Design, Fabrication and Testing of An Infrared Ratio Pyrometer System for the Measurement of Gasifier Reaction Chamber Temperature

FINAL REPORT

Period of Performance: October 1, 1999 through September 30, 2006
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ABSTRACT

Texaco was awarded contract DE-FC26-99FT40684 from the U.S. DOE to design, build, bench test and field test an infrared ratio pyrometer system for measuring gasifier temperature. The award occurred in two phases. Phase 1, which involved designing, building and bench testing, was completed in September 2000, and the Phase 1 report was issued in March 2001. Phase 2 was completed in 2005, and the results of the field test are contained in this final report. Two test campaigns were made. In the first one, the pyrometer was sighted into the gasifier. It performed well for a brief period of time and then experienced difficulties in keeping the sight tube open due to a slag accumulation which developed around the opening of the sight tube in the gasifier wall. In the second test campaign, the pyrometer was sighted into the top of the radiant syngas cooler through an unused soot blower lance. The pyrometer experienced no more problems with slag occlusions, and the readings were continuous and consistent. However, the pyrometer readings were 800 to 900 ºF lower than the gasifier thermocouple readings, which is consistent with computer simulations of the temperature distribution inside the radiant syngas cooler. In addition, the pyrometer readings were too sluggish to use for control purposes. Additional funds beyond what were available in this contract would be required to develop a solution that would allow the pyrometer to be used to measure the temperature inside the gasifier.

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EXECUTIVE SUMMARY

Introduction and Background

In 1999, Texaco Inc. was awarded a contract by the U.S. DOE to design, build and bench test an infrared ratio pyrometer system. The contract was one of several awarded that year to academic and industrial research organizations to develop advanced instrumentation for measuring the temperature inside gasifiers. The DOE program under which these awards were given envisioned a three-phase approach in which advanced temperature measurement concepts were developed in the first phase, built and bench tested in a the second phase and then field tested in the third phase. In the case of Texaco, the basic pyrometer system concept had already been developed and tested in the pilot units at Texaco's Montebello Technology Center in South El Monte, California (see US Patent 5,000,580). So, the program for this particular award was modified so that Phase 1 consisted of building and bench testing an updated version of an existing device, and Phase 2 consisted of the field testing.

The Phase 1 work for this program was completed from October 1, 1999 through September 30, 2000. A Phase 1 Final Report was written and issued by DOE on March 31, 2001. That report covered six tasks: 1) drawings and specifications, 2) procurement, 3) fabrication, 4) assembly and bench testing, 5) controller programming and testing and 6) field test planning. Included were complete drawings of the design and assembly, lists of parts, photographs of the completed components, a description of the control program, instructions for operating the equipment and plans for testing the system in the field. Results of the successful calibration and testing of all equipment were also reported. In addition to the detailed results reported for each of the six tasks, an extensive discussion of the gasifier temperature measurement, in general, was also given. Because all of the foregoing have already been officially reported, they will not be repeated in this final report other than in summary form, where appropriate.

Because of the successful completion of all the Phase 1 work, Texaco was awarded a follow-on contract for Phase 2. Phase 2 consisted of an expansion of Task 6 in Phase 1. The expanded list of Task 6 subtasks includes: 6.1) site test agreement, 6.2) packing and transportation of the system to the test site, 6.3) mechanical installation, 6.4) electrical and instrumentation installation, 6.5) distributed control system integration, 6.6) training, 6.7) final installation and startup, 6.8) monitor commercial operations and 6.9) pyrometer system performance evaluation report. The subsequent sections in this report provide a brief summary of results for each of these subtasks.

Before proceeding to the results, it should be explained that, in November 2001, Texaco Inc. merged with Chevron Corporation to form ChevronTexaco; and ChevronTexaco assumed responsibility for the Phase 2 contract. In June 2004, GE Energy acquired from ChevronTexaco the gasification business originally developed by Texaco, along with all of the associated intellectual property. This included the personnel who had developed the pyrometer system and worked on Phases 1 and 2 of this contract. However, GE Energy did not acquire this DOE contract. Therefore, GE Energy has written this brief final report as a courtesy to DOE and Chevron Corporation in order to allow DOE to close out this contract.

Field Test Results (Phase 2 – Subtasks 6.1 through 6.9)

Subtask 6.1 – Site Test Agreement

This subtask involved contacting a number of commercial gasification facilities to determine their suitability and willingness to host a commercial demonstration of the pyrometer system. After a thorough evaluation, Tampa Electric's Polk Power Station was selected. However, the negotiation of a Site Test Agreement between Tampa Electric and Texaco (and then ChevronTexaco) took much longer than expected. Consequently, installation of equipment was delayed, and the first test of the pyrometer system did not occur until June 2004.

Subtask 6.2 – Packing and Transportation of the System to the Test Site

Figure 1 shows the equipment that was shipped to the test site in Polk County, Florida. It consisted of two control boxes and a series of items that bolt directly to the gasifier to form the pyrometer optical train. One of the control boxes contained electrical components, including the pyrometer transmitter and the Programmable Logic Controller (PLC) that ran the entire system. The second control box contained all of the pressure and flow control valves and instrumentation for the sight tube purging and sight glass safety systems. The two control boxes were sent first so that field installation of utilities and instrument connections could begin as soon as possible. The elements of the optical train were shipped shortly before actual testing began. All components for the entire system arrived safely and in good condition at Tampa Electric's Polk County Power Station.

Figure 1a. Equipment Shipped to Test Site – Control Boxes

Figure 1b. Equipment Shipped to Test Site – Optical Train

Subtask 6.3 – Mechanical Installation

Mechanical installation occurred in two phases. First, the two control boxes were installed in close proximity to the connection point on the gasifier where the pyrometer would be located. Later on, the pyrometer optical train was bolted onto one of the flanges on the sidewall of the gasifier that normally was used for a gasifier thermocouple. The insertion point on the gasifier was prepared by removing the existing thermocouple, redrilling the hole through the refractory lining of the gasifier to a diameter that was large enough to accommodate the pyrometer sight tube and then installing the sight tube and the rest of the optical train equipment. This installation procedure, as well as the optical alignment procedure, were described in the final report for Phase 1. Figure 2 shows the interior of the two control boxes installed on site. Figure 3 shows the pyrometer optical train installed on one of the gasifier thermocouple nozzles.

As will be explained under Subtask 6.8, the pyrometer installation was moved once during the test program. Because of difficulties encountered in keeping the sight tube from plugging with slag when it was sighted into the gasifier reaction chamber, a decision was made to sight the pyrometer into the top of the radiant syngas cooler. To do this, one of the soot blower lances from the top bank of soot blowers was modified to act as a sight tube for the pyrometer. This modified sight tube allowed the pyrometer to view the interior of the radiant syngas cooler just a few feet below the transition duct between the gasifier reaction chamber and the top of the radiant syngas cooler. Figure 4 shows the pyrometer installed on the top of the radiant syngas cooler.

Figure 2. Interior of Installed Control Boxes Installed Near Pyrometer

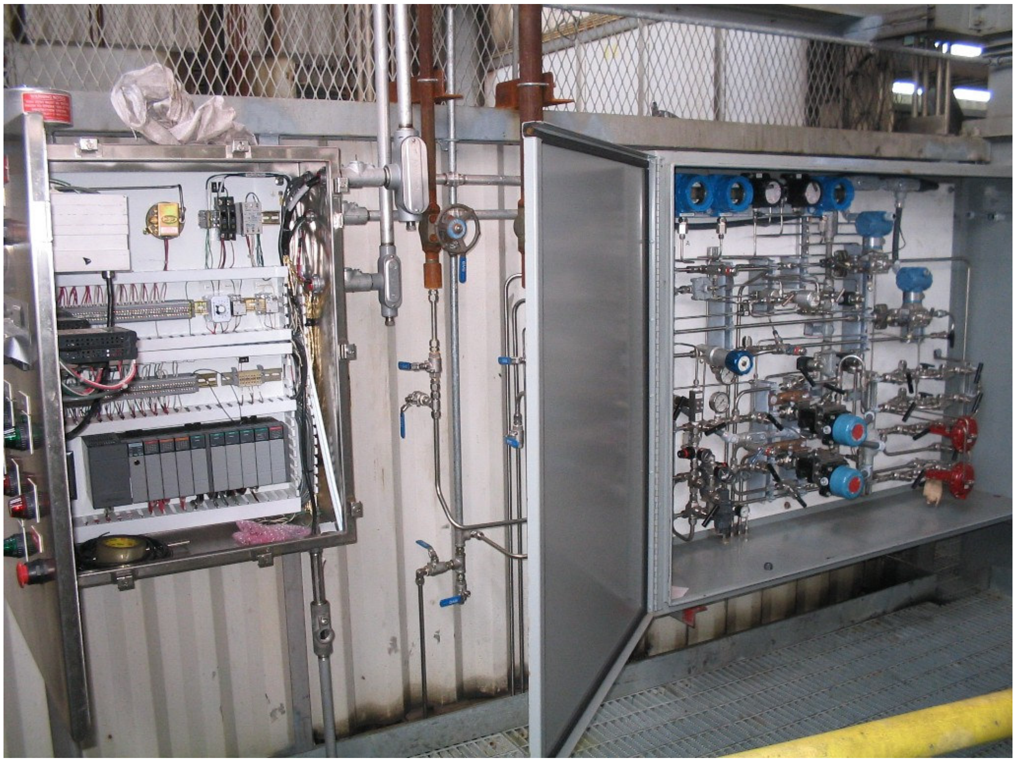
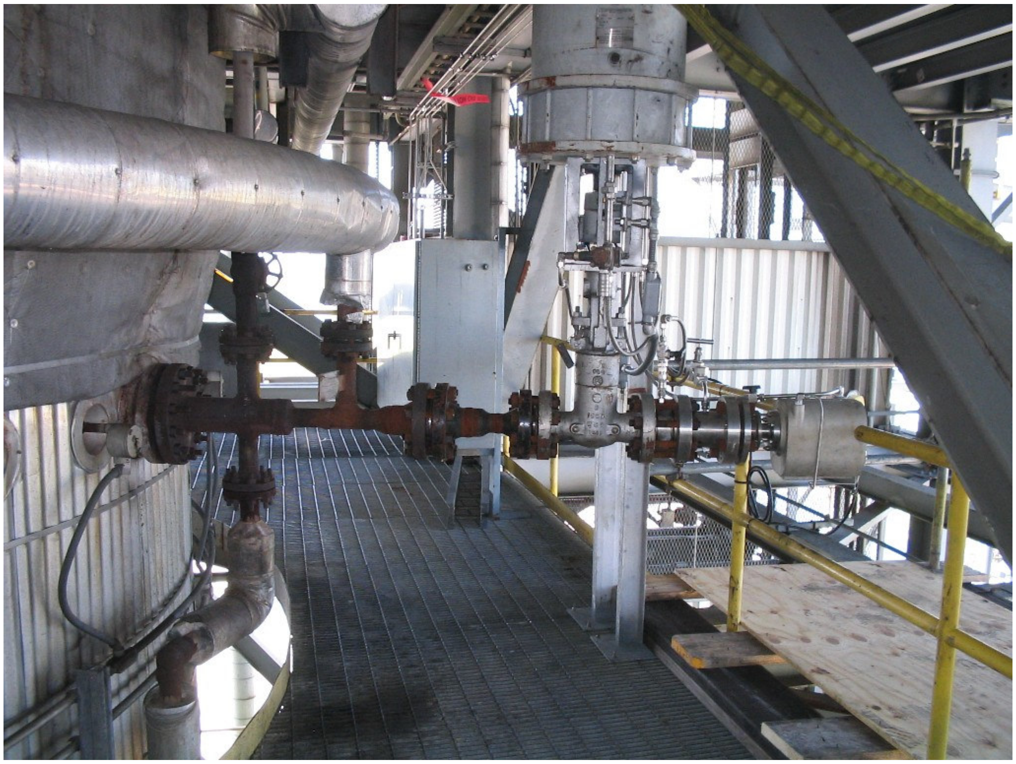


Figure 3. Pyrometer Optical Train Installed on Gasifier Nozzle

Figure 4. Pyrometer Installed on Top of Radiant Syngas Cooler



<u>Subtask 6.4 – Electrical and Instrumentation Installation</u>

The electrical and instrumentation connections to the pyrometer system were designed and installed by Tampa Electric personnel, both for the installation on the gasifier as well as on the top of the radiant syngas cooler.

<u>Subtask 6.5 – Distributed Control System Integration</u>

The integration of the pyrometer system into the plant distributed control system (DCS) was rather simple. A 4-20 mA signal from the pyrometer transmitter was connected to the DCS and displayed on one of the control consol display screens. This allowed the control operators to view and compare the pyrometer temperature with the gasifier thermocouple temperatures. This signal was also sent to the DCS data historian.

The rest of the pyrometer system operation – the control of the sight glass purges, the operation of the sight tube clearing procedure and the operation of the safety system, were set up and controlled locally by the programmable logic controller (PLC). Local control of the pyrometer system by the PLC was designed to make this unit as portable as possible, as it was not clear which commercial gasification facility would host the field test at the time when the unit was built. However, this arrangement ended up hampering operating and troubleshooting of the unit, as the pyrometer and control equipment were located

14 decks above ground level (12 decks, when connected to the radiant syngas cooler).

Subtask 6.6 – Training

A comprehensive training class was prepared and given to Tampa Electric engineers and technicians prior to the initial startup of the pyrometer system. The training allowed plant personnel to assume the operation of the system after the ChevronTexaco personnel had left the plant.

Subtask 6.7 – Final Installation and Startup

Tampa Electric personnel completed virtually all of the installation work, both for the initial installation on the gasifier as well as for the installation on the radiant syngas cooler. In both instances, ChevronTexaco personnel came on site just prior to startup to inspect the installation, to assist with optical alignment and calibration and to supervise the operation of the unit by Tampa Electric personnel.

Subtask 6.8 – Monitor Commercial Operations

Commercial operation of the pyrometer system began with the gasifier preheat that preceded the gasifier run on June 4, 2004. During much of the preheat schedule, the pyrometer tended to read about 100 to 300 ºF higher than the highest reading gasifier thermocouple. After maximum preheat was established, the thermocouples caught up to the pyrometer reading, and the readings were fairly close to one another. This was as expected. The pyrometer has a millisecond response time and measures the surface temperature of the gasifier's brick lining, which is heated directly by the natural gas flame of the preheat burner. In contrast, the thermocouples have response times on the order of minutes, are retracted slightly from the hot face of the brick lining and measure the temperature of thermocouple junctions that are encased in thick, protective refractory sheathes. So, during temperature transients, one always expects the pyrometer to lead and the thermocouples to lag. However, once preheating is complete, and all of the thermal transients have had a chance to work themselves out of the system, it is not surprising to see the pyrometer and thermocouple readings very close to each other.

Just prior to gasifier startup, the pyrometer began experiencing problems with residual slag on the gasifier wall slumping down over the sight tube. This caused the reading to decrease considerably. (The sight tube purge gas cools the growing accumulation, and this cooled accumulation of slag is what the pyrometer measures.) A procedure to clear slag from the sight tube was programmed into the pyrometer system PLC as part of the original installation. It involved temporarily shutting off the nitrogen purge gas to the sight tube. This removed the cold spot in the wall due to the influx of cold nitrogen and allowed the slag accumulation to reheat and soften by exposure to the tremendous heat within the gasifier. After a period of time, a pulse of nitrogen purge gas was used to blow the softened slag accumulation away from the opening of the sight tube.

Then, the normal nitrogen purge flow was reestablished. Unfortunately, this procedure had to be initiated manually from the control panel near the pyrometer. However, gasifier startup procedure requires that all personnel must vacate the gasifier structure immediately before and after gasifier light off. Thus, right at startup it was not possible to clear the slag accumulation, and so the pyrometer was not reading when the gasifier started.

After startup, when personnel were allowed back on the gasifier structure, the slag clearing procedure was manually initiated and the sight tube was cleared. The pyrometer then read approximately 50 to 100 ºF higher than the highest reading gasifier thermocouple. This positive offset in readings between the pyrometer and thermocouples had been seen before in pilot testing at the Montebello Technology Center and was expected. A layer of slag develops over the thermocouples during operation that tends to insulate them somewhat from the temperature inside the reaction chamber. However, the pyrometer is able to look directly into the reaction chamber and measure the temperature of the hot, reacting fuel particles.

The pyrometer continued to give reasonable and relatively stable gasifier temperature readings during one to two hours of operation, as long as the sight tube clearing procedure was periodically activated. However, over the course of the next few hours, the sight tube clearing procedure became increasingly less effective in opening up the sight tube, and the average pyrometer reading decreased until it was several hundred degrees lower than the thermocouple readings. This indicated that a large amount of slag had accumulated on the gasifier wall around the opening of the sight tube. This slag was not responding to the sight tube clearing procedure. Eventually there was no response at all. The pyrometer system continued to operate, but the temperature reading was 1500 ºF, which is the reading that is displayed when the detector goes below scale.

At this point the difference between pilot unit and commercial operations became clear. At the Montebello Technology Center, most gasification test runs lasted no more than five days, after which the gasifier was shut down for inspection. Usually the pyrometer sight tube stayed open throughout a test run. But on those occasions when it did not, it was easy to clean out the sight tube in preparation for the next test run. However, in commercial power plant operations, the objective is to keep running as long as possible. So, the Polk Power Station gasifier continued to operate. Over the next several months Tampa Electric personnel made a number of attempts to reactivate the pyrometer using the sight tube clearing procedure, but without success.

There are at least three possible explanations for why the sight tube clearing procedure, which worked so effectively in the pilot unit, did not work in this first commercial demonstration. First, both the gasifier geometry and the feed injector in the Tampa Electric facility were slightly different than at the Montebello pilot units. It is possible that, in the Tampa Electric gasifier, the combination of feed injector design and geometry contributed to more slag being deposited directly on the pyrometer sight tube opening than in the Montebello gasifier.

Second, the ash composition may have been responsible for the failure of the sight tube clearing procedure. During this gasifier run, Tampa Electric was feeding a combination of petroleum coke and two other coals to the gasifier. The three feed components were chosen both for their low cost as well as for the ash characteristics of the resulting mixture. The composition of the ash must result in a slag viscosity that falls within a narrow range. The lower bound of the slag viscosity range is set by the need to prevent significant penetration of slag into the refractory because slag penetration decreases brick life. The upper bound is set by the need to ensure adequate flow of molten slag through the bottom exit of the reaction chamber. (See the explanation involving the T_{250} temperature, below.) Petroleum coke slag by itself will not flow out of the gasifier because of the very high melting temperature of the vanadium in the slag. That's one of the reasons why Tampa Electric adds coal to the feed along with the inexpensive petcoke. The ash from the coal helps to "wash" the ash from the petcoke out of the gasifier.

In the case of the slag accumulation at the opening of the pyrometer sight tube, there may have been a certain amount of slag separation that was occurring as a result of the sight tube clearing procedure. When the purge gas was shut off to allow the slag accumulation to reheat, it may have been that a portion of the coal ash melted and drained away from the accumulation, leaving behind a progressively higher melting deposit rich in petcoke ash components. Of course, without further investigation, including the sampling and analysis of the deposit, it cannot be determined for sure if this was actually occurring.

Third, perhaps the most likely explanation for the pyrometer sight tube operating problems is that Tampa Electric tends to run their gasifier very close to the slag T_{250} temperature. The slag T_{250} temperature is the temperature at which the viscosity of the slag is 250 Poise. In practice it has been found that a viscosity of 250 Poise is about the maximum viscosity that will allow the slag to drain reliably from the bottom of a slagging gasifier. Below the T_{250} temperature, the slag begins to thicken to the point were slag removal from the gasifier can be difficult. This, of course, is a simple rule of thumb, and the actual flow characteristics for any slag depends upon its composition. In practice, Tampa Electric runs their gasifier temperature as low as they can without encountering slag removal difficulties. This method of operation results in the maximum practical slag viscosity which, in turn, results in the maximum lifetime for the gasifier refractory (because of reduced slag penetration).

What this means for the pyrometer operation is that the gasifier temperature may never be quite hot enough for the sight tube slag clearing procedure to work properly. When the sight tube purge is turned off as part of the procedure, the slag accumulation around the opening of the sight tube does heat up. But it never heats up enough so that the accumulation can be blown out of the way by a subsequent pulse of purge gas. The viscosity, even of the reheated slag accumulation, is just too high. (This was usually not a problem in the pilot unit gasifiers at Montebello which tended to operate at temperatures high enough for the slag clearing procedure to work.)

Two responses to the sight tube slag deposit problems were considered. The first approach involved increasing the size of the nitrogen purge valves to allow more purge gas to be used to move the slag deposit out of the way during the sight tube clearing procedure. In addition, several control points would be added to the DCS to allow the sight tube clearing procedure to be manually initiated from the control room. The second approach was to move the pyrometer system to a new location where slag was not expected to be a problem. The plant had not used most of its soot blowing lances in the radiant syngas cooler for several years because slag and ash deposition in the radiant syngas cooler turned out to be much less of a problem than expected. One of the lances in the top-most bank of soot blowers was available, and the lance could easily be modified to accommodate the sight tube for the pyrometer.

A joint decision was made by Tampa Electric and ChevronTexaco to try the second approach, and so Tampa Electric moved the pyrometer system down to the top of the radiant syngas cooler. This location allowed the pyrometer to view the interior of the radiant syngas cooler just a few feet below the transition duct between the gasifier reaction chamber and the top of the radiant syngas cooler. The relocation of the pyrometer system was completed in time for the gasifier operations which began in April 2005.

With the pyrometer in this new location, no problems with slag accumulations around the sight tube were encountered. Pyrometer readings were continuous and relatively steady for months at a time. However, they were roughly 800 to 900 ºF lower than the highest reading gasifier thermocouple. The reason for this temperature difference most likely has to do with the geometry of the radiant syngas cooler and the way syngas and molten ash flow into it from the gasifier.

The gasifier is connected to the radiant syngas cooler via a vertical, cylindrical passageway (the throat) that conducts hot syngas and molten slag down into the top of the cooler. Most of the radiant syngas cooler is filled with vertical heat exchange surface that recovers heat from the syngas. However, in the cylindrical space immediately below the throat, there are no heat exchange surfaces. This allows the droplets of molten slag coming down through the throat to fall straight down the center of the radiant syngas cooler without encountering any metal surfaces to which they could adhere and form deposits. Instead, the droplets go straight down to the bottom of the cooler where they are rapidly quenched and solidified in a pool of water. A significant portion of the droplets descends along the periphery of this cylindrical volume because they form by the breakup of the molten slag layer that runs down the wall of the throat. These droplets form, as it were, a cylindrical curtain of slag droplets with hot gas on the inside, and cooler gas on the outside. The side of this descending curtain of droplets which faces outwards from the centerline and views the cold heat exchange surfaces in the periphery of the syngas cooler rapidly cools by radiation. It is most likely this cooler side of the “slag curtain” that is being measured by the pyrometer and explains why the measured temperature is so much lower than that of the gasifier. Apparently the number density of slag droplets is high enough that the pyrometer cannot “see” the hotter gas and particles in the very center of the cooler.

In any case, although the pyrometer reading in this location was continuous and steady, it was not suitable for use as a gasifier temperature measurement; the offset was too great, and the response time was too slow. Still, this measurement provided a valuable data point. It validated computer simulations of the temperature distribution within the radiant syngas cooler because the pyrometer readings were very close to the values calculated by the simulation for that region of the syngas cooler.

A number of potential improvements to the design and operation of this device have been identified. However, all of the funds that were available in this U.S. DOE contract have been spent, and work on this device will not continue under this program. In the future, GE Energy may choose to implement some or all of the improvements as part of its own internal gasification R&D program.

Subtask 6.9 – Pyrometer System Performance Evaluation Report
This task is fulfilled by the writing and submitting of this final report to DOE on behalf of ChevronTexaco, the contract owner.

Concluding Summary

Under Phase 1 of U.S. DOE contract DE-FC26-99FT40684, Texaco’s Montebello Technology Center successfully designed, built, and bench tested an infrared ratio pyrometer system for measuring gasifier temperature. Under Phase 2 of the contract, ChevronTexaco completed two field test campaigns at Tampa Electric’s Polk Power Station in Florida. During the first test campaign, the pyrometer was sighted into the gasifier. It performed well for a brief period of time and then experienced difficulties in keeping the sight tube open due to a slag accumulation which developed around the opening of the sight tube in the gasifier wall. In the second test campaign, the pyrometer was sighted into the top of the radiant syngas cooler through an unused soot blower lance. The pyrometer experienced no more problems with slag occlusions, and the readings were continuous and consistent. However, the pyrometer readings were 800 to 900 ºF lower than the gasifier thermocouple readings, which is consistent with computer simulations of the temperature distribution inside the radiant syngas cooler. With this large temperature offset and slow response time, the pyrometer sighted into the radiant syngas cooler is probably not suitable for use as a gasifier temperature measurement that could be used for gasifier control or safety system purposes. A number of potential improvements to the design and operation of this device have been identified. However, all of the funds that were available in this U.S. DOE contract have been spent, and work on this device will not continue under this program. In the future, GE Energy may choose to implement some or all of the improvements as part of its own internal gasification R&D program.

GE Energy would like to gratefully acknowledge the assistance of Mark Hornick, John McDaniel, Lloyd Webb, Tim Pedro and the rest of the staff at Tampa Electric's Polk Power Station. Without their interest and expert assistance, this project would not have been possible.