and infrared, have undergone a similar order of magnitude increase in reliability. The thermal imaging control system uses a periscope, the complete thermal imaging system, a process control computer, and a series of software codes including digital signal processing, control algorithms, field set point input, and output signals to the main furnace controller. All of the hardware is now in place to commercialize this technology. Now, this project is focusing on combining this available hardware and developing the software to operate the control system.

Several previous efforts have moved in the same direction as the one used in this project. Several companies market thermal imaging systems for high temperature furnaces. Some of these systems include signal-processing software to generate false-color temperature maps of the full furnace. However, none of these systems has been employed to provide a field control system to assist the main furnace controller. This project will work with available technology to the full extent possible and focus on developing the needed software and links with the control systems for operating furnaces.

Work was conducted by Northwestern University and BIRL under Gas Research Institute sponsorship to develop a thermal imaging control system. The project focused on controlling a furnace to provide a uniform temperature profile in a moving steel slab. A working control system was developed and demonstrated successfully on a pilot scale furnace. No commercial products came from this project, possibly because work focused on developing a full control system based on thermal imaging instead of a system to assist the main furnace controller. The project team feels a control approach providing added control will be much more attractive initially to end-users and should have a much shorter road to commercial success.

Every high-temperature industrial furnace operates with some type of control. The near-infrared thermal imaging control technology provides a means to improve furnace control, decrease energy usage, and reduce emissions, all at relatively low cost and with very little risk to the end user. The cost is low because existing periscope and thermal imaging hardware is used for field temperature measurements, computer costs have dropped dramatically, and the main furnace controlled is assisted, not replaced. Industry would generally be reluctant to replace

existing, working control systems with an entirely new, unproven technology. This technology addresses this concern by working in conjunction with existing furnace controllers, without overriding or replacing them.

Once the thermal imaging control system is demonstrated, the project team believes the low cost, simple installation, and lack of interference with present furnace operation and control will lead to rapid industrial adoption. An estimated market penetration of 20 percent is predicted within 5 years in all seven-furnace application areas identified. Other furnace applications are also anticipated.

Projected Benefits to Gas Consumers

Natural gas is the fuel of choice in many industrial processes. Efforts to improve technologies, reduce energy costs, and save emissions put pressure of industry to switch to more costly furls, such as electricity. The thermal imaging control system enables furnaces and combustors to be operated more efficiently while generating lower levels of NO_x, CO, and CO_2. Expected benefits for a number of large industrial users of natural gas were summarized in Figure 1. Overall, the thermal imaging control system will help the natural gas industry to retain industrial furnace load and to help natural gas to remain the fuel of choice for most industrial processes

TECHNICAL SECTION

Work Planned

The program to develop the near infrared thermal imaging control system for high temperature furnaces (>1600°F) and combustors was carried our in three Phases including eight tasks over a 39-month period. The following describes the work effort in detail proposed by the project team.

Phase I. Control System Development

The objectives of this project Phase were to better define present high temperature furnace control systems, to evaluate commercially available near-infrared thermal imaging equipment and analysis software, and to develop the input, computational, and output methodology for combustion control using the thermal imaging information.

Task 1. System Definition and Industry Needs

High temperature industrial furnace control systems vary from manual to sophisticated PID computer control. The project team would survey furnace operators in the steel, glass, metal casting, and chemicals industries to learn the primary control systems in current operation. Survey results will determine the type of thermal imaging control system inputs, control algorithms, and outputs to be prepared in Task 2. The thermal imaging control system was to be designed to work in conjunction with current control systems and not as a stand alone furnace controller.

Several companies sell thermal imaging hardware and software. Detailed information would be collected on CCD sensors, optical and electronic sensors, and data processing software. Commercially available equipment and software was to be used as much as possible. The following materials were selected for evaluation in later Tasks:

- Three CCD sensors .providing high resolution near-infrared radiation images in the range of 700+10, 750+10, and 800+10 nm. Sensors must be sensitive enough to respond to a 1600°F surface with emissivity of 0.1 at a resolution of 0.5 million pixels.
- One or two filters capable of filtering out >99 percent of unwanted radiation.
- One software to digitize the CCD image.

Task 2. Control System Development

The algorithms, control code, input format, and output signal information for the near-IR thermal imaging control system would be developed in this Task. Existing thermal imaging software will be used to interpret the CCD sensor signal, provide furnace data, and generate false-color temperature maps. Together with information on current control systems, the project team would develop a thermal imaging control system with these characteristics:

- Flexible input programming to handle furnace shapes and dimensions, number and type of burners, flame shapes, oxy-gas and air-gas firing, different types of refractory and loads, and other furnace characteristics,
- Flexible controller programming to allow the operator to specify the desired temperature and thermal characteristics of the furnace. Unlike traditional controller of a single sensor, the thermal imaging control system must balance the desired thermal conditions of the full furnace to achieve the best possible control,
- Interface with the primary furnace control system to exert secondary control on independent variables of concern including firing rate, oxidant/fuel ratio, etc.,
- Feedback control to evaluate effects of control changes to independent variables. The thermal imaging control system must reach an optimum match to desired furnace conditions without matching all points,
- Self-calibration with checks provided by calibrated thermocouples positioned at known locations.

Phase II. Bench-Scale Development

The objective of this project Phase was to evaluate the proposed thermal imaging control system hardware and to evaluate and modify the control system software. Testing was to be conducted on two, existing laboratory bench-scale furnaces: a flexible, 3000°F furnace and a specially instrumented heat treating furnace with four tubes.

Task 3. Bench-Scale System Assembly

A near-IR thermal imaging control system would be assembled using a Combustion Tec 45° right-angle water-cooled periscope. A CCD camera thermal imaging system, from Land Infrared or other manufacturer, would send field signals (mapping the combustion space) to a

beam splitter. One beam was to be used to optically focus the system. The other beam was to be sent to a computer containing data processing software. The digitally processed field signal would be sent to a control box assembled by the process team. False-color temperature maps would be stored and displayed on a monitor to enable monitoring and modification of the control system hardware and software.

The control box would incorporate the control algorithms and feedback controls developed in Phase I and be flexible enough to connect with the primary controls for two laboratory furnaces. An open architecture will allow modifications during testing. The periscope will be positioned in the corner of each furnace to provide the widest possible combustion space view for obtaining field data. Because near-infrared wavelengths of 700, 750, and/or 800 nm will be used to observe the flame, walls, and load, substantially free from glowing combustion gases distortions, optical filters and the CCD sensor may need to be changed.

Task 4. Bench-Scale Evaluation

Testing was to be conducted on two GTI combustion laboratory furnaces: a heat treating furnace and a flexible, high temperature furnace capable of operation up to 3000°F. Figure 2 shows simplified drawings of these furnaces with inputs, outputs, and heated surfaces. The high temperature furnace has a combustion space 15-inch square and 7 feet long. The furnace is heavily instrumented with thermocouples, total and radiative heat flux probes, on-line exhaust gas compositions, and multiple gas and oxidant flows to the burner. The heat-treating furnace is a stand Super Allcase furnace modified to include additional process measurement equipment.
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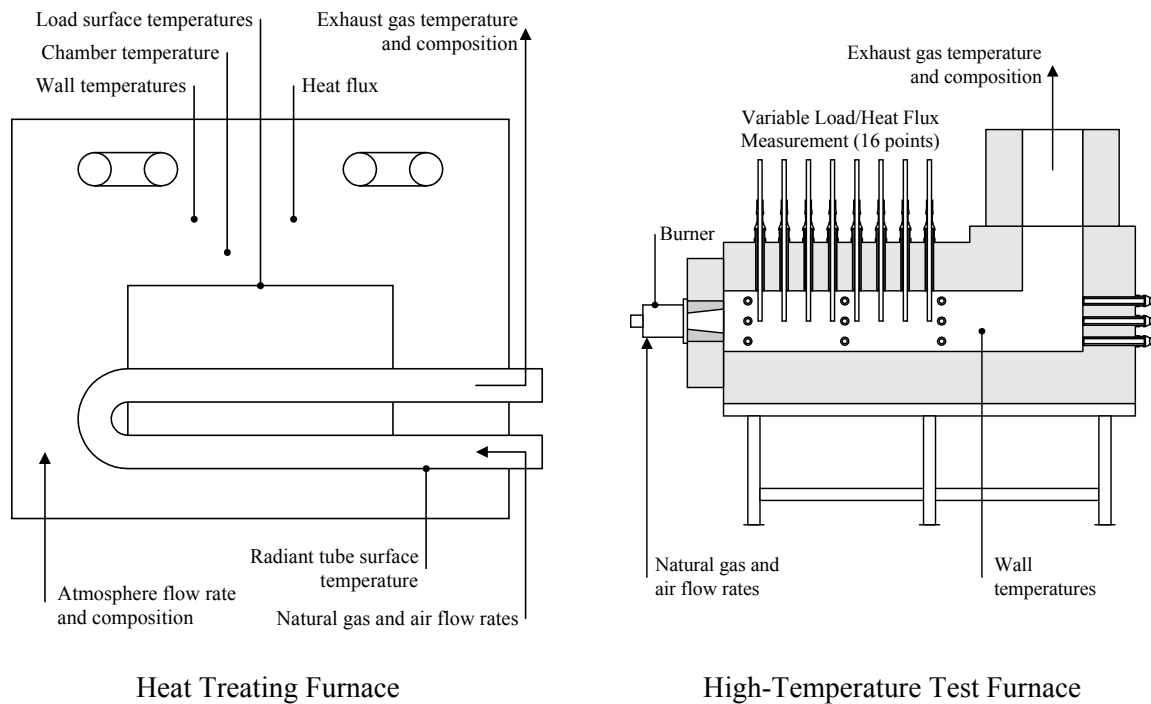Heat Treating Furnace   High-Temperature Test Furnace

Figure 2. BENCH-SCALE FURNACES FOR THERMAL IMAGING CONTROL SYSTEM DEVELOPMENT

A series of tests were to be conducted on both furnaces to adjust the thermal imaging control system calibration and to modify the control scheme as needed. The measured and controlled variables were to include:

Measured variables	• Wall, load, flame, and radiant tube temperatures by optical pyrometers, thermocouples, and thermal image mapping • Wall and load surface characteristics • Furnace gas compositions • Flame size and shape from thermal imaging
Controlled variables	• Burner air/fuel ratio for all burners • Firing rate for all burners

The thermal imaging control system will provide the most benefit on large, multi-burner furnaces. Testing was to be conducted first on the single-burner furnace to adjust the control system and complete calibration. Then the system was to be installed on the heat-treating furnace and used to control all four radiant tubes to improve the furnace temperature uniformity. Results from this Task will be used in Phase III to design and build the field test system for thermal imagining control evaluation on industrial furnaces.

Task 5. Commercialization Plan Outline

The near-infrared thermal imaging control technology offers important process advantages to many industries operating high temperature furnaces including steel, glass, metal casting, aluminum, chemicals, refractory, cement, etc. The wide range of furnace types, sizes, loads, and control methods requires this technology to be extremely flexible and adaptable. The initial product to be developed is a control system to work along with the many primary control systems currently employed. This will provide the widest possible application of the thermal imaging control technology.

The project team was to begin work in this Task with a major combustion equipment and controls manufacturer to develop a commercial product. The control system components will be defined and standardized, and markets will be listed. An initial plan for approaching end use customers in these markets and for marketing and manufacturing the technology was to be outlined. A summary of technology benefits and a cost/benefit analysis will be prepared as a marketing tool for discussions for potential customers. Combustion Tec, a division of Eclipse Combustion, is a project team member. As a major world producer of burners, combustion systems, and furnace control systems, Eclipse is ideally suited to conduct market surveys and to bring this technology to the market.

Phase III. Field Demonstration

The objective of this project Phase was to demonstrate the complete thermal imaging control system on one or two industrial furnaces. Owens-Brockway was to provide an air-gas or oxy-gas fired container glass furnace as a commercial host site. The steel partner, such as Acme or Bethlehem Steel, would provide a steel reheating furnace as a host site for commercial testing.

Task 6. Field System Assembly

The project team was to identify two industrial furnaces, one making container glass and one reheating steel, for field demonstration of the near-IR thermal imaging control system. GTI and UIC were to work closely with Owens-Brockway and the steel producer to meet industrial needs to reduce hot spots, increase furnace stability, decrease emissions, and improve thermal efficiency (lowering fuel costs) while not interrupting furnace control and while being relatively transparent to the operator. Complete imaging and control systems were to be assembled for each furnace. The systems would allow flexible definition of optimum furnace conditions, interface with furnace controls as a secondary controller, and modification during testing.

Task 7. Field Evaluation

A water-cooled periscope was to be installed in each host furnace at a position to provide the best overall view of the full combustion space including walls, load, and flames. The full field will be observed through near-IR filters and processed by a CCD sensor. This data will be processed in with a dedicated computer and signal processing software. The digitally processed data will be sent to a project team-constructed control box that will interface directly with the host furnace primary controller(s). A series of tests was to be conducted to demonstrate the improved control capabilities of the near-IR thermal imaging control system on each furnace.

- Calibration of the system using calibrated thermocouples and optical pyrometers,
- Baseline furnace monitoring with no active control,
- Control as a secondary controller to the furnace primary control,
- Control system adjustments to optimize control and to improve operation of the system,
- Long-term operation with active secondary control at optimized control system settings.

Testing data would be collected throughout both parametric system modification tests and long-term testing. Comparisons were to be made between furnace operation and control with and without using the thermal imaging control system.

Task 8. Commercialization Plan

A final plan for the marketing of the thermal imaging control system would be developed, focusing initially on the target markets in the DOE industries of the future. The plan was to include a description of a commercial version of the control system, an outline to calculate cost-benefit analyses for each application, and a listing of energy efficiency and emissions reduction advantages.

Work Performed

Phase I

The first Phase of the project to develop the near infrared thermal imaging control system for high temperature furnaces (>1600°F) has been completed. The following describes the work effort and results from this Phase and the first 12 months of the project.

<u>Control System Development</u>

The objectives of this project Phase were to better define present high temperature furnace control systems, to evaluate commercially available near-infrared thermal imaging equipment and analysis software, and to develop the input, computational, and output methodology for combustion control using the thermal imaging information. These were accomplished by completing the following two tasks:

High temperature industrial furnace control systems vary from manual to sophisticated PID computer control.   The project team surveyed furnace operators in the steel, glass, metal casting, and chemicals industries to learn the primary control systems in current operation. The results determined that that following types of furnaces could be operated using thermal imaging control:

- Glass
- Steel reheat
- Process heaters
- Aluminum remelt
- Heat treating

The survey found the following manufacturers of thermal imaging systems for high temperature furnaces:

- Thermoteknix
- Mikron Instrument
- FLIR Systems
- Raytheon
- Land Infrared
- Ircon

The first three manufacturers use field images compared to the others that use only point images. All except Thermoteknix focus on acquisition of thermal images for visual review and manual control. Thermoteknix can use the data signal for processing and the data is generally more accurate. The general thermal imagining system capabilities of the manufacturers can be summarized as:

- Measurement of 1,000,000 points
- Scan rates of up to 30 times per second
- Maximum measured temperature of 4000°C
- Resolution of 1°C at high temperature
- Single near-IR wavelength used to minimize error and interference
- Used in a wide range of furnaces - kilns, glass tanks, steel reheat, heat treating, etc.
- Systems use either scanned or focal plain arrays
- Sensors can be installed through furnace walls
    - With provisions for external cooling

- - - With automated lens clearing
- Self-focusing with focal length of 1 m. to infinity with a standard 50 mm lens
- Measurement accuracy of $\pm$1% or $\pm$1°C
- Detector spatial resolution up to 750 x 500 pixels
- All points stored and available for processing
- Operating humidity of 10 to 95% non-condensing
- Operating temperature of 0 to 50°C

In order to utilize the thermal imaging technology, a sophisticated control system will be required. Manufacturers of advanced control systems for high temperature furnaces include:

- Foxboro
- Allen Bradley
- Honeywell
- Other control companies and control systems developed by furnace operators

THE CAPABILITIES OF THESES ADVANCED CONTROL SYSTEMS ARE:

- Multi-variant control
- Systems can handle over 500 control loops
- Flexible control loop design
  - PID and high level control options
  - Open architecture
  - Capability to accept new types of algorithms
- Text or object-oriented control systems
- Flexible, user-friendly interface software
- Sophisticated data processing software integral to control system with access to all process data

Open architecture is very important in a control system to work with thermal imaging system input because open architecture allows the controller to use the thermal imaging signal as a control input signal.

Two-Color Thermal Imaging Temperature Measurement (concept)

The Thermal Imaging System (TIS) consists of a specially designed lens system, controllable near infrared, narrow band filtering system, a CCD sensor/camera and computerized control and data acquisition system. The lens and filters can be mounted on a water-cooled periscope sold by team partner Combustion Tec, a division of Eclipse Combustion. The periscope is mounted in a corner of a furnace to allow viewing of the entire field of the combustion space. This system can collect field temperature signals on the complete furnace without physical movement of the imaging system or the periscope. Field temperature measurements are made with two filter wavelengths. These wavelengths are selected to provide a clear view, undistorted by visible light and by glowing combustion gases that radiate mainly at frequencies above 1000 nm. Temperature measurements are obtained by comparing the pixel

intensities at two distinct IR wavelengths, and then applying Planck's law pertaining to the spectral distribution of the emissive power of thermal radiation. This technique allows accurate temperature measurements to be made without needing to know the surface emissivity.
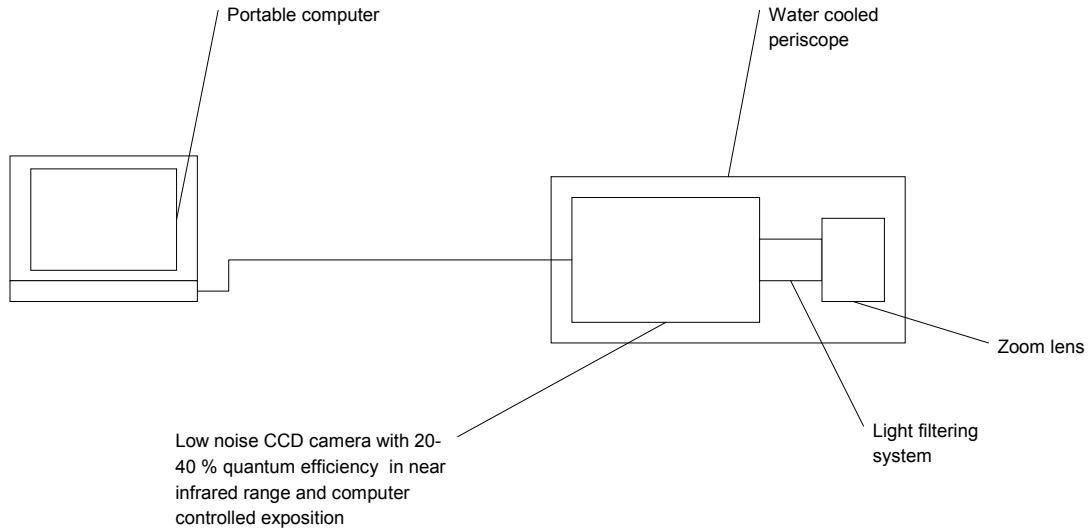

Figure. 3. THEMAL IMAGING SENSOR SCHEMATIC

Combustion Furnace Control Using TIS (concept)

The field temperature measurements (up to 1 million points, up to 30 times a second) are digitally processed and the results sent as a color temperature map to a monitor for operator review and to the thermal imaging control algorithm process. The control algorithms use the digital temperature data and the field control settings to determine needed adjustments to the furnace control system. Output signals are sent to the main furnace controller where adjustments are made to gas and oxidant flows, air/fuel ratios, and distributions of gas between burners. The overall thermal imaging control system is self-calibrating with black body radiation measurements. Feedback control is used to operate the control algorithms from reading to reading. The control scheme for the furnace is operated as before, with the main furnace controller making most adjustments and all large adjustments. The thermal imagining control system assists the main control system with the objective of tuning combustion to increase thermal efficiency, lower NO_x emissions, eliminate hot spots, and handle instabilities that arise.
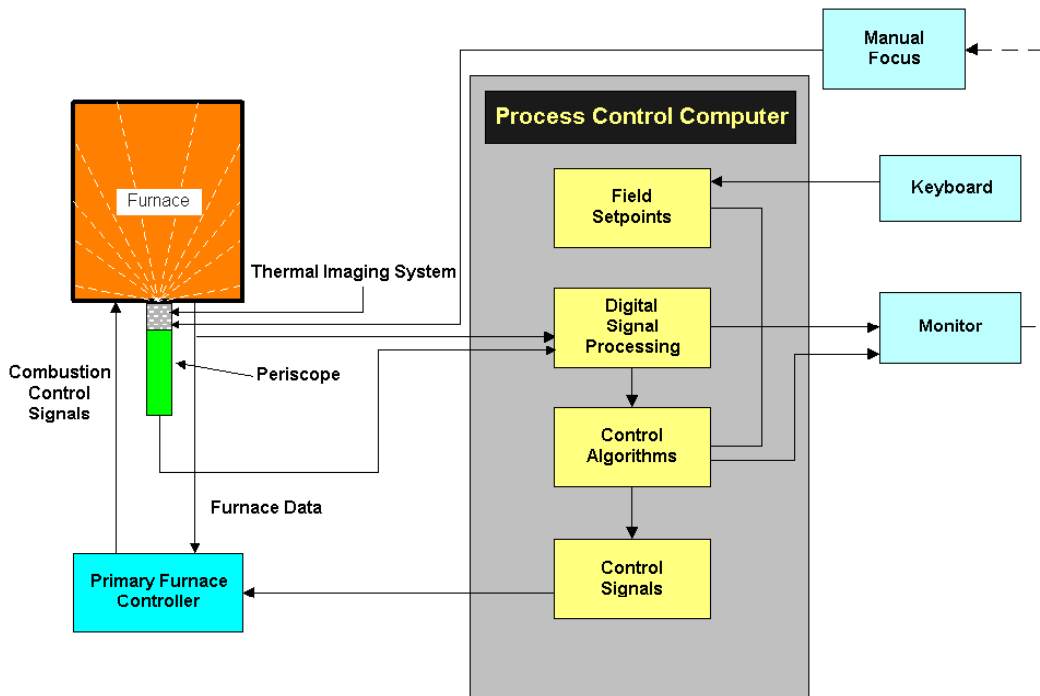
Figure 4. NEAR-INFRARED THERMAL IMAGING CONTROL SYSTEM

Phase II. Two color thermal imaging system development.

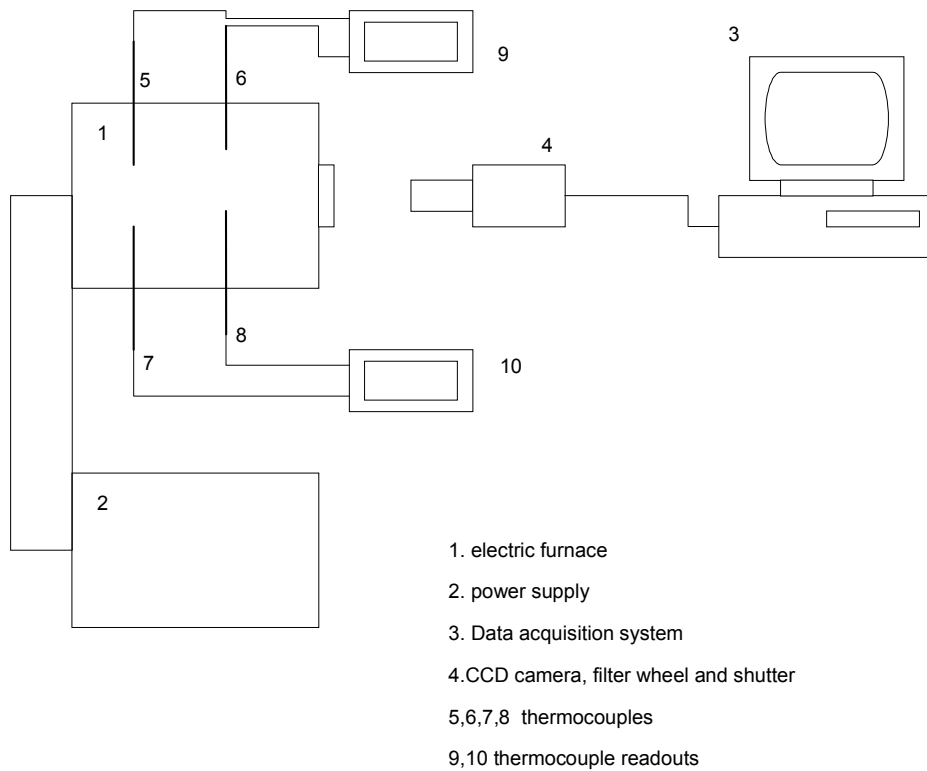Bench-Scale Testing

Figure 5. .BENCH-SCALE SETUP ASSEMBLY

1. electric furnace

2. power supply

3. Data acquisition system

4.CCD camera, filter wheel and shutter

5,6,7,8 thermocouples

9,10 thermocouple readouts

.

Figure 6. BENCH SCALE TEST SETUP

The Thermal Imaging System hardware includes the following components.

    Near infrared CCD camera
    Filter wheel
    Electronic shutter
    F-mount Lens
    Data acquisition and hardware control system

      The Thermal imaging system includes a high-resolution 8-mega pixel, digital camera CCD specially designed for low light scientific and industrial applications. This camera has additional computer-controlled futures such as binning, controlled exposure, and light intensity integration. This camera is capable of delivering high-resolution, 12-bit images across the full spectral band, especially into the near infrared spectral range. The new CCD technology provides a high quantum efficiency of 20-40 % in the near infrared portion of the spectrum. The

camera has to provide 4,096 levels of grayscale data for quantitative analysis of gray scale images. The new system is capable of obtaining temperature maps of surfaces with temperature as low as 700°C and as high as 2000°C. The TIS is capable of measuring temperature distributions on surfaces where the surface temperature varies significantly at different surface' locations.   This variation can be as much as 300°C, with even higher variations possible.

Figure 7. THE TIS ASSEMBLY

The light filtering system consists of a six position motorized, computer-controlled filter wheel and a set of narrow band interference filters. A GTI-developed data acquisition system allows synchronized camera, grabber and filter wheel operation. The TIS work sequence can be briefly described in several steps. First, the filter wheel positions "band one" filter between the lens-electronic shutter and CCD, providing uniform illumination of the CCD surface with narrow band filtered light. Then a gray scale image is acquired and stored in the computer memory. As soon as the image storage is completed, the data acquisition system sets the filter wheel to the "band 2" filter. The second gray scale image is acquired and stored along with the first image. These two images are then mathematical processed together and a temperature map is calculated and displayed.

Software Description

Some of the features under development are listed below. The Thermal Imaging System can provide interior surface furnace temperature to the operators. With further controls software development, the Thermal Imaging System can provide information to furnace controllers.

The software is written in a C++ multithreaded structure. Major components and capabilities of the present software package include the following:

1. Gray scale real time imaging

2. Grabbing, storing and loading gray scale images
3. Zooming in gray scale imaging mode and temperature map displaying modes
4. Calculating, displaying and saving temperatures maps from previously saved gray scale images or from gray scale images as they are grabbed in the real time mode
5. Displaying temperature maps in false color or true color palettes.
6. Analyzing the obtained temperature maps using area and point temperature tester.
7. Displaying temperature in Kelvin Celsius or Fahrenheit temperature scales.

The software package interface includes three hardware control menus. Camera settings and controls include:

1. Binning, gain, integration time, anti-bloom mode setting
2. Shutter operation setting via camera controls: active, inactive, delay, integration time synchronization.
3. Timing mode: internal triggering, external triggering, external integration time control

Frame grabber settings and controls include:

1. Gain (1-16)
2. Offset (0-4095)

Filter wheel control includes:

1. Motion direction
2. Motion to position
3. Delays

A specially designed electric furnace was used to establish the uniform temperature environment necessary for TIS calibration. The Thermal Imaging System was tested by taking thermal imaging measurements of objects with various shapes, different surface properties, and varied positioning relative to the TIS. Objects were placed inside the furnace and observed at different temperatures through the furnace's observation port covered with a quartz window
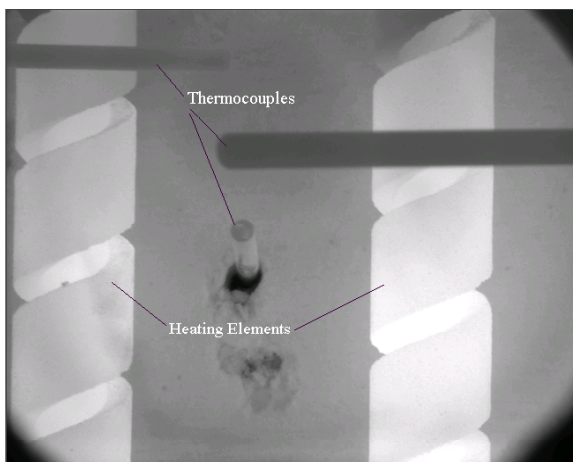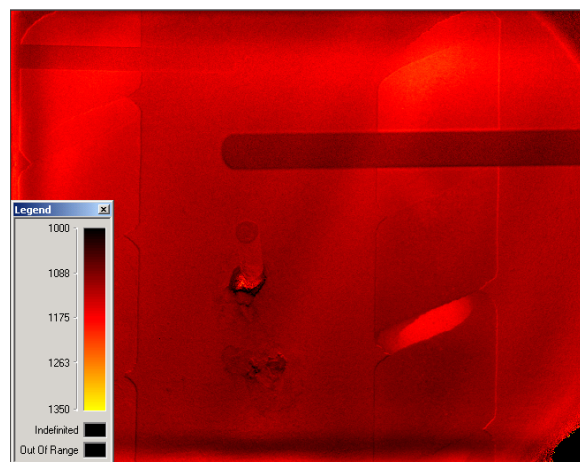

Figure 8. GRAY SCALE IMAGE   Figure 9. TRUE COLOR TEMPERATURE MAP

.   The furnace temperature was set to a given value using a standard controller with a thermocouple input. Figure 10 shows images for furnace temperature settings of 500°C to 1100°C. Details are more easily detected at higher temperatures, but good resolution is achieved even at temperatures as low as 500°C.
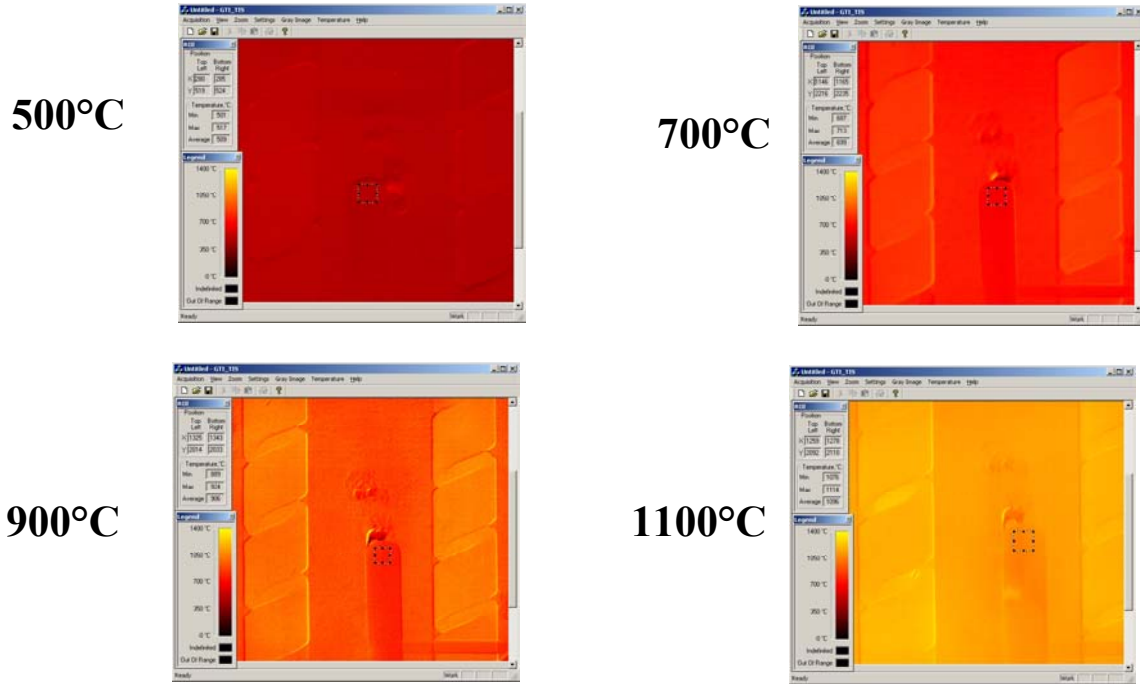

Figure 10. TEMPERATURE MAPS AT DIFFERENCT TEMPERATURES

Thermal Imaging System Testing and Calibration

The following algorithm was used for TIS calibration and temperature calculation. The spectrum of light intensity emitted by any surface with any temperature T can be calculated via Wien's law:

$$I(\lambda,T) = F(\lambda)\cdot\varepsilon(\lambda,T)\cdot(2C_1/\lambda^5)\cdot\exp(-C_2/(\lambda\cdot T)) \qquad (1)$$

where $I(\lambda,T)$ is blackbody emission, $F(\lambda)$ is the efficiency of the light measuring system, $\varepsilon(\lambda,T)$ is an emissivity of the material, λ is wavelength [mkm], and T is temperature [K]. $C_1=3.742\times10^8$ [W·mkm^4·m^{-2}] and $C_2=1.439\times10^4$ [mkm·K] are constants.

For temperature calculations, the Wien's law of radiation can be rewritten as

$$R(\lambda,T)\cdot= I(\lambda,T)\cdot k = k\,F(\lambda)\cdot\varepsilon(\lambda,T)\cdot(2C_1/\lambda^5)\cdot\exp(-C_2/(\lambda\cdot T)) \qquad (2)$$

where the product $R(\lambda,T)$ is an intensity measured by any appropriate means (a CCD in the work under this project) and is calculated as $R(\lambda,T)=I(\lambda,T)k$. In equation (2), k [Wt^{-1}] is a gray scale

conversion factor. The value of this coefficient depends on the type and sensitivity of the detector as well as on the distance between the object and the detector. The Gray Scale Value R depends on the resolution of the CCD data acquisition system. For instance, for our UNIQ UP-900 CCD data acquisition system R changes from 0 to 1023. The efficiency of the measuring system can be calculated as $F(\lambda) = c(\lambda) \cdot d(\lambda) \cdot t(\lambda) \cdot w(\lambda)$, where $c(\lambda)=0\ldots1$ is the CCD camera spectral response, $d(\lambda)=0\ldots1$ is the filter transmission, $t(\lambda)=0\ldots1$ is the lens transmission, and $w(\lambda)=0\ldots1$ is the window transmission.

Therefore to calibrate the dual wavelength Thermal Imaging System we must determine the efficiency the TIS $F(\lambda)$.

By measuring the intensities $R(\lambda_1,T_0)$ and $R(\lambda_2,T_0)$ from a material with known temperature T_0, equation (2) can be used to determine the product $k\,F(\lambda) \cdot \varepsilon(\lambda,T_0)$ at two wavelengths λ_1 and λ_2:

$$k\,F(\lambda_1) \cdot \varepsilon(\lambda_1,T_0) = R(\lambda_1,T_0) \cdot \lambda_1^5 \cdot \exp(C_2/(\lambda_1 \cdot T_0))/(2C_1), \tag{3}$$

$$k\,F(\lambda_2) \cdot \varepsilon(\lambda_2,T_0) = R(\lambda_2,T_0) \cdot \lambda_2^5 \cdot \exp(C_2/(\lambda_2 \cdot T_0))/(2C_1). \tag{4}$$

The emissivity ε is a function of wavelength and temperature, but the emissivity can be assumed to not change significantly within the observed wavelength range, i.e. $\varepsilon(\lambda_1,T_0) \approx \varepsilon(\lambda_2,T_0)$. Equations (3) and (4) can be used to derive equation (5)

$$F(\lambda_1)/F(\lambda_2) = [R(\lambda_1,T_0)/R(\lambda_2,T_0)] \cdot (\lambda_1/\lambda_2)^5 \cdot \exp(C_2 \cdot (\lambda_2-\lambda_1)/(\lambda_1 \cdot \lambda_2\,T_0)). \tag{5}$$

With this equation in hand, consider an emitting surface at an unknown temperature. If emission intensities $R(\lambda_1,T)$ and $R(\lambda_2,T)$ are measured at two wavelengths λ_1 and λ_2 (assuming $\varepsilon(\lambda_1,T_0) \approx \varepsilon(\lambda_2,T_0)$), the following equation can be written by analogy with equation (5):

$$F(\lambda_1)/F(\lambda_2) = [R(\lambda_1,T)/R(\lambda_2,T)] \cdot (\lambda_1/\lambda_2)^5 \cdot \exp(C_2 \cdot (\lambda_2-\lambda_1)/(\lambda_1 \cdot \lambda_2\,T)). \tag{6}$$

From (5) and (6), the temperature calculation can be written in the form of equation (7).:

$$1/T = 1/T_0 + \ln[\mu \times R(\lambda_2,T)/R(\lambda_1,T)] \times (\lambda_1 \cdot \lambda_2)/(C_2(\lambda_2-\lambda_1)), \tag{7}$$

where $\mu = R(\lambda_1,T_0)/R(\lambda_2,T_0)$ becomes the only calibration coefficient. This coefficient can be calculated as a ratio of two narrow band intensities measured at wavelength λ_1 and λ_2 emitted by a surface with known temperature T_0. $R(\lambda_1,T_0)$ and $R(\lambda_2,T_0)$ are gray scale intensity values of the energy spectrum emitted by the surface at a known temperature T_0. The values of $R(\lambda_1,T_0)$ and $R(\lambda_2,T_0)$ were measured at narrow wavelength bands around λ_1 and λ_2. $C_2=1.439\times10^4$ mkm·K is a known constant. Equation (8) can be rewritten as:

$$1/T = A_0 + \ln[R(\lambda_2,T)/R(\lambda_1,T)] \times (\lambda_1 \cdot \lambda_2)/(C_2(\lambda_2-\lambda_1)), \tag{8}$$

where $A_0 = 1/T_0 + \ln\mu \times (\lambda_1 \cdot \lambda_2)/(C_2(\lambda_2 - \lambda_1))$ becomes the only calibration coefficient.

A single calibration parameter A_0 was calculated for different values of the surface temperature T_0 for the "Rodenstok" and "Cosmicar" lens system (see Figure 10) used in testing. Figure 11 shows the calibration parameter A_0 does not change significantly with T_0 over the temperature range from 900ºC to 1200ºC (1652ºF to 2192ºF). The tests showed that the coefficient does not depend on the temperature of the surface and depends only on the optical properties and sensitivity of the thermal imaging system. The value of A_0 was found to be equal to $4.27 \cdot 10^{-4}$ for the subsequent surface temperature measurements, using specific test hardware.
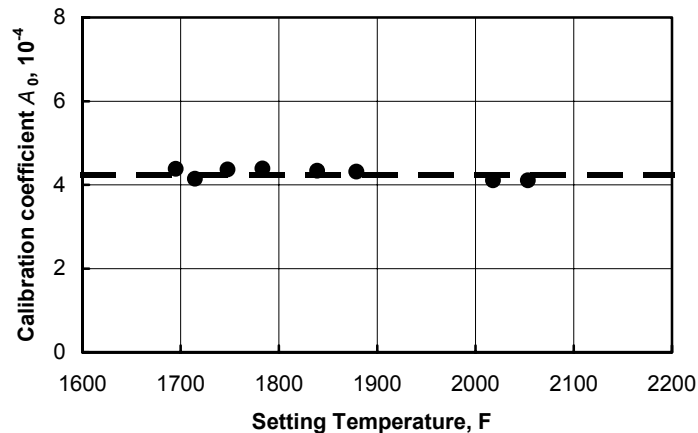

Figure 11. TIS CALIBRATION COEFFICIENT VS. SETTING TEMPERATURE

Calculated temperatures of two different surfaces for two different lens setups are shown in Figure 12. The agreement of calculated temperatures with actual temperature is quite good. Some data scattering can be explained by the high noise to signal ratio of the CCD currently in use. Temperature deviation shown on Figure 12 is partly due to hardware imperfections and light scattering from the lens surfaces.
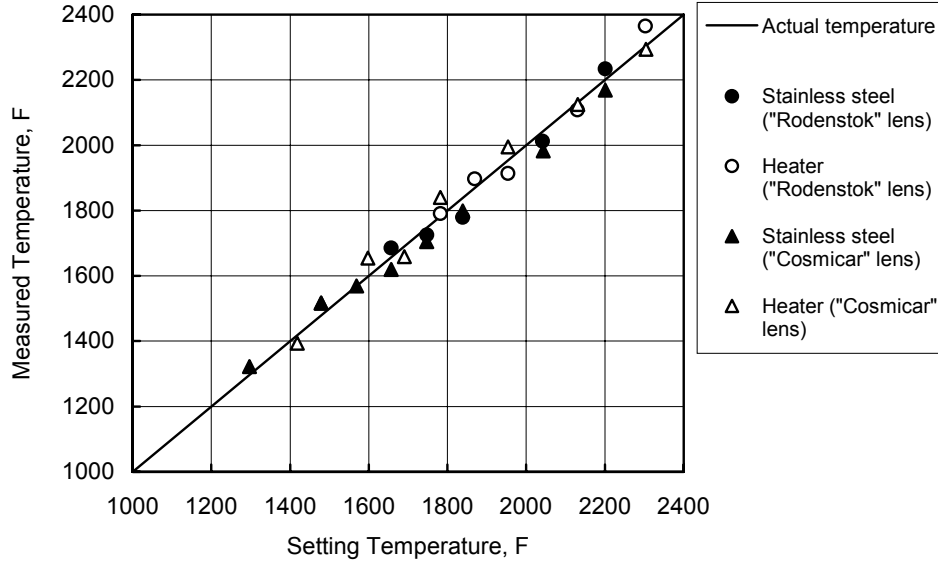
Figure 12. DEVIATION BETWEEN TEMPERATURES MEASURED WITH TIS AND
ACTUAL (SETTING) TEMPERATURE.

Several tests were also conducted to establish the thermal imaging system capabilities to measure temperatures of different surfaces (ceramic, stainless steel and carbon steel). The experiments were conducted with the test surfaces positioned in parallel to the CCD array plane as well as in non-parallel configuration (see Figure 13).
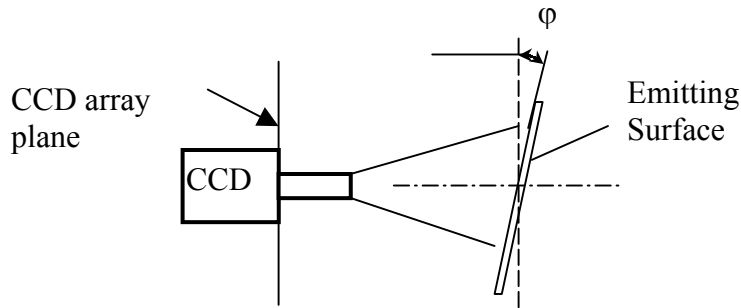

Figure 13. SCHEMATIC FOR INCLINED SURFACES TESTS

The tests showed that the developed TIS system can accurately measure the temperature of surfaces non-parallel to the CCD array plane. The accuracy of these measurements is not affected by the value of the surface inclination in the range tested ($0° \leq \varphi \leq 75°$).

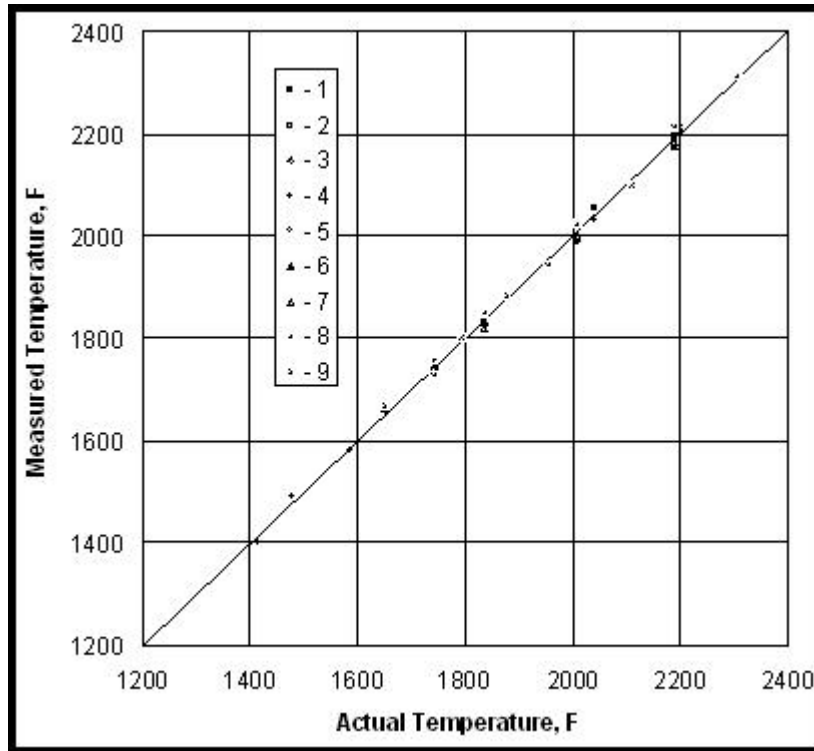Figure 14. TIS TESTS FOR INCLINED SURFACES
1 – carbon steel (φ = 0°); 2 – carbon steel (φ = 30°); 3 – carbon steel (φ = 60°);
4 – stainless steel (φ = 0°); 5 – stainless steel (φ = 30°); 6 – stainless steel (φ = 45°);
7 – stainless steel (φ = 60°); 8 – stainless steel (φ = 75°); 7 – ceramic (φ = 0°)

Phase III. Pilot scale testing

Thermal Imaging System Testing

The Thermal Imaging System was installed on a Heat-treating furnaces at GTI. A photograph and schematic of GTI's heat treating furnace are shown in Figure 15 below.
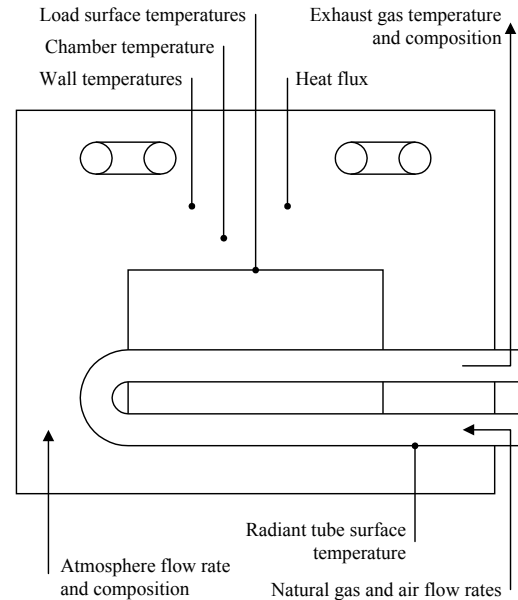
Figure 15. BATCH-TYPE HEAT TREAT FURNACE

Combustion takes place in the burner at the inlet of the radiant tubes. The products of combustion flow to the exhaust through the radiant tube housed inside the furnace. The combustion products heat the tubes, and the tubes radiate heat to the charge and the furnace wall. A circulating fan helps to maintain uniform temperatures in the gas volume of the furnace. The experimental furnace was prepared for testing with the following conditions and parameters

- Two radiant tubes along with a burner for each
- A motor that controls the air supply rate to both burners through lines branching after the motor
- A control valve in each fuel line supplying gas to each burner
- A manually operated high-low control system that sets the common air-line valve setting
- A gas analyzer system connected to the exhaust stacks to measure the exhaust gas composition. Exhaust gas compositions will be used to set the fuel-line control-valve settings to obtain the acceptable amount of exhaust gas excess air
- Thermocouples measuring gas-volume temperature, load temperatures, furnace wall temperatures and radiant-tube wall temperatures
- Pressure and flow sensors in the air and gas supply lines
- Data acquisition system interfaced with thermocouples, pressure and flow sensors and the gas analyzers

Exposing the load to the high temperature furnace environment changes the material properties of the load. The temperature of the furnace environment is controlled by varying burner firing rates. Most existing controls work in an open loop and are usually of the on-off or high-low types. This type of control maintains the temperature around a band of the desired level. If the temperature approaches the upper level, the control is switched to off or low setting,

and if the temperature approaches the low mark, the control is switched on or high. Proper control is essential for imparting desired properties to the load with minimum waste while economizing the use of fuel and oxidant, preventing overheating of furnace refractory, ensuring operational safety, and observing emission standards. The present state of high-low control practice for batch-type furnace combustion must be improved to take advantage of advances in control theory and practice. This is the motivating force for the present work plan.

In initial tests, thermocouples were used as the temperature sensor. Updating temperature sensing through thermal imaging served as the next step of the work plan. Using this more sophisticated sensor provides more freedom to decide the best combination of measurement locations to generate effective feedback. Such measurements could be very effective and provide much better temperature monitoring and much needed redundancy.

Improvements in the Thermal Imaging System (TIS) hardware were focused on enabling the system to operate in automatic mode utilizing all the system's capabilities in a field test environment. The new TIS hardware elements have been configured as shown in Figure 16.
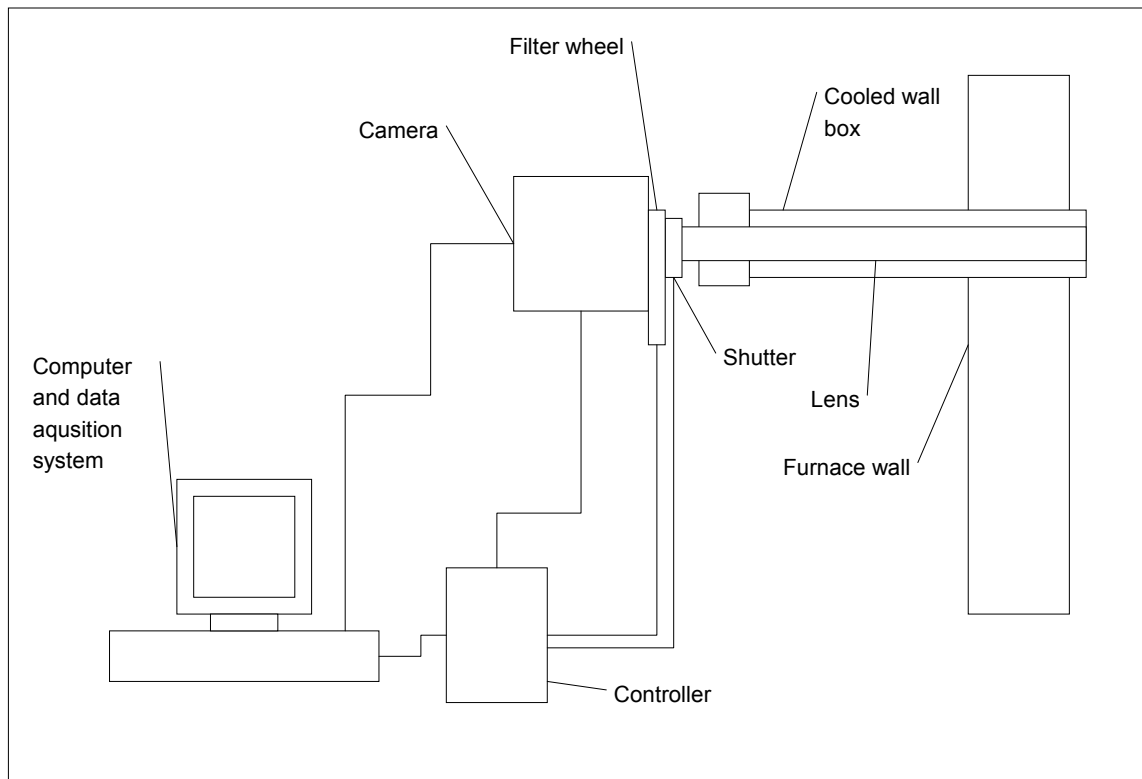

Figure 16. SCHEMATIC OF FIELD TEST READY THERMAL IMAGING SYSTEM

A water-cooled periscope was designed and manufactured for the GTI TIS. The water-cooled periscope allows instillation of the TIS directly inside high temperature apparatuses.

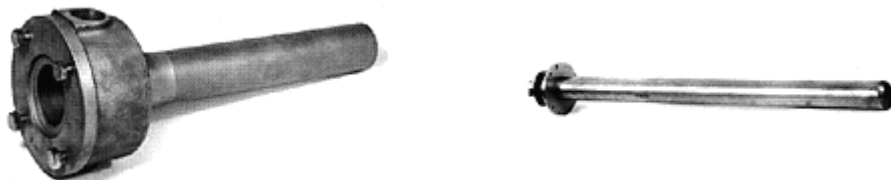Figure 17. FURNACE AND TIS SET-UP AND TIS COMPONENTS

FIGURE 18. PERISCOPE AND PERISCOPE SHELL

The water-cooled periscope consisted of a cooled periscope shell and a twenty-four inch long furnace lens (Figure 18). In practice, the periscope penetrates the wall of a boiler or furnace through an existing opening. The cooled shell provides a protective housing and is the primary coolant shroud. The periscope operates in temperatures up to 3,500°F.

Temperature maps of the heat treating furnace were made over a range of firing conditions for both tubes. Also, one tube was instrumented with a set of eight thermocouples, and the temperatures at those locations were compared when measured by thermocouples and the thermal imaging system.
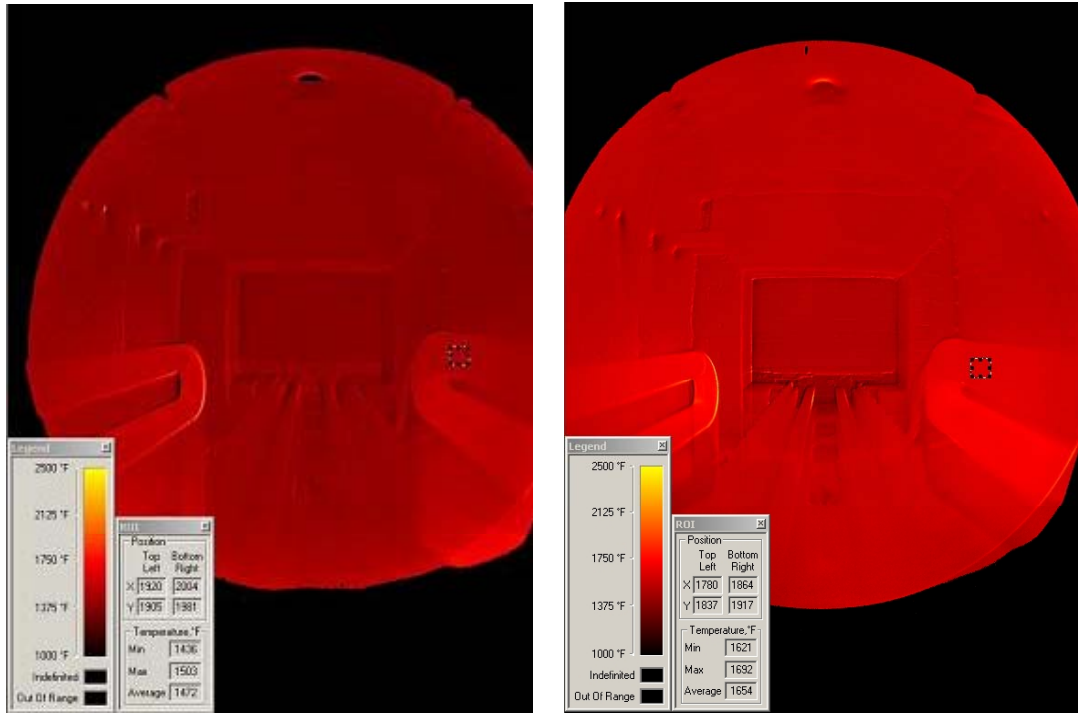
Figure 19. TEMPERATURE MAPS OF THE FURNACE INTERIOR

The figure below shows the locations of the thermocouples on the tube and a comparison of temperatures measured by the two techniques.
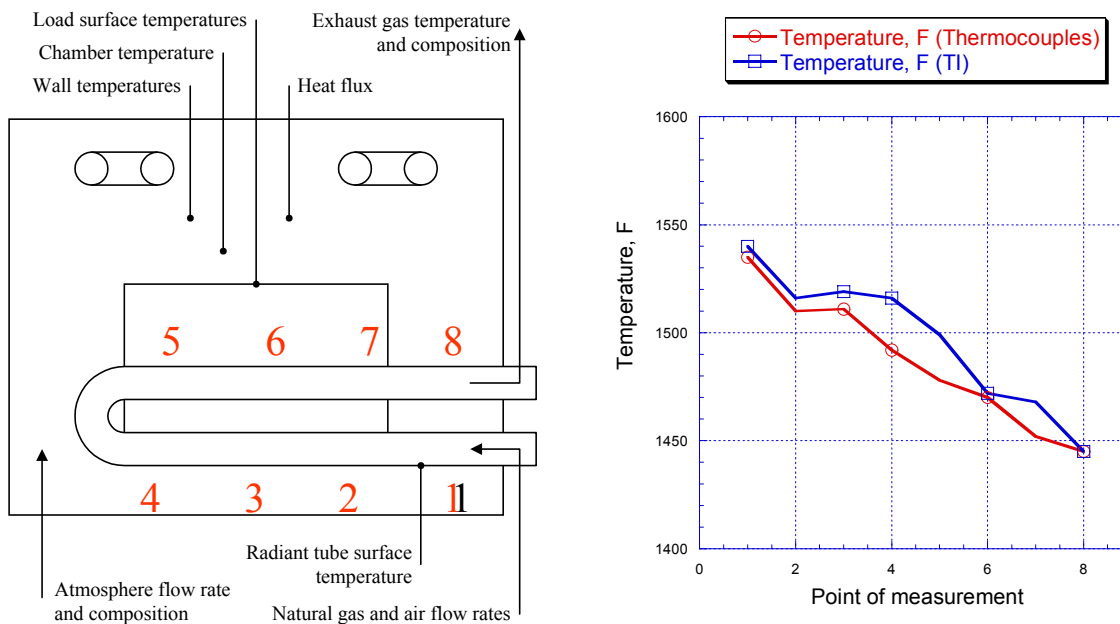

Figure. 20. COMPARISON OF THERMOCOUPLES WITH THERMAL IMAGING SYSTEM

<u>Thermal Imaging Control System Testing</u>

For the purpose of implementing Thermal Imaging on the heat-treating furnace a new controller purchased From Allan-Bradley (AB) was installed on the GTI Heat Treat furnace. The new control system includes two NA valves, pressure regulators, flow meters and a data acquisition and control system The modulating of the firing rate for each burner is achieved by the use of a North American motorized valve, which controls the flow of the combustion air. The gas flow is subsequently controlled by a pressure regulator, which is slaved to the air pressure of the main combustion air. Both airflow and natural gas flow are measured independently via Sierra flow meters for each burner. Thermocouples are monitored and recorded on four locations; ceiling, left wall, right wall and furnace. The first three thermocouples are placed so that the tip is flush with refractory walls whereas the furnace thermocouple is measuring furnace chamber temperature. The AB controller regulates the motorized valves to establish desired furnace temperature by controlling the firing rate to each burner.

All controller programming, data acquisition and process data is carried out on a personal computer running the ControlLogix software RsLinx and RsLogix 5000. The latter software is used during the controller programming/tuning stage as well as for troubleshooting. RsLinx serves as a monitor to all process parameters and real time data as well as a gateway for third party data input in OPC format. To enable direct communication between the GTI thermal Imaging system and AB controls, GTI developed a special interface C++ subroutine. This program is capable of converting multiple temperature information acquired by the thermal imaging system into a standard control input format compatible with most of the modern control systems including Alan Bradley controls.

Figure 21. THERMAL IMAGING CONTROL OF THE GTI HEAT TREAT FURNACE

<u>Experimental Procedure and Results</u>

After the burners were ignited the temperature set point was set to 1200°F. The furnace chamber thermocouple was used as sensor input to the controller. The furnace temperature was allowed to stabilize for approximately 3 hours (See Figure 22).   The thermal imaging system was then activated and the furnace load temperature was chosen for input to the controller. A new set point of 1300°F was entered into the controller. Under these conditions, the load temperature was allowed to stabilize for 2 hours. The resulting temperature profile recorded by the thermal imaging system indicated that as the load approached the set-point the temperature oscillated above and below the set-point with decreasing magnitude, eventually settling to a load temperature of 1298°F ± 2°F (Figure 22). Burner control was then returned to the furnace chamber thermocouple and a new temperature set point of 1600 °F was entered. The furnace was again allowed to stabilize (Figure 23). The thermal imaging system was once more activated. The load temperature was used as controller input. The new temperature set point was entered as 1650°F. After approximately 2 hours of operation, the load temperature was found to be oscillating above and below the set point but with no sign of convergence (See Figure 23). The average load temperature was recorded by the thermal imaging system as 1640°F with intermittent jumps in the temperature profile. One possible reason for this non-convergence is the shutter speed of the thermal imaging camera used to obtain the gray-scale images. At this higher temperature, light intensity from the furnace interior overwhelmed the shutter's capability to open and close quickly enough to obtain accurate exposures and create more precise temperature profiles.
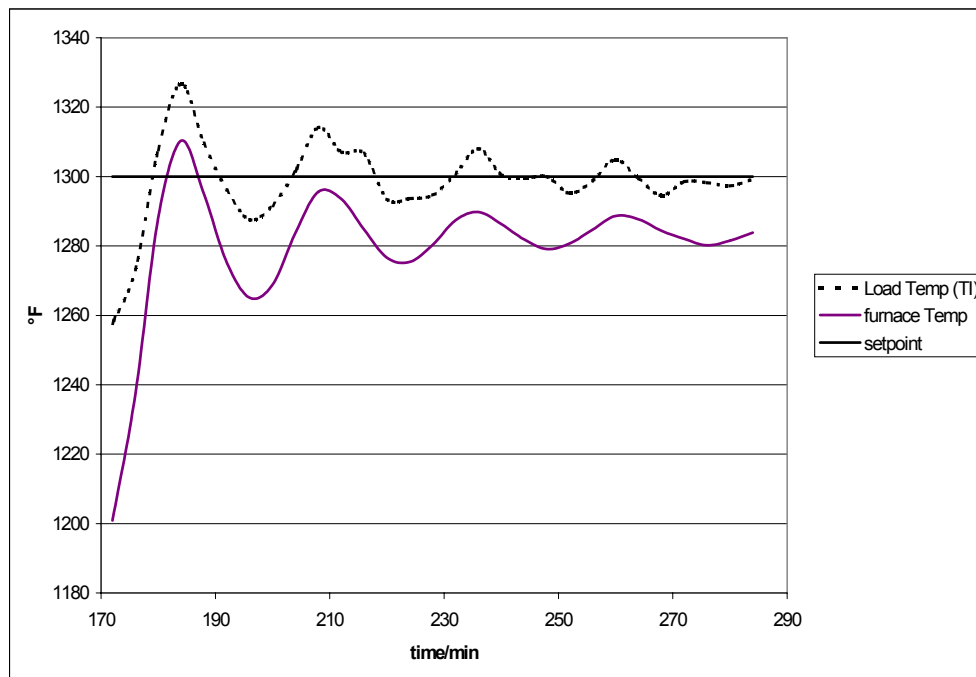

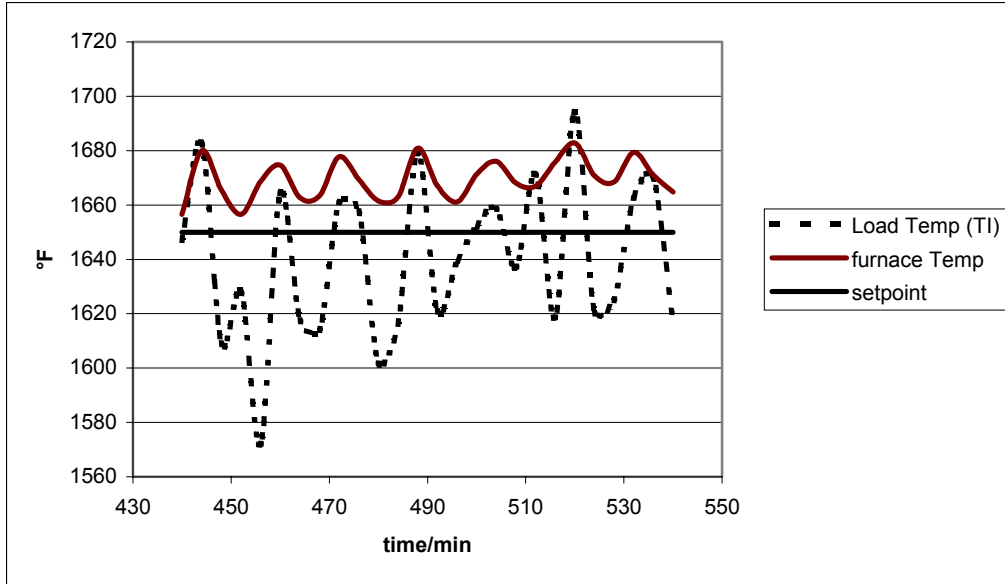FIGURE 22. HEAT TREATING FURNACE TEMPERATURE CONTROL

Figure 23. HEAT TREAT FURNACE TEMPERATURE CONTROL AT ELEVATED
TEMPERATURES

The results of the experiments show that the thermal imaging system has the potential to
significantly improve the existing control of furnaces and other combustion apparatuses. The
technique will be especially beneficial when utilized for multi-burner, high capital cost furnaces,
kilns etc. Availability of multipoint temperature measurements or averaged temperatures of key
surface areas will allow control systems to incorporate more sophisticated control algorithms
leading to higher efficiency, improved product quality, and lower emissions. The input the
thermal imaging system can be collected simultaneously with temperatures collected with
thermocouples form heaters, loads, and furnace surfaces.

Control Strategy

Following tests on the heat treat furnace at GTI, the thermal imaging and control system
was to be installed on an industrial furnace selected through partners Eclipse Combustion and
Owens Brockway. This objective of this test is to demonstrate the ability to use the water-cooled
periscope, lens, filters, camera, and computer based data processing hardware and software to
collect calibrated thermal image information on a large working furnace. No control interface
will be employed for this test, since that demonstration has been conducted on the GTI heat treat
furnace. This second industrial furnace demonstration has been postponed to the new
NYSERDA-funded project starting after this project. The NYSERDA-funded project will focus
on developing an industrial prototype thermally imaging system and demonstrating this system
on an industrial furnace.

Industrial processes can be considered as batch or continuous (or some combination of
the two). In batch processes, a load is charged and the furnace is taken through a temperature
cycle. In continuous processes, the furnace or furnace zones are held at desired temperatures,

and the load is moved through the furnace. Figure 24 below illustrates these two types of industrial furnace operation.
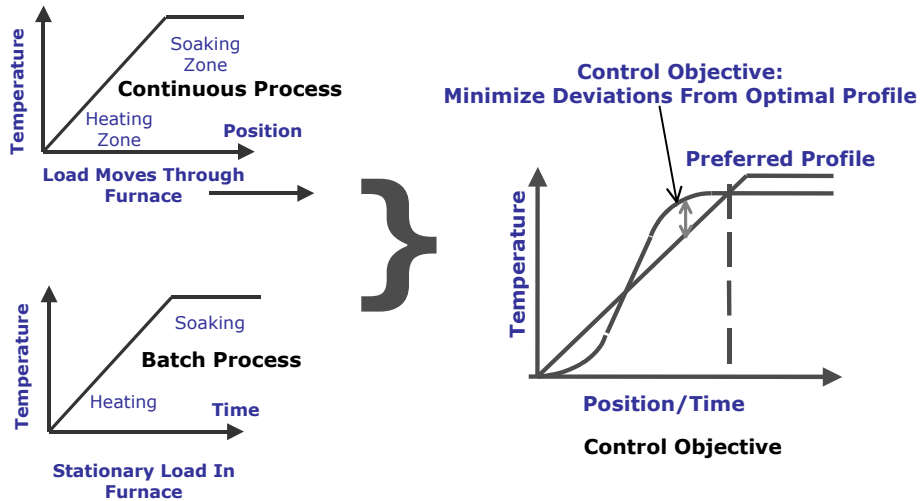

Figure 24. INDUSTRIAL PROCESS CONTROL APPROACHES

The field temperature measurements are digitally processed and the results sent as a color temperature map to a monitor for operator review and to the thermal imaging control algorithm process. The control algorithms use the digital temperature data and the field control settings to determine needed adjustments to the furnace control system. Output signals are sent to the main furnace controller where adjustments are made to gas and oxidant flows, air/fuel ratios, and distributions of gas between burners. The overall thermal imaging control system is self-calibrating with black body radiation measurements. Feedback control is used to operate the control algorithms from reading to reading. The control scheme for the furnace is operated as before, with the main furnace controller making most adjustments and all large adjustments. The thermal imagining control system assists the main control system with the objective of tuning combustion to increase thermal efficiency, lower NO_x emissions, eliminate hot spots, and handle instabilities that arise.

Industrial Adoption Plan

During this project, team engineers spoke with a number of sensor instrument and control system suppliers as well as industrial end users. Both end users and suppliers made two points repeatedly.

- All parties agreed that the cost of a sensor or sensor/control technology is weighed against its benefits. Therefore, less expensive technologies, flexible technologies, and technologies that provide several types of data are the most attractive.
- End users want sensors that provide known types of data in formats (such as OPC) that can be used by their control systems. The primary desire is to have these data available so end user engineers can incorporate these data into the end user's control strategy.

With these points in mind, the project team resolved to focus on developing a low-cost thermal imaging system that also provide recordable video images of furnace interiors and to provide thermal imaging data in a flexible format that could be easily used by end users. This is seen as the best means to provide a wide range of industrial users a tool that they want, need, and will purchase to improve energy efficiency in their furnaces and combustors.

An original project strategy was to input the thermal imaging system data into a set of control system algorithms that would give secondary control instructions to burners (air-fuel ratios, etc.) for tuning control. This was intended to not interfere with primary furnace control. Full process control was never the goal of this project. The original strategy was found to be too complex and did not adequately address the capabilities of modern multiple input-multiple output (MIMO) process controllers to operate multiple control loops with a wide range of inputs. The power of the thermal imaging control system under development is to provide 'field' temperature data of furnace walls and loads in essentially real time. These data can be processed by 'thermal imaging control' algorithms to convert data into a format usable by already available PLC control logic control loops. This was accomplished in this project.

This adjustment in approach to providing data in a format useful for process control has been described in project review meetings and in later project quarterly technical reports. From this clearer understanding of modern process control strategy, the project has been successful. Thermal imaging temperature data from an area, not just a single point (thermocouples and pyrometers provide single point temperatures) was averaged, and then processed by a 'thermal imaging control' algorithm. The resulting information was provided in OPC format to a control loop that controlled firing rate for two burners on a GTI heat treating furnace. The development of more complex data processing algorithms to utilize the real-time, area temperature data from the thermal imaging system is simply a matter of additional, process-specific, software code writing.

This revised project emphasis has enabled the project team to redirect resources to developing software for robust and flexible data input into industrial controllers and PLC control systems.

The flexible pilot-scale thermal imaging system including lens, periscope, filter wheel, CCD camera, frame grabber, computer, control software, and data processing software has been demonstrated on a heat treating furnace. The generic output, in OPC format can be input into any commercial PLC controller. The other emphasis has been on moving the technology toward commercialization. GTI has formed a working relationship with International Electronic Machines, Inc. of Albany, New York to make the next step toward commercialization. IEM is a small digital imaging and sensors manufacturer. This small, dynamic company is ideally suited to converting the laboratory thermal imaging sensor into an industrial prototype. GTI will work closely with IEM by providing software and development support. A marketing and sales company is being sought to join the team to provide means to reach a large market. Several leads are being pursued in locating this firm and having them join the project team.

IEM Corp. and GTI submitted a proposal to the New York State Energy Research and Development Authority (NYSERDA) in August, 2002 for funding. This project will serve as the

next step in developing the GTI thermal imaging and control technology into a commercial product. This new project will focus on converting the thermal imaging control technology into an industrial product. This will involve hardware modifications to convert the portable laboratory very of the thermal imaging sensor into a hardened industrial prototype and continued software development to increase flexibility and adaptability to multiple furnaces and control systems. Flexibility improvements will involve expanding temperature ranges, improving speed of data acquisition, and increasing stability in an industrial environment. Stability improvements involve vibrations and involve acquiring comparable fields of view when the camera is moved and replaced. A field test of the industrial version of the thermal imaging system is also included in that project. NYSERDA awarded this project to the team, and this work is scheduled to begin in April, 2003. This will have a large impact on commercialization of this technology.

During the NYSERDA project, GTI and IEM will seek industrial partners for sales and support. IEM is a small electronics firm and can serve as system fabricator. For sales, installation, and support, a large sensors or controls company will be needed. Discussions have already begun with several companies that fit these requirements, and these relationships will be aggressively pursued during the NYSERDA project. By the end of this new project, the thermal imaging and control system will be industrially demonstrated with an industrial prototype system, a sales and distribution channel will be in place, and commercial introduction to industry will be ready to begin.

MAJOR ACHIEVEMENTS OF THE PROJECT

The project team was successful in developing and demonstrating the thermal imaging control technology. Major achievements included –

- Determination of appropriate near-IR wavelengths for accurate thermal imaging
- Selection of all system hardware including filters, filter wheel, water-cooled periscope, CCD camera, and frame grabber card for low-cost thermal imaging system
- Software allowing thermal imaging of multiple surfaces at angles up to 75 degrees from the lens
- Software to calculate thermal maps at temperatures of 500°C and above
- Software to select points or areas and output temperatures or average temperatures of those points and areas
- Software to prevent 'blooming' effects and to eliminate edge effects between different surfaces
- Successful demonstration of the thermal imaging system hardware and software on a GTI heat treating furnace.
- Operation of the GTI heat treat furnace using thermal imaging data from point and averaged areas as input in OPC format to the furnace PLC controller.

MAJOR TECHNICAL PROBLEM AREAS ENCOUNTERED

Thermal imaging systems require multiple components to be both compatible and controllable by a single controller. This was accomplished by beginning work with hardware including a CCD camera and an LCD filter that were eventually replaced with more rugged and

lower cost components better suited to the final version of the hardware. The project team of GTI and IEM has won a NYSERDA project to begin in April 2003 that will continue this work to develop an industrial version of the thermal imaging control system ready for sale and industrial usage.

CONCLUSIONS

The project team has developed the following conclusions from this project.

- There is a strong industrial need and desire for thermal imaging control systems, but those systems must be rugged, reliable, self-calibrating, low-cost, and easily maintained.
- Other thermal imaging systems available are too costly or do not address the needs of many industrial customers.
- The two wave near-IR approach is reliable, accurate, and works over a wide range of temperature from 500°C to more than 1200°C. The hardware is readily available and can be assembled at an attractive cost to industrial customers.
- Temperatures can be acquired from any point or area in the sensor field of view and have been demonstrated to be deliverable in OPC format to PLC control systems.
- The technology is laboratory and pilot-scale demonstrated and is now ready for development into a marketable commercial technology.

RECOMMENDATIONS

The project team strongly recommends continued development of the thermal imaging control technology. Several modifications in approach are seen as appropriate for intended industrial markets. This change in emphasis is driven by the need for rugged, reliable sensors, the desire to combine multiple sensors, and the strong emphasis on low-cost devices providing high benefit to cost ratios.

The project team of GTI and IEM will develop the thermal imaging system into a dual purpose sensor. Thermal maps and black and white video will be acquired in near real time. The hardware will include low-cost, reliable filter wheels and CCD cameras. The software will be further developed to address the interests of various furnace operators. Control interfacing will focus on providing point and average area temperature information from any point or area in view of the sensor. This will serve to improve process efficiency and flexibility of control. The need to position and calibrate large numbers of high-temperature thermocouples will also be eliminated or greatly reduced.