SECTION 1: TITLE PAGE

I&I FINAL TECHNICAL REPORT

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**SYSTEM FOR DETECTION AND CONTROL OF DEPOSITION IN
KRAFT CHEMICAL RECOVERY BOILERS AND MONITORING
GLASS FURNACES**

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SECTION 2: NARRATIVE

A. Brief Summary of the Original Project Goals

The purpose of this project, as originally stated, was to finish the development of a system to monitor and control deposition on the pendant tubes of recovery boilers and investigate the applicability of the system to utility power boilers, and glass furnaces.

The critical R&D challenges identified in the original proposal were:

- ?? Development of survivable off-axis imaging optics to capture images of deposits deep in boiler convection passes.
- ?? Development of software needed to process the captured images to reliably detect deposits in different locations from different viewing angles.

In addition, the following technical goals were identified:

- ?? Integration of the system output with the sootblower control system.
- ?? Demonstration that the system works properly through extensive testing in recovery boilers.
- ?? Demonstration of infrared imaging in a glass melting furnaces and utility boilers

B. Variance from Project Goals

The goals of this project have been achieved.

- ?? Survivable off-axis imaging optics have been developed and images of deposits deep within the convective sections of several recovery boilers have been obtained.
- ?? Image analysis software has been developed and demonstrated
- ?? A detailed design has been developed for the integration of the imaging system with a Clyde Bergemann sootblower and a Solvera sootblower control system using off-the-shelf components.
- ?? Numerous tests have been performed in three recovery boilers and the ability to obtain clear images deep in the convective sections has been demonstrated.
- ?? Images have been obtained in a glass melter and several tests were performed in coal-fired utility boilers to assess the utility of infrared imaging in those applications.

C. Narrative Discussion of Project Results

Executive Summary

Combustion Specialists, Inc. has just completed a project designed to develop the capability to monitor and control the formation of deposits on the outside of boiler tubes inside an operating kraft recovery furnace. This project, which was carried out in the period from April 1, 2001 to January 31, 2003, was funded by the Department of Energy's Inventions and Innovations program.

The primary objectives of the project included the development and demonstration of the ability to produce clear images of deposits throughout the convective sections of operating recovery boilers using newly developed infrared imaging technology, to demonstrate the automated detection and quantification of these deposits using custom designed image processing software developed as part of the project, and to demonstrate the feasibility of all technical elements required for a commercial "smart" sootblowing control system based on direct feedback from automated imaging of deposits in real-time.

All of the individual tasks have been completed and all objectives have been substantially achieved. Imaging of deposits throughout the convective sections of several recovery boilers has been demonstrated, a design for a combined sootblower/deposit inspection probe has been developed and a detailed heat transfer analysis carried out to demonstrate the feasibility of this design, an improved infrared imager which can be sufficiently miniaturized for this application has been identified, automated deposit detection software has been developed and demonstrated, a detailed design for all the necessary communications and control interfaces has been developed, and a test has been carried out in a glass furnace to demonstrate the applicability of the infrared imaging sensor in that environment.

The project was completed on time and within the initial budget. A commercial partner has been identified and further federal funding will be sought to support a project to develop a commercial prototype sootblowing control system employing automated deposit imaging.

Technical Report

Background

At the end of the twentieth century, about 82% of the wood pulp consumed at US paper/paperboard plants was produced via the Kraft process [1]. While the proportion of pulp from this source is likely to decline as new processes come on line, in 2025 the Kraft process will still account for well over 50% of wood pulp production. Kraft chemical recovery furnaces are large and expensive, with capacities of furnaces installed in the last 30 years typically exceeding 1000 tons of pulp per day [2]. Since it is difficult to economically add small incremental units of capacity, the capacity of the chemical recovery boiler is often the factor limiting the capacity of the entire pulp mill.

Processes governing the deposition of fume and carryover on heat transfer surfaces and attendant plugging of gas passages frequently determine the recovery boiler's effective burning capacity [3]. Much effort has been devoted ([3, 4, 5, 6] and 30 references therein) to improving understanding of the mechanisms of particulate deposition. However, there are still no reliable on-line methods for systematically detecting the presence and the build-up rates of these deposits. Control efforts have therefore necessarily been based on indirect measurements and considerations and have often yielded unsatisfactory results.

Near-IR smelt-bed imaging systems, developed by one of the collaborators [7, 8] have been widely used for smelt bed imaging in recovery boilers for many years, and some interesting results have been obtained by automatically processing these smelt bed images for use in control applications [9, 10, 11]. Attempts have been made to use near-IR cameras for direct monitoring of pendant deposits. However, it has been difficult to get good images in the near-IR, while devices operating at longer wavelengths have, until recently, been impractical for boiler-side use because of prohibitive expense and the need for reliable cooling to low (liquid nitrogen) temperatures.

Recently, ferroelectric and microbolometer detector arrays have become commercially available from a number of sources including Raytheon [12], LIRIS [13], Amber Engineering [14], the Santa Barbara Research Center [15] and the ULTRA Consortium [16] consisting of Honeywell, Rockwell, Inframetrics and the New Jersey Institute of Technology. These devices are relatively inexpensive and do not require cooling, making them suitable for boiler applications. Moreover, the price of computing power continues to plummet, making sophisticated multi-point data processing schemes quite practical for on-line application. The current project has been focused on applying these technologies to produce clear images of boiler tube deposits throughout the convective sections of operating kraft recovery boilers and applying computer image analysis techniques to these images so as to accurately detect and measure the deposition of pluggage-causing materials.

Project Description

The purpose of this project, as originally stated, was to finish the development of a system to monitor and control deposition on the pendant tubes of recovery boilers and investigate the applicability of the system to utility power boilers, and glass furnaces. This effort built on previous projects partially sponsored by the US Department of Energy (DE-FC36-99GO10375) and by the Washington Technology Center (FTI 96-A9).

The system envisioned to achieve the goal of automated on-line deposit inspection and control consists of a number of sensing devices mounted in the upper furnace and in the convection pass sections of a boiler, connected to a data processor feeding a control system, as schematically shown in Figure 1.

Figure 1. Sensor locations

The deposit monitoring sensors developed prior to the start of this project consisted of packaged low-cost ferroelectric arrays manufactured by Raytheon, and modified both optically and electronically for operation below 7 microns in a spectral band that had been shown to provide optimal visibility in the recovery boiler environment, and in such a way as to avoid chopper-induced artifacts (the development and packaging of these devices was a primary focus of an earlier R&D program). Mid-IR ZnSe imaging optics had been used in a survivable, axially arranged lens tube to look directly into the boiler through an inspection port and had been shown to provide clear images of the interior of the boiler. However, many of the more important measurement locations in the convection passes are not readily accessible with this type of lens arrangement, so a major focus of the current project was to develop optical trains that image off-axis, and can be inserted some distance into an operating boiler.

The second major focus of this project was the development of an automated data processor capable of analyzing the images of deposit-laden tubes to provide quantitative measures of the size and location of the deposits. The two key elements of the data processor are the image analysis software, and the software needed to integrate the sensing system with boiler cleaning control systems. A preliminary version of the image processing software had been developed as part of the earlier Agenda 2020 project, but it had been optimized for images obtained with axial optics viewing the front of the superheater from the front wall of the boiler. In these images, the vertical superheater and screen tubes were all nearly parallel and were always viewed from a fixed perspective. In the current project, our objective was to obtain images from locations inside the convective sections using a side-looking probe that could be rotated 360 degrees. This meant that we had to deal with images taken from a variety of perspectives and new software had to be developed to deal with these much more complex scenes.

The project objectives have been realized. All significant components of a system to monitor and control recovery boiler pendant tube deposits have been either designed, fabricated and demonstrated through field testing or studied in sufficient detail to provide a clear understanding of viable and practical approaches that could be used in a commercial prototype.

Experimental prototypes developed during the course of the project have been thoroughly tested in several kraft recovery boilers, in a glass furnace and in a coal-fired electric utility boiler. Some of the designs developed during the course of the project have also been incorporated into commercial products.

Project outline

This project was divided into 15 tasks shown in the Completed Milestone Table (see attachment A) which also shows the planned and actual completion dates and costs by task. Of the 15 tasks shown in the milestone table, 6 involved reporting activities. Thus, the actual development work was focused in 9 areas:

1. Refined Axial Optical Train
2. Image Capture System
5. Particle Scattering Analysis

6. Improved Imaging Device
8. Off-Axis Optical Train
10. Image Processing Software
12. Control System Integration
13. In-Boiler Testing
14. Glass Furnace Tests

These tasks will be discussed in detail in the following section. The actual timeline of the individual tasks is shown in the final Gantt chart in attachment B.

Discussion of Individual Tasks

Task 1. Refined Axial Optical Train

The lens train developed as part of the earlier Agenda 2020 project, which utilized ZnSe lenses, was based on a design that proved to have insufficient light throughput to allow its use in the coolest regions of a Kraft recovery boiler. Therefore, Task 1 of the current project was intended to refine the design of the lens tube to correct this deficiency as well as a vignetting problem encountered with the earlier design.

In April, 2001 a new optical design was developed which called for the use of AMTIR (GeAsSe glass) lenses. A set of these lenses was obtained and a short lens tube employing the new design and lens material was tested in the laboratory. In addition, three field tests were conducted in May and June of 2001. The light throughput and image forming capability of the new design was found to be quite acceptable; however, significant difficulties were encountered in applying a suitable anti-reflective coating to this material and the material was found to shatter easily.

Figure 2 shows the layout of the new axial lens train which consists of an objective lens at the front end and a series of 3 field lenses and 2 relay lenses to transfer the image formed by the objective back to the focal plane of the infrared imager.

Figure 2. Axial lens train used in short lens tube

Based on conversations with a number of IR lens manufacturers, the decision was made to switch to silicon for the lens material. In July, 2001 the optical design was modified to account for the difference in refractive index and it was determined that the predicted performance of the

lens train using silicon lenses was significantly better than the AMTIR lens train. Silicon is a more durable material than AMTIR and, in addition, excellent anti-reflective coatings for silicon are available and in widespread use. In mid-August, 2001 a sufficient number of silicon lenses was ordered to allow us to assemble either five standard length axial lens tubes or one 6-foot long side-looking lens tube.

The silicon lenses for the revised axial lens design were received in October, 2001 and a new forward looking lens tube was assembled. As anticipated the performance of the silicon lenses was quite similar to that of the AMTIR lenses we had previously been using. Several boiler tests were performed during November and the new design appeared to work very well in regions of the boiler as far back as the economizer inlet. In the back-pass region (downstream of the economizer), the light levels are very low due to the low temperatures and the image quality obtainable with our lens tube was found to be marginal but usable. By the end of November, 2001 we believed that this task had been completed, but in late February, 2002, we encountered a boiler where we were unable to obtain usable images even at the economizer inlet.

This led us to re-examine our lens design and we began assessing possible approaches to increasing light throughput even further. In March, 2002 we concluded that this could be accomplished in two ways: by eliminating the relay lens train and using only a low f/# objective assembly or by redesigning the relay lens train using shorter focal length relay and field lenses. The former approach can only be used with the current camera when viewing through a man-door or, alternatively, with a miniaturized camera which would be placed within the tip of an insertable probe. This option will be described further in the discussion of task 8. The latter approach would allow us to maintain the current air-purged lens tube arrangement, but would also require us to decrease the lens spacing which, in turn, would result in an increase in the number of lenses required. This would not be a serious problem with the short forward-looking lens tube used in the portable inspection camera or with cameras permanently mounted on the front wall of the boiler used to inspect the front of the superheater since these applications can use relatively short lens tubes with only a few relay and field lenses. However, this approach would be very undesirable for longer lens tubes employing a large number of field and relay lenses such as those which will be discussed under task 8.

At the conclusion of the project, a much improved design for the axial optical train had been developed and implemented and is now incorporated as the standard lens tube in the commercial boiler inspection camera (BIC) which is being sold through a licensing arrangement with Clyde Bergemann, Inc.

Task 2 – Image Capture System:

An image capture system will be required in a permanently installed deposit inspection and sootblowing control system to gather images from an array of cameras viewing a variety of locations within the convective sections of the boiler (see figure 1). The image capture system must be capable of receiving video inputs from several cameras. These images must be stored and tagged with information as to the particular probe associated with that image as well as the

insertion depth and rotational position of the probe at the time the image was captured (where the camera was and which direction it was looking).

At the beginning of this project, it was anticipated that an image capture system would be assembled and demonstrated with an array of camera probes such as that which would be required in the full commercial system. However, a preliminary survey of the vendor literature completed in June, 2001 suggested that the image capture part of this task could be accomplished using off-the-shelf components. Therefore, further work on this task was postponed until much later in the project when the control system integration task (task 12) was addressed.

The image capture, image processing, and control system integration tasks are intimately related and subsequent discussions of the latter two tasks will refer back to the image capture task. However, since a discussion of the various events associated with these three interrelated tasks requires an understanding of the overall structure of the system, that structure will be described here.

As described above, images of deposits deep within the convective sections will be obtained using off-axis optical probes that will be inserted periodically into the boiler and will rotate to provide images taken from a variety of positions (insertion depths) and viewing angles (rotational positions). In order to simplify the job of assigning locations to the observed deposits, we have adopted an approach that relies on providing the image processing software package with additional information on the insertion depth and rotational position of the right angle optical probe which will be provided by encoders mounted on the insertion mechanism of each probe.

Quantitative measures of deposit severity produced by the image processing software are combined with the position information obtained from the probe encoders and signals representing deposit severity and location are generated and passed to the sootblowing control package resident in the boiler DCS system.

Because tasks 2 (Image capture), 10 (Image processing), and 12 (Control system integration) turned out to be so closely coupled, and since tasks 2 and 12 were deemed to require no research or development activity based on the observation that they could be accomplished with off-the-shelf components, the bulk of the activity on task 2 was combined with task 12 and addressed after task 10 was substantially completed – in the last few months of the project. A controls specialist was hired to specify the required components to accomplish all the image capture functions, the camera and probe control and communications functions, and the necessary interfaces with the boiler DCS system. The system design which was developed will be described in detail in the discussion of task 12.

At the end of the project, a detailed specification including a parts list with part numbers and prices, wiring diagrams, and process flow diagrams has been developed for a system capable of addressing all of the image capture requirements using off-the-shelf components.

Task 5 – Particle Scattering Analysis:

Data on the size distribution and concentration of fume [17] and intermediate size particles (ISP) [18] were obtained from in-situ measurements performed at Weyerhaeuser's Longview recovery boiler in November, 2000 and May, 2001. These data were obtained as part of two DOE funded Agenda 2020 projects and reported at the International Chemical Recovery Conference, which was held at Whistler, B.C. in June 2001.

In September, 2001 a commercial Mie scattering software package [19] was obtained to perform light scattering and absorption calculations with which we can determine the impact of suspended particles on visibility as a function of wavelength in a number of industrial process environments. The particle data referred to above were used to perform calculations for the recovery boiler environment and, as expected, the results show that particle scattering has a significant, but tolerable impact on visibility at the 4 micron wavelength utilized by the IR camera being used for this project. These calculations predict that at 4 microns, approximately 45% of the light emanating from an object such as a boiler tube will propagate over a distance of 10 meters without experiencing scattering by the particles present in the recovery boiler environment. The remaining 55% will undergo scattering by the particles and will be randomized. This scattered radiation will contribute to a more or less uniform background of light which contains no image information. Thus, the image contrast will be significantly reduced by particle scattering. Let the contrast be defined as follows:

$$C = \frac{I_{\max} - I_{\min}}{I_{\max}} \quad (1)$$

where, $I_{\max}$ is the intensity of the brightest object in the image and $I_{\min}$ is the dimmest. In the ideal case of no absorption or scattering, when viewing a black and white target, $I_{\max}$ will be 100% and $I_{\min}$ will be 0%. In this case the contrast, $C = 1$. In the case where 55% of the light is scattered the resulting contrast will be 45%. This is certainly a serious degradation, but still sufficient to provide usable images for deposit detection.

As shown in Figures 3 and 4 below, this modeling work predicts that particle scattering and absorption become somewhat less severe at longer wavelengths suggesting that better visibility could be obtained by increasing the wavelength if spectral windows could be found where molecular absorption is small. However, previous modeling work has shown that the 4 micron region is preferable from the standpoint of molecular interference and the current particle scattering calculations do not negate that conclusion. Furthermore, the superiority of the 3-5 micron band in the recovery boiler application was confirmed experimentally in the preceding Agenda 2020 project using several infrared cameras operating in both the 3-5 and 8 – 12 micron band.

Figure 3. Light extinction from fume and ISP particles

Figure 4. Light transmission predicted from particle scattering analysis.

Initially, it was anticipated that a similar analysis would be carried out for the environment inside

glass furnaces to provide a basis for analysis and optimization of the glass furnace tests conducted in task 14. However, discussions with glass industry experts and a review of the literature revealed that the temperature inside most glass furnaces is well above the vaporization temperature of silica, the only significant species that could lead to significant numbers of suspended particles in the gas stream inside the furnace. Consequently, fume formation, which was initially expected to impact visibility, doesn't occur in these units until the gas has traveled a significant distance into the exhaust stack. Thus, conditions inside glass furnaces tend to be quite clear, even in the visible part of the spectrum. Therefore, no particle scattering analysis was conducted for glass furnaces.

At the end of the project, the effects of scattering by suspended particles on the transmission of light through the gases inside a recovery boiler have been analyzed. Previous speculations with respect to visibility at various infrared wavelengths which were based on earlier experimental observations have been confirmed and placed on a firm theoretical footing.

Task 6 – Improved Imaging Device:

Initially, this task was intended to cover modifications to the ferroelectric array camera such as increasing the frame integration time or switching to different wavelengths in order to increase the sensitivity of the camera to compensate for low light levels in the cooler regions of the boiler. However, that activity was put on hold when a more serious problem was encountered during field tests at the Westvaco Roanoke, VA mill in July, 2001. The ambient temperature near the boiler at that mill was approximately 130 deg F and the compressed air supply used to purge and cool the lens tube on our system was also about 130 deg F. Under these conditions, the camera would operate properly for only a few minutes before the image became covered with black dots, which rapidly coalesced to obscure most of the image. Significant effort was expended in August and September to find solutions to this problem. Three modifications were adopted which have overcome the overheating problem and have also resulted in a significant improvement in image quality.

The first modification was the addition of a pair of commercial vortex coolers to the system. These coolers reduce the temperature of the incoming air supply by as much as 70 deg F, although the presence of a standing shock wave in the hose fitting at the exit of the vortex coolers reduces this advantage somewhat. A modification to the chopper was also introduced to minimize the temperature “contrast” between image and background, and a small modification was made to the electronics to prevent saturation of the signal by large temperature differences in the scene.

Subsequent field trials performed at the Longview Fibre mill in Longview, WA and at the International Paper mill in Augusta, GA in late September, 2001 showed that these modifications had eliminated the overheating problem.

Following a series of boiler trials using our six foot right angle probe which employs a series of relay and field lenses (described in the next section), we concluded that this relay lens train design will not be suitable for longer probes. However, in a permanently installed, automated

boiler inspection and sootblower control system, it will be necessary to obtain images from locations up to 20 feet from the side wall of the boiler. After examining several possible options, we have determined that the most feasible approach for a fifteen to twenty foot long probe will be to place a miniature IR imager at the tip of a sootblower lance tube. This will eliminate the need to transfer an infrared image by means of relay lenses or fiber optics over the length of the probe. Instead, only electrical power and video signals will need to be conveyed to and from the camera through the bore of the lance tube. This approach will also allow the optical system to be reduced to only a simple one or two lens assembly, which should greatly improve its optical performance and light gathering capability. Adequate cooling will need to be provided to maintain the temperature of the camera at or below 130 deg F. Design of such a system was not anticipated at the beginning of the project, but, because the success of a commercial system appears to hinge on the viability of this approach, two additional activities were undertaken as part of this "improved imaging device" task, the first being an investigation of possible approaches to miniaturization of the IR imager, and the second being a study of the feasibility of providing adequate cooling for the camera in an insertable probe.

The IR imager currently being used is a ferroelectric array device manufactured by Raytheon. Because the ferroelectric array is responsive only to changes in illumination and not to a constant IR scene, a rotating chopper is employed to modulate the intensity of the image. The chopper currently being used is approximately 2.5 inches in diameter, which sets the lower limit on the size of the current camera. In reality, with the current chopper it would be difficult to reduce the size much below about 3.5 inches in diameter which would be difficult to accommodate in an insertable probe of reasonable size. A study was performed to investigate alternate chopper designs and one promising design was identified. However, during the course of the project, an alternate infrared imaging technology came to our attention. This is a MEMS-based device originally developed by the Oak Ridge National Lab and being commercialized by Sarcon Microsystems, Inc. [20]. This device does not require a chopper and could be placed in a much smaller package than the Raytheon camera. Also, it has the potential to be much more sensitive and have a much wider dynamic range than the ferroelectric array device. Sarcon anticipates offering a commercial product in early 2004 and CSI has made arrangements to be a beta-tester of this unit.

In addition to the challenge of obtaining a smaller IR imager, placing the imager at the tip of an insertable probe poses the serious challenge of providing adequate cooling to allow the imager to survive and operate for at least 5 minutes at a time when inserted into the recovery boiler. The five minute limit reflects the fact that in normal operation, a typical sootblower takes approximately 4 minutes to be fully inserted and retracted. In developing the probe design, we decided to avoid the use of liquid coolants due to the greatly increased complexity associated with recirculating systems which would require pumps, tanks, heat exchangers, flow monitors, valves, etc. and the unacceptable hazard of smelt-water explosions associated with the use of water inside the recovery boiler. Therefore, the design we have developed employs only air and steam to provide the needed cooling. The probe we envision consists of three concentric tubes forming two annular spaces plus an inner bore.

Two critical concepts have allowed us to develop this design and to show that it is capable of providing adequate cooling. The first concept is based on the observation that incorporating the camera into an operating sootblower actually makes the job of cooling the camera easier than it would be in a dedicated camera probe. This is because the steam flowing through the annular space formed by two outer concentric tubes, provides a boundary condition at the surface of the second tube equal to the steam temperature (~ 486°F for saturated 600 psi steam) rather than having the outer surface of the probe exposed to the combustion gases at temperatures between 1000 and 2000°F. The second concept is to use an evacuated space between two of the concentric tubes as an insulator and to incorporate highly reflective surfaces to minimize radiative heat transfer as in an ordinary Thermos[®] bottle.

Figure 5 shows a schematic of the conceptual design of a modified sootblower probe which would incorporate a miniature IR imager at its tip. As described above, the annular space between the outermost and the middle tube carries the steam required by the sootblower. The space between the middle and innermost tubes is evacuated. The inner surface of the middle tube, and the outer surface of the inner tube are plated with a highly reflective (low emissivity) metal to minimize radiative heat transfer across this insulating barrier. Cool air flows through the inner bore which also carries wiring to provide power to the IR imager and carry video signals back from the imager.

Figure 5. Modified sootblower design used in heat transfer calculations

The design developed here assumes that the sootblower consumes 20,000 lb/hr of saturated steam at 600 psi, typical of sootblower operation. The outer tube is assumed to be a 4 inch schedule 40 stainless steel pipe and the outer annular space has been sized to accommodate this steam flow with minimal pressure drop.

An engineering model was developed to evaluate the thermal performance of the probe and predict the temperature of the cooling air stream after traveling the full length of the probe. The calculations were carried out in steps and in each step, the most conservative estimates were made to ensure the actual performance would match or exceed that predicted by the model.

The first step was to determine the heat load on the probe due to radiative and convective heat transfer from the combustion gases to the probe. For this step, the probe surface temperature was assumed to be at the saturation temperature of the 600 psi steam. The actual temperature will always be higher than this, so the heat flux calculated using this assumption represents an upper limit. Based on typical conditions inside a kraft recovery boiler, the radiative heat flux was

calculated to be 62 kW for a 15 foot long probe and the convective heat transfer was calculated to be 10 kW for the same probe.

In the second step, the temperature rise of the steam flowing through the outer annular space was calculated and found to be only 14°F. Therefore, for the next step, the outer surface of the middle tube was assumed to be at the steam saturation temperature for the full length of the probe.

The third step involved calculating the heat flux through the steel wall of the middle pipe and through the vacuum gap between the middle and inner tubes. To set an upper limit on this heat flux, the outer surface of the inner tube was assumed to be at the inlet air temperature. In actual operation, the tube surface temperature will always be higher than this leading to a smaller heat flux than that predicted by the model. Thus, the actual temperature rise in the cooling air stream will always be less than what the model predicts.

The model shows, not surprisingly, that the heat flux across the vacuum gap depends very sensitively on the emissivity of the two surfaces bounding the vacuum gap. Therefore, it is critical to choose a very low emissivity material for these surfaces in order to minimize the heat flux. Figure 6 shows the calculated heat flux to the cooling air stream for a variety of surfaces and for both a vacuum gap and an atmospheric air filled gap. In the latter case, heat conduction through the air has been added to the model.

Figure 6. Heat load on cooling air stream for a fifteen foot long probe

In the labels on each of the curves in figure 7, the first material refers to the inner surface of the outermost tube and the second material refers to the outer surface of the middle tube. As can be seen, an evacuated gap produces substantially lower heat flux than if the gap is filled with air at atmospheric pressure. Also, the very low emissivity of electrolytic nickel produces the lowest heat flux across the gap. In the best case – an evacuated gap with nickel on both surfaces – we can see that the heat flux is remarkably low – about 65 watts.

The fourth step, then, is to calculate the temperature rise in the cooling air as a function of the heat flux determined in step 3 and the cooling air flow rate. Figure 7 shows the predicted temperature rise of the cooling air over the full length of the 15 foot long probe as a function of air flow rate for a number of heat flux values. As can be seen, in the case where the heat flux is 65 watts, even an air flow rate as low as 5 scfm results in a temperature rise of only about 22°C (40°F), so if the inlet air temperature were, say, 60°F, the cooling air temperature at the tip of the probe would be 100°F, well below the 130°F limit for acceptable camera operation.

Figure 7. Dependence of cooling air temperature rise on air flow rate and heat flux

These calculations show that placing an infrared camera inside a modified sootblower is feasible from the standpoint of being able to provide adequate cooling. The availability of the Sarcon MEMS IR imager early next year will provide a sufficiently compact IR imager to make it possible to implement the approach described here.

In June, 2002, CSI submitted a proposal to the NICE³ program for a project to develop a commercial deposit inspection and sootblowing control system. Clyde Bergemann, Inc., a leading manufacturer of sootblowers and sootblowing control systems, agreed to participate in this project and provide a substantial cost sharing contribution. It was our intention to build a commercial prototype system based on the design concepts developed in the current I&I project with funding provided by the NICE³ program. However, that proposal was not selected for funding and we are currently looking for another program with suitable objectives to provide the needed funding to move forward towards our ultimate objective.

At the end of the project we have identified a sufficiently small IR imager with suitable performance attributes to allow us to build a modified sootblower/deposit inspection probe. We have also developed a detailed heat transfer model and used it to demonstrate the feasibility of providing adequate cooling to allow an imager mounted in such a probe to survive in the target environment.

Task 8 – Development of Off-Axis Imaging Optics:

A major objective of this project was to demonstrate the ability to obtain useful images of deposits in the convective sections of recovery boilers in areas that are not observable using axial optics viewing from a sidewall inspection port. This capability will be required to detect deposits throughout the boiler and provide feedback to a "smart" sootblowing control system. In addition to the objective of demonstrating this capability, it was also recognized that it would be necessary to obtain such images in order to develop the image processing software required to demonstrate automated detection and quantification of deposits in the convective sections of a recovery boiler. This latter requirement made it essential that we develop the off-axis imaging capability fairly early in the project so as to be able to obtain the needed images in time to develop the image processing software by the end of the project.

Because of this time constraint, we chose to develop a probe of modest length based on the relay lens train design used for the axial imaging optics already in use in our commercial Boiler Inspection Camera. We determined that a six foot length would allow us to penetrate to a depth sufficient to obtain representative images from the necessary perspective for use in the development of the image processing software. By incorporating a right angle mirror at the tip of the probe we were able to provide right angle viewing capability to allow us to gather images of boiler tubes and gas passages looking at right angles to the probe axis. A detailed design for the optical train, utilizing a series of 22 relay and field lenses and a right angle mirror, was developed based on the design of our axial lens tube. The required silicon lenses, anti-reflection coated for operation at 4 microns, and a gold-coated diagonal mirror were obtained and tested in the lab. (see figure 8.)

Several designs were considered for the water cooling jacket and a final decision was made based on considerations of cooling capacity and mechanical stiffness. In order to provide the needed stiffness in the vertical plane while being narrow enough to fit through a standard boiler inspection port (typically 2 inches wide by 10 inches tall) a design was selected that employed rectangular tubes mounted above and below a central circular multi-wall tube. These rectangular

tubes provided the required stiffness and also served as return passages for the cooling fluid. Heat transfer calculations were performed that showed an anticipated temperature rise in the cooling water of 95°F at a flow rate of 5 gallons per minute when the probe is inserted 6 feet into the boiler. This was considered quite acceptable and indicates that the probe can be operated for an indefinite length of time without overheating. One important feature of the design is that it allows the optical train and camera to rotate relative to the cooling jacket which remains fixed. This is necessary since the cooling jacket cannot be rotated when inserted through an inspection port, whereas one major objective was to be able to rotate the optics in order to provide 360° viewing capability within the boiler's convective section.

Figure 8. Optical train on bench (shown without right angle mirror)

Figure 9 shows a cutaway view of the probe and cooling jacket and figure 10 shows a closeup of the tip.

Figure 9. Cutaway view of lens tube and cooling jacket

Figure 10. Tip of probe showing objective lens, mirror and protective window

The mechanical design was completed in February, 2002 and construction of the mechanical components was completed in mid-March. The optical and mechanical components were assembled and except for a few very minor problems, the design was found to be quite functional. A leak check was performed on the cooling jacket and one minor leak was remedied by re-welding the offending joint. Figures 11 and 12 show the assembled probe and a close-up of the tip.

Figure 11. Assembled probe with IR camera

Figure 12. Tip of probe showing sapphire window and right angle mirror

The first field test of the six foot right angle probe was conducted at the Port Townsend Paper facility in Port Townsend, WA on April 4th and 5th, 2002. The six foot right angle probe worked quite well, although significant fouling of the sapphire window was observed despite an air purge that had been intended to keep the window clean. A second test was conducted at the Simpson Tacoma Kraft mill in Tacoma, WA on July 11th, 2002, following a redesign of the air purge nozzle used to blow air over the sapphire window. Although there was still some fouling, the new arrangement maintained a clear area at the center of the window and visibility was only slightly degraded. The fouling pattern observed with the initial arrangement is shown in figure 13 and the fouling pattern observed after several minutes in the boiler using the modified purge arrangement is shown in figure 14.

Clearly, further refinement of the air purge will be necessary for long-term, unattended operation of a permanent installation which employs probes which are automatically inserted periodically. However, these tests have shown that the current air purge is adequate to keep the window sufficiently clean for up to 10 minutes at a time. Since the typical sootblower is inserted into the boiler for only 4 minutes at a time, this should be adequate if a means of cleaning the window each time it's retracted can be devised. An easy way to accomplish this would be to blow steam on the window for a few seconds following retraction or just prior to insertion.

Figure 13. Window fouling with initial purge arrangement

Figure 14. Window fouling with modified purge arrangement

At the end of the project, a six foot long, water-cooled, off-axis optical probe employing a set of relay and field lenses had been designed, fabricated and tested in three different recovery boilers. Images of boiler tubes and deposits were collected from a variety of locations within the convective sections of these boilers. Image quality was observed to range from fairly good to rather poor – especially in cooler regions where the intensity of infrared radiation is low. As discussed in the previous section, an alternate design in which the infrared imager would be placed at the tip of a modified sootblower would eliminate the need for the relay lens train which is responsible for the poor image quality and low light gathering power of the current optical system. Fouling of the sapphire window which was observed in the first test was moderately well corrected in subsequent tests by redesign of the air purge nozzle. The cooling system employed with this probe worked flawlessly and allowed the probe to operate for extended periods without any evidence of overheating.

Task 10 – Image Processing Software

The software for the deposit inspection system must be able to take captured images from a series of cameras—each of which will be viewing different regions of the boiler using a rotating off-axis imaging system—and determine the size and location of observed deposits. The imaging probe must be capable of rotating in order to allow the system to view upstream, downstream, above and below the location of the probe itself. Therefore, the perspective of the captured images will be constantly changing. In order to simplify the problem as much as possible, the algorithm will rely on independent measurements of the insertion depth and rotation angle of the probe. Two possible image processing approaches were considered: a perspective transformation approach in which all scenes would be transformed to appear as if the tubes were being viewed along a line of sight perpendicular to the tube axis allowing the use of a single detection algorithm, and a “content-invariant matching” approach in which reference images would be captured at each location and viewing perspective when the boiler is clean, allowing direct comparison of images with deposits to those without deposits. The first approach offers greater rigor, but requires a detailed 3-D model of the interior of the boiler and is likely to be sensitive to errors such as changes in tube spacing. The second approach, although somewhat heuristic in

nature, is likely to be more robust and does not require a physical model of the scene. Therefore, our efforts in this project have focused on the latter approach.

In this approach, detection of deposits is accomplished by comparing “features” from each point of view (POV) to those features of the associated calibration images obtained from the same POV. Key features are selected such that changes in these features correlate strongly with the existence of deposits. The specific processing steps or algorithms involved for each POV can be different and the choice of algorithms for each POV is determined during calibration. The processing architecture for implementing this processing strategy is shown in figure 15.

Figure 15. Image processing architecture

One possible measure applied to an image could be the total length of straight edges relative to the length of straight edges in the reference scene. One very simple piece of a-priori knowledge that can be applied to images is that the edges of parallel tubes will appear parallel or will converge to a common vanishing point. This fact can be used to distinguish short line segments that appear straight, but which are actually surfaces of deposits, from actual tube edges. Other features which can be utilized are object size and contrast or texture.

At the beginning of the project, no infrared images were available from inside the convective sections since the off-axis probe had not yet been constructed. Therefore, some preliminary tests were performed using visible light images obtained during a water-wash using a miniature CCD camera and light source mounted on a long probe that was manually inserted into the boiler and rotated to obtain images of deposits. This kind of probe has been used in several boilers, but requires the boiler to be off-line during the inspection. These preliminary tests showed that the edge finding and dynamic background correction algorithms developed during the prior Agenda 2020 project worked well on images with varying perspective. Figures 16 and 17 show an example of these results for a partly fouled set of tubes.

Figure 16. Visible light image of partly fouled tubes

Figure 17. Processed image showing detected edges

Once the water-cooled off-axis probe had been developed, we began testing at the Port Townsend Paper mill and at the Simpson Tacoma Kraft mill and obtained several hours of video tape within the convective sections in each of these two boilers. After examining these images, we concluded that one simplification that could be made was to concentrate on detecting bridging between rows of tubes rather than bridging between tubes in the same row in the streamwise direction since the streamwise bridging has only minimal impact on heat transfer and no significant impact on gas flow. To test this approach we applied an edge detection algorithm and a series of grouping and filtering operations to reduce the scene content. This approach leaves regions between tube banks free of detail when no bridging between platens is present. Figures 18 through 23 show the sequence of processing steps.

Figure 18. Initial image

Figure 19. Filtered image

Figure 20. Grouping

Figure 21. Fill holes and reshape

Figure 22. Image processing result

Figure 23. Extract measurements
from Specified areas
for deposit classification

In the example shown in these figures, measurements in the center region would reveal the presence or absence of bridging between adjacent tube banks. It should be noted that these images were obtained in the superheater region where the spacing between adjacent tube banks is rather large. In the generator section, the spacing is much tighter and bridging is much more likely.

Because of the rather low contrast and clarity of some of the images obtained with the six foot right angle lens tube, an effort was made to devise a robust method for averaging multiple frames taken while the camera probe is rotating and translating in the hope that this would enhance contrast and clarity. This would be the case if the source of the poor signal to noise ratio were from time varying interferences in the scene. Frame averaging requires an automated approach to shifting successive frames before averaging to ensure proper registration. Frame registration is accomplished by performing a neighborhood search (5x5 neighbor minimum) & match. In general, averaging of adjacent frames results in lower white noise and slightly higher SNR, but the contrast remains similar. By averaging more frames (3 or more) the contrast improvement is

slightly better but the resulting images seem to be fuzzier near the edges, maybe due to distortion in the original images resulting from field curvature, which is known to be significant with the current lens design.

Demonstration of the selected approach based on comparison of images obtained during normal operation against reference images obtained on a clean boiler required us to be able to obtain examples of "before" and "after" scenes inside a single boiler. This opportunity did not present itself until very late in the project when we were able to run tests at the Weyerhaeuser Springfield, OR plant in October, 2002 just prior to an annual outage when the boiler was nearly completely plugged, and again in mid-November, 2002, about two weeks after the boiler was brought back on line.

Several problems were encountered that impacted our ability to obtain the kinds of images we had hoped for. First, we found that during the October tests, the boiler was so plugged that in most locations, we had difficulty obtaining any usable images. We believe that this was due to the deposits having grown to such a large size that the deposit surfaces were within only a few inches of the probe tip causing them to be out of focus, since the optics were designed to be able to focus no closer than about 12 inches from the probe window. Second, because of the nearly complete pluggage, the contrast was extremely low making it difficult to get good images even where there were gaps in the deposits. In several locations, we were able to see complete bridging between tube banks except for holes where the sootblowers had kept a narrow passage clear. Third, the probe included a number of threaded tubes which were supposed to remain fixed relative to one another even as the camera and lens tube were rotated. However, we found that some of these threaded joints came unscrewed as we were rotating the camera. This caused the camera and the right angle mirror to lose registration which resulted in random changes in orientation of the image. Instead of having the vertical tubes appear vertical in the image, they appeared as diagonal lines across the frame, and the degree of misalignment changed as we rotated the camera to view in different directions. At the time we did not realize that this would make it very difficult to compare the before and after scenes. Fourth, during the October testing, the mill was preparing to install several new sootblowers and one of these new sootblowers was placed on the grate floor right in front of the only inspection port available at the mid-superheater location. We were able to get the mill personnel to move the sootblower enough to allow us to use the port, but we had to insert the probe at an angle to the wall. This made it very difficult to accurately reproduce the exact probe position during the November testing. Fifth, when we returned in November, shortly after the outage, we expected the boiler to be very clean and expected that we would get good reference images. However, even after only two weeks of operation, the superheater showed significant deposits on the leading edges of most tubes and, even in the generating bank, there were small amounts of deposits almost everywhere. This made the November images far from ideal for use as a baseline.

Despite all these difficulties, we were able to identify a few pairs of images taken from roughly the same perspective that we were able to compare using the image processing algorithms we had developed. In the following images, the scores determined by the deposit detection algorithms are obtained in the following way: in each image, the edge detection algorithm determines the length of each line segment and the contrast in the region of each line segment (brightness on

either side of the line). An overall score for the image is computed for by adding up scores for each line segment based on the length of the segment and the local contrast in the vicinity of that segment. Then, a deposit number is calculated by taking the difference of the overall scores between the reference image and the "dirty" image and dividing this difference by the overall score for the reference image. This approach has the advantage that long, high contrast edges receive more weight than short or low contrast edges. A high score means heavy deposits while a low score indicates the test and reference images are similar.

The following two examples show the ability of the deposit detection algorithm to determine the degree of fouling even with low contrast images and with very poor registration. The first pair show a view from the mid superheater looking forward towards the front wall of the boiler. In the November image, the front wall membrane wall is clearly visible with superheater tube platens to the left and right. In the October image, there is almost complete pluggage with only a faint outline visible in the center.

Figure 26. Intermediate result after edge detection.

Figure 27. Intermediate result after edge

Figure 28. Cleaned up edges after dilation/erosion.

Figure 29. Cleaned up edges after dilation/erosion.

Normalized Score = 90%

The second pair of images were taken at the generator bank entrance looking upwards towards the roof. In the November image, the tubes are quite clean, whereas in the October image, the leading edge of the generator bank tubes are heavily coated.

Figure 30. November: Generator bank entrance. Clean tubes.

Figure 31. October: Generator bank entrance. Some deposits.

Figure 32. Intermediate result.

Figure 33. Intermediate result.

Figure 34. After edge detection and erosion/dilation to eliminate noise

Figure 35. After edge detection and erosion/dilation to eliminate noise

Normalized Score = 40%

These results show that the algorithm we have developed is capable, even with these rather poor images, to distinguish between clean and heavily fouled conditions and an intermediate condition independent of the perspective or tube geometry.

At the end of the project we have developed and demonstrated automated deposit detection algorithms which can be used in a smart sootblowing control system. We have developed a number of software tools and customized algorithms that we can select from in specific cases to optimize the effectiveness of the deposit detection software. Development of further refinements to the software will become much easier once a permanently installed system is in place and images are available for a range of fouling conditions.

Task 12 – Control System Integration

As discussed earlier under task 2 – Image Capture – a controls engineer was employed to develop a detailed design for the image capture hardware and software package, the sootblower / deposit inspection probe command interface, and the DCS interface. A schematic of the entire system is shown in figure 36.

Figure 36. Data processing, command, and communications architecture

Inspection events are initiated by a supervisory software package resident in the deposit inspection system's main computer (CPU), which also serves as the host for the image processing software. Signals are generated specifying the desired insertion depth and rotational position for a particular modified sootblower probe. These signals are passed to the PLC, which controls the insertion mechanism for that probe, and the probe is driven to the desired position. In addition to

the linear and position target values sent to the PLC, a camera focus signal will be sent by an RS-422 link specifying the distance at which the camera should focus. This will be pre-determined by a calibration process during system commissioning or may, possibly, be actively controlled by an algorithm that adjusts focus while monitoring and optimizing scene contrast. One proven way to accomplish this is by minimizing the width of the line spread function of a selected edge. A video switch will be used to select the appropriate video signal from the array of camera inputs and route this analog video signal to the frame grabber board in the CPU. A commercial software package provided by Flashpoint[®] will be used to measure the amplitude and dynamic range of the video signal. The supervisory software package will generate and send a signal to the PLC via RS-422 to adjust the aperture to a new setpoint. An iterative process will be carried out to optimize the brightness and contrast of the image. Once an appropriate aperture setting has been reached, video frames will be captured from the selected camera and stored for subsequent analysis by the image processing software. These frames will be tagged with time, position, focus, and aperture information. The CPU will then send the next target position and focus signals to the next PLC in the queue and the process will be repeated. The image analysis software discussed in the previous section, will generate deposit scores for each camera position. These will be converted into deposit values for specified zones within the boiler and these deposit values will be sent to the DCS via 4-20 mA signals.

All of these functions can readily be implemented using commercial off-the-shelf components. Because this task involved no research or development, we chose to concentrate our efforts on solving the challenges associated with some of the other tasks already discussed.

At the end of the project we have developed a detailed design for a control interface that will accomplish all of the tasks required to implement a complete, integrated deposit detection and smart sootblowing control system.

Task 13 – In Boiler Testing

As already discussed, a large amount of testing in several recovery boilers was accomplished as part of this project. A total of seven trials were performed in three different recovery boilers. These trials were conducted for specific purposes already alluded to in the discussion of the other tasks. These included testing and refinement of the optical components, testing of camera performance, demonstration of the water-cooled right angle probe and demonstration of the ability to obtain clear images of gas passages and deposits throughout the convective sections of several recovery boilers, and collection of images for use in developing and demonstrating the deposit detection software.

Figure 37 shows the probe being inserted into the boiler at the Port Townsend Paper mill. The rest of the figures are images collected during these trials.

Figure 37. Right angle probe being inserted into the Port Townsend Boiler

Figure 38. Port Townsend mid-superheater looking towards the roof.

Figure 39. Port Townsend mid-superheater Looking downstream and up towards the roof

Figure 40. Port Townsend: mid-superheater looking down into the firebox

Figure 41. Port Townsend: Economizer inlet. A plugged economizer tube appears bright due to its high temperature.

As can be seen in figure 41, the image quality at the economizer inlet was very poor due to the low level of infrared radiation and the low light gathering capability of the long relay lens train.

Figure 42. Simpson Tacoma Kraft: mid-Superheater looking up towards the roof.

Figure 43. Simpson Tacoma Kraft: Deposits Near roof in mid-superheater

Figure 44. Simpson Tacoma Kraft: View of liquor sprays from side wall looking down.

Figure 45. Simpson Tacoma Kraft: View of liquor sprays from front wall looking down.

Images obtained in the Weyerhaeuser Springfield recovery boiler can be found in the discussion of task 12.

Task 14 – Glass Furnace Tests:

After considerable effort, we finally were able to arrange a visit to a glass manufacturing facility to conduct a test of our mid-IR imaging Boiler Inspection Camera in a glass furnace. On September 24th we visited the Wheaton Glass plant in Park Hills, MO, which has two nearly identical furnaces the layout of which is shown in figure 46.

Figure 46. Layout of Park Hills facility glass furnaces.

Our first observation was that visibility inside this glass furnace, using just a dark glass shield and the naked eye, is quite good except where the extremely bright gas flame obscures the visible image. Nevertheless, the plant didn't have any permanently mounted cameras and it appeared that they were somewhat reluctant to perform visual inspections because of the blow-back of extremely hot gasses through the inspection ports which occurred quite frequently. This furnace has two regenerators, which are used to reclaim heat from the flue gas. Every hour or so, the gas flow is reversed for about 20 minutes to reclaim this heat which has been absorbed in the ceramic regenerator brick. During this period, it is quite hazardous to make any visual inspections due to the severe blowback. We began by looking through the primary regenerator towards the melter from the back (left) wall of the regenerator. This gave us an unobstructed view down the length of the melter. Using just a dark viewing glass the visibility from this location was very clear except when the burners were firing at which time the view was largely obscured. Our IR camera was able to see clearly through the flame, although the clarity of the image was never quite as good as it was when viewed directly through the dark viewing glass. Figure 47 shows a typical image from this location.

Figure 47. View of melter through primary regenerator

Figures 48 and 49 show a view from the sidewall of the melter looking across towards the doghouse where the batch is introduced into the furnace.

Figure 48. Doghouse seen through gas flame

Figure 49. Doghouse seen without gas flame

The unmelted material is clearly visible as mounds floating on top of the molten glass pool. In figure 48 the gas burner just to the right is operating, but the mid-IR camera can see through the flame quite clearly. In the video image, a slight flickering is visible when the burner is operating. In figure 49, the gas burner is off. The clarity of the image is not noticeably different in these two cases. Copies of these video images were distributed to several glass industry personnel at the request of Michael Green of the Glass Industry Manufacturing Council but no interest has been expressed in further discussion of potential applications of this imaging technology in the glass industry.

A market study of the potential for this technology in the glass industry was conducted by Christopher Allen of New Horizon Technologies under separate contract to the DOE. This study looked at the growth of infrared technology in industrial process control applications, the glass industry and its use of process control methods, and attempted to characterize the industry in ways that would be useful in assessing the potential market for an infrared imager capable of surviving and operating continuously in the glass furnace environment. Unfortunately, this study failed to reveal a number of critical statistics, such as the number of glass furnaces in operation in the US and worldwide, the process monitoring and control needs that might justify the use of an infrared imager in a glass furnace, and the price level at which such a device might find acceptance within the marketplace.

At the end of the project, we have demonstrated the ability to obtain clear images inside a glass furnace, but remain unconvinced of the need for this technology as a control tool for glass furnace operation.

D.

Attachment A:

Completed Milestone Table

	Milestone/Task Title	Original Planned Completion Date	Revised Planned Completion Date	Actual Comple- tion Date	Responsible Organization	Original Projected Cost (Fed/ Non- Fed)	Original Projected Cost (Fed/ Non- Fed)	Actual Completion Cost (Fed/ Non- Fed)
1	Refined Axial Optical Train	7/31/01	4/30/02	4/30/02	CSI	\$2,000/ \$500	\$25,000/ \$2,000	\$18,617 /\$6,742
2	Image Capture System	10/31/01	5/31/02	10/30/02	CSI	\$20,000/ \$5,000	\$20,000/ \$5,000	\$21,214/ \$7,682
3	Attend Annual Project Review				CSI	See task 15	See task 15	
4	Semi-Annual Report through 9/30/01	10/31/01	10/31/01	10/31/01	CSI	See task 15	See task 15	
5	Particle Scattering Analysis	1/31/02	9/31/01	9/31/01	CSI/UW	\$5,000/ \$1,250	\$5,000/ \$1,250	\$3,176/ \$1,150
6	Improved Imaging Device	4/30/02	6/30/02	9/30/02	CSI	\$15,000/ \$3,750	\$30,000/ \$8,000	\$28,751/ \$10,411
7	Semi-Annual Report through 3/31/02	4/30/02	4/30/02	4/30/02	CSI	See task 15	See task 15	
8	Off-Axis Optical Train	7/31/02	10/31/03	1/31/03	CSI	\$50,000/ \$12,500	\$45,000/ \$11,250	\$29,741/ \$10,770
9	Attend Annual Project Review				CSI	See task 15	See task 15	
10	Image Processing Software	10/31/02	4/30/03	4/30/03	UW/CSI	\$50,000/ \$12,500	\$37,000/ \$8,500	\$33,386/ \$12,090
11	Semi-Annual Report through 9/30/02	10/31/02	10/31/03	10/31/03	CSI	See task 15	See task 15	
12	Control System Integration	1/31/03	2/28/03	2/28/03	CSI/WeyCor	\$15,000/ \$3,750	\$2,500/ \$1,500	\$1,059/ \$383
13	In-Boiler Testing	1/31/03	1/31/03	1/31/03	WeyCo/CSI	\$30,000/ \$7,500	\$30,000/ \$7,500	\$34,224/ \$12,393
14	Glass Furnace Tests	10/31/01	11/31/02	1/31/03	CSI	\$10,000/ \$2,500	\$10,000/ \$2,500	\$6,993/ \$2,532
15	Project Management / Reporting	1/31/03	4/30/03	4/30/03	CSI		\$3,500/\$3,500	\$19,839/ \$7,184
	Complete Project	1/30/03	4/30/03	4/30/03	CSI	\$197,000/ \$49,250	\$197,000/ \$49,250	197,000/ \$67,084

E.

Attachment B:

Final Gantt Chart

[illegible]

15	Project Management / Reporting																		
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F. *Attachment C:*
Updated Energy, Waste, and Economic Savings (Conventional vs. Proposed vs. Actual)

The installed unit for the ***I&I project*** technology is one kraft recovery boiler

The installed unit for the ***comparable competing*** technology as presented in the original proposal is one kraft recovery boiler

Energy Savings

Provide the energy savings for the project technology versus the comparable competing technology.

Recovery boilers typically operate three sootblowers at a time (some run 2 at a time, some 4, some as many as 6). Each sootblower consumes ~20,000 lbs of steam per hour, so the average boiler uses 60,000 lbs/hr. The minimum energy needed to produce steam is about 1100 BTU/lb., so the average boiler uses 6.6×10^7 BTU/hr. for soot blowing. This amounts to some 5.5×10^{11} BTU/yr per boiler. Assuming that 15% of this energy can be saved by operating the sootblowers only as needed, the energy use for sootblowing in the average recovery boiler with the ***I&I project technology*** would be approximately

4.7×10^{11} BTU per year.
--

Industry-wide energy use for 225 recovery boilers with the ***I&I project technology*** would be approximately

1.05×10^{14} BTU per year.

In addition to the energy savings due to reduction in sootblower steam usage, there should be an increase in heat transfer to the superheater tubes (due to improved cleanliness) since transferring the heat at high temperature is more efficient than taking it out in the cooler downstream regions of the boiler. Estimating the quantitative impact is rather complicated and is not attempted here, but this increased efficiency would be expected to translate into a decrease in the energy use stated above.

The comparable competing technology comprises the current practice of operating sootblowers on a timed sequence established on the basis of past experience over the course of many operating runs (startup to shutdown). This performance is judged by performing partial visual inspection of the convective sections after a preliminary cleaning at the end of each run. In this

case there is no energy savings normal operation and the energy consumption per boiler for sootblowing using the *comparable competing technology* is approximately

5.5×10^{11} BTU per year.

Industry-wide energy use for 225 recovery boilers using the *comparable competing technology* is approximately

1.25×10^{14} BTU per year.

Thus the industry-wide energy *savings attributable to the I&I project technology* is approximately

2×10^{13} BTU per year.

Environmental Savings

Provide the environmental savings for the project technology versus comparable competing technology.

The production of 1 lb of steam requires combustion of 0.3 lb of black liquor, which produces about 0.18 to 0.23-lb of CO₂. Scaling the other combustion products accordingly, the emissions of the important air pollutant species per pound of steam produced are found to be:

CO ₂	0.18 to 0.23 lb/lb of steam
CO	1.67×10^{-3} to 1.67×10^{-2} lb/lb of steam
SO ₂	5.55×10^{-5} to 3.33×10^{-4} lb/lb of steam
H ₂ S and Mercaptans	3.33×10^{-5} to 1.67×10^{-4} lb/lb of steam

Based on the projected use of steam for sootblowing with and without the project technology, the *projected* wastes other than power generation emissions for the project technology in tons/yr/unit using the *I&I project* unit described above (at the beginning of the project) were:

Species	Tons / Year / Unit	Tons / Year Industry-Wide
CO ₂	3.85×10^4 to 4.94×10^4	8.66×10^6 to 1.11×10^7
CO	358 to 3,580	8.06×10^4 to 8.06×10^5
SO ₂	11.9 to 71.5	2.68×10^3 to 1.61×10^4
H ₂ S and Mercaptans	7.15 to 35.8	1.61×10^3 to 8.06×10^3

Determination of actual emissions using the project technology would require a long-term study using the commercial system that has yet to be developed. Therefore, no adjustment in these projections has been made as a result of the activities of this project.

The wastes other than power generation emissions for the ***comparable competing*** technology in tons/yr/unit using the ***I&I project*** unit described above (at the beginning of the project) were:

Species	Tons / Year / Unit	Tons / Year Industry-Wide
CO ₂	4.53×10^4 to 5.80×10^4	1.02×10^7 to 1.31×10^7
CO	421 to 4,212	9.47×10^4 to 9.47×10^5
SO ₂	14.0 to 84.1	3.15×10^3 to 1.89×10^4
H ₂ S and Mercaptans	8.41 to 42.1	1.89×10^3 to 9.47×10^3

Therefore, the **reduction in emissions** expected from the use of the ***project technology*** is:

Species	Tons / Year / Unit	Tons / Year Industry-Wide
CO ₂	6.80×10^3 to 8.7×10^3	1.53×10^6 to 1.96×10^6
CO	63.2 to 632	1.42×10^4 to 1.42×10^5
SO ₂	2.10 to 12.6	4.73×10^2 to 2.84×10^3
H ₂ S and Mercaptans	1.26 to 6.32	2.84×10^2 to 1.42×10^3

Economic Savings

The reduction and control of recovery boiler pluggage should yield the following benefits to the end user:

1. Reduced sootblower steam usage
2. Increase of boiler up-time due to reduction of pluggage
3. Reduction of other pluggage-related problems such as slag-falls
4. Better environmental compliance through increased operating stability

5. Reduced consequences of pendant tube leaks due to earlier detection (an important benefit of continuously viewing the pendant tubes)
6. Improved operator confidence.

At \$3/MM BTU, the value of benefit (1) amounts to approximately **\$0.25 M per plant per year.**

The approximate economic value of the other benefits to a typical plant may be estimated based on the following assumptions:

- ?? Plant throughput is 3.6 MM lb. of dry black liquor solids per day
- ?? 1.5 tons of dry black liquor solids are processed for each ton of pulp
- ?? Lost pulp production is worth about \$180 per ton (based on a Weyerhaeuser study)
- ?? Recovery boiler availability is 90-95%
- ?? 10%-15% of downtime is directly due to plugging
- ?? 10% of downtime is due to other preventable causes related to plugging
- ?? 1 smelt-water incident occurs every 100 years with 2 months of average capacity loss

If the net result of effectively deploying the deposition monitoring system is to achieve a 20 % decrease in the downtime due to pluggage and pluggage-related causes, then the economic value of benefits 2 and 3 could amount to about \$0.2 M per year per plant (assuming 95% availability).

The economic value of benefits 4 to 6 are somewhat difficult to estimate, but should be significant, amounting to perhaps another \$0.2 M per plant per year.

Thus, the total economic benefit for the installed unit resulting from the use of the ***I&I project*** technology would be:

\$650,000 per year.

Since there are about 225 large recovery boilers in the US, the total economic benefit to US industry could be:

\$147,000,000 per year.

The ***initial projected*** unit cost for the ***I&I project*** technology (at the beginning of the project) was less than \$100,000.

The ***current estimated*** unit cost of the ***I&I project*** technology (at the end of the project) is approximately \$175,000 to \$200,000. Therefore, the anticipated payback period is roughly 3 to 4 months.

G.

Attachment D:

Fuel / Energy Source BTU Conversion

<u>Fuel Source</u>	<u>BTU/Barrel</u>	<u>BTU/Gallon</u>	<u>BTU/Pound</u>	<u>BTU/Cubic Foot</u>
Crude Oil	6×10^6	142×10^3	18.6×10^3	1×10^6
Fuel Oil – 6	6.2×10^6	150×10^3	17.8×10^3	1.1×10^6
Fuel Oil – 2	6×10^6	140×10^3	18.6×10^3	1×10^6
Gasoline	5.2×10^6	126×10^3	18.9×10^3	940×10^3
Propane – L	3.8×10^6	92×10^3	19.9×10^3	690×10^3
Wood	-----	-----	6.5×10^3	148×10^3
Natural Gas	87×10^6	2×10^3	21×10^3	1×10^3
Methane	87×10^6	2×10^3	21×10^3	1×10^3
Methanol	2.9×10^6	69×10^3	9.6×10^3	517×10^3
Ethane	-----	-----	20×10^3	1.8×10^3
Ethanol	3.7×10^6	87×10^3	12×10^3	652×10^3
Hydrogen	-----	-----	51×10^3	270
CO	-----	-----	4.3×10^3	316
Coal - Bit.	-----	-----	12.6×10^3	800×10^3
Coal - Lig.	-----	-----	8.6×10^3	541×10^3
Coal - Ant.	-----	-----	12.6×10^3	800×10^3
Carbon	-----	-----	14.6×10^3	1.9×10^6
Ethylene	-----	-----	20×10^3	1,477

Electricity generated from 32.4% efficient power plant = 10,500 Btu/kwh.

H.

Attachment E:

Commercialization Table

Category	U.S. Market				
	Project Completion Year	5 Years after Completion	10 Years after Completion	15 Years after Completion	20 Years after Completion
(A) Total Number of Units in U.S. Market (Addressable Market)	225	225	225	225	225
(B) Total Number of Installed Units Using Your Technology (Capturable Market)	0	11	23	56	79
(C) Market Penetration = B/A x 100%	0	5%	10%	25%	35%

I.

Attachment F:
Final Cost Sharing

	Company Name	Company Type	In-Kind Contribution	Cash Contribution	Total
1	Enertechnix (Combustion Specialists, Inc.)	Small Business	\$20,915.03	\$19,110.47	\$40,025.50
2	University of Washington	University	\$17,895.23		\$17,895.23
3	Weyerhaeuser (Springfield)	Business	\$4,596.00		\$4,596.00
4	Pt. Townsend Pulp	Business	\$3,840.00		\$3,840.00
5	DanzCo	Small Business	\$3,180.00		\$3,180.00
6	Westvaco/Roanoke (Covington)	Business	\$780.00		\$780.00
7	International Paper (Riverdale)	Business	\$360.00		\$360.00
8	PacifiCorp (Centralia)	Business	\$360.00		\$360.00
9	Longview Fibre	Business	\$300.00		\$300.00
10	DOE			197,000.00	197,000.00
11	Total		\$52,226.26	\$216,110.47	\$268,336.73

J.

Attachment G:
Partners and Contractors

#	Company Contact	Address	City	ST	ZIP	Phone / Fax / e-mail
1	Prof. Martin Afromowitz – Univ. of Washington	429 Electrical Engineering, FT-10 Box 352500	Seattle	WA	98195	(206) 543-6244 afro@ee.washington.edu
2	Leonard Kuan, Ph.D. Hampton Technologies, Inc.	5020 139th Place SE	Bellevue	WA	98006	(425) 644-7879 leonardk@hampton-technologies.com
3	Ed Danzer Danzco	1006 143rd Ave. S.E.	Tenino	WA	98589	(360) 264-2141 Danzco@thurston.com
4	Mike Anna Consultant	24229 92nd Ave. W.	Edmonds	WA	98020	(206) 542-0608 MAnnaWa@aol.com
6	Jim Monroe Port Townsend Paper Company	P.O. Box 3170	Port Townsend	WA	98368	(360) 379-2035 jamesm@ptpc.com
7	Jim Quandt Weyerhaeuser Company	P.O. Box 275	Springfield	OR	97477	(541) 741-5428 jim.quandt@weyerhaeuser.com
8	Kevin Cole MeadWestvaco	104 E. Riverside St.	Covington	VA	24426	(540) 969-5226 krcole@meadwestvaco.com
9	Mike Closson International Paper Riverdale Mill	601 County Road 78 P.O. Box 1409	Selma	AL	36702	(334) 418-5533 michael.closson@ipaper.com
10	Jim Khorsand PacifiCorp Power Centralia Plant	913 Big Hanaford Road	Centralia	WA	98531	(360) 330-2319
11	Mike Haas	P.O. Box 639/300 Fibre Way	Longview	WA	98632	(360) 575-5575 mehaas@longfibre.com

	Longview Fibre Co.	Fibre Way				
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- 1) Prof. Martin Afromowitz, a consultant, provided consulting on imaging system design and modifications to the infrared imager used in this project.
- 2) Leonard Kuan, a subcontractor, developed and demonstrated the image processing software for automated deposit detection and quantification.
- 3) Ed Danzer, a subcontractor, performed the mechanical design and fabrication of the right angle water-cooled lens tube and several other components utilized in performing the field trials.
- 4) Mike Anna, a consultant, developed the detailed designs for the control system interface and image capture system.
- 6) Jim Monroe provided access to the Port Townsend Paper Company recovery boiler and provided support for the field trials conducted at that mill.
- 7) Jim Quandt provided access to the Weyerhaeuser Springfield, Oregon recovery boiler and provided support for the field trials conducted at that mill.
- 8) Craig Lane provided access to the Westvaco Roanoke, Virginia recovery boiler and provided support for the field trials conducted at that mill.
- 9) Mike Closson provided access to the International Paper Company recovery boiler at their Riverdale mill and provided support for the field trials conducted at that mill.
- 10) Jim Khorsand provided access to the PacifiCorp coal fired utility boiler at their steam plant in Centralia, WA and provided support for the field trials conducted at that plant.
- 11) Mike Haas provided access to the Longview Fiber facility in Longview, WA and provided support for the field trials conducted in the recovery boiler at that mill.

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- 20 Sarcon Microsystems, Inc., Pellissippi Center, 9737 Cogdill Road - Suite 110, Knoxville, TN 37932-3300