FINAL PROJECT REPORT

Project Title: Development of a Versatile Laser-Ultrasonic System and Application to the Online Measurement for Process Control of Wall Thickness and Eccentricity of Seamless Tubes

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Subcontractors: National Research Council Canada – Industrial Materials Institute
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EXECUTIVE SUMMARY

The LUT project was proposed in answer to a 1998 solicitation for 'Industrial Process Control with Laser-based Ultrasonics.' The solicitation was made by the U.S. Department of Energy's Sensors & Controls Cross-Cutting program and carried the requirements of enhancing economic competitiveness, reducing energy consumption, and reducing environmental impacts of the steel industry. It called for the development and use of an integrated laser-ultrasonic system for in-process control of a manufacturing application in the U.S. steel industry.

The LUT project objective was to develop an online, non-contact sensor for measuring the wall thickness and eccentricity of hot steel tubing and demonstrate it on a seamless mechanical tubing production line at the Timken Company. The project aimed to build a cost-effective, modular system that could be easily upgraded and that was mobile and could be relocated if desired. The project, which received a funding award from the DoE (#DE-FC07-99ID13651), began in January 1999 and was successfully completed in July 2002. Appropriate agreements are in place and commercialization efforts are underway with an expert partner.

Methods available at the outset of this project for in-process wall thickness measurement were limited to radiation-type gauges. Such gauges do not work in the presence of a forming bar inside the tube, nor can they be used for small tube diameters. Laser-generated ultrasound has been shown to be a viable method of measuring thickness in metal. The LUT project aimed to transition the technology into an industrial environment to demonstrate its long-term utility.

The project has shown that the system elements necessary to make this measurement can be accomplished in a mill setting, subject to dirt, water spray, temperature extremes and vibration. Ultrasound can be induced in hot steel tubing using fiber-coupled laser light and return echoes detected using laser-based interferometry. The measurement location can be determined by laser Doppler velocimetry and the temperature determined with fiberized pyrometry.

The LUT system was integrated and tested for performance and safety in the laboratory before being transported to Timken for installation in June 2001. Changes were made at a Timken mill to install necessary tube guiding and shielding, devices to manipulate the inspection system, and in-plant controls and displays. Use of the system in production mode began in March 2002 and the LUT measured over 200,000 tubes during the first six months of deployment. Scheduled system availability was 90% during that period and can reasonably exceed 95%.

Wall measurements have been verified to be within 1% of actual value, for tubes of all steel grades with wall thickness from 5 to 25 mm and O.D. from 6 to 14 cm. While this error is slightly higher than targeted for the system, no attempt is expected to refine the calibration equation to improve accuracy. Measurement precision, estimated at 20% of manufacturing tolerances, has been judged acceptable. The LUT already has proven to be a very valuable process tool.

Savings from the LUT deployment are being accumulated at a rate exceeding projections. The major components are time savings to achieve target size and reduced scrap costs. Use of the LUT has contributed to attainment of record low tube wall scrap rates. Annual energy savings in tube making due to the LUT for this installation have been estimated at 5%, or 2.3×10^{10} BTUs.

FOREWORD

The Alloy Steel Business of the Timken Company with its partners the Industrial Materials Institute (IMI) of the National Research Council Canada and the Instruments and Controls Division of the Oak Ridge National Laboratory (ORNL) developed the Laser Ultrasonic (LUT) system under Award #DE-FC07-99ID13651.

This final report is structured to follow the work breakdown structure contained in the proposal for the project. In addition to commenting on the project management, it reports on engineering and construction of the prototype gauge, system integration and testing, and deployment of the system at a steel seamless mechanical tubing plant at Timken. The report documents system reliability and accuracy, and describes the cost and energy savings realized from implementation of the gauge.

The U.S. Department of Energy sponsored the project, which was administered by the Idaho Operations Office, with Mr. Robert G. Trimberger serving as project manager. Ms. Elizabeth E. Dahl has succeeded Ms. Connie H. Osborne as contract specialist, and Mr. Gideon Varga succeeded Mr. Eric Lightner as project monitor in leading the DoE Sensors & Controls program.

Dr. Robert V. Kolarik II served as program manager, succeeding Mr. Gerald V. Jeskey, the original project manager, who retired from Timken during the project, but continued to support the project as a consultant. Those assisting included Mr. Steven E. Agger, Mr. Larry J. Duly, Mr. Michael L. Mester, Mr. Kenneth J. Roush and Mr. Kenneth J. Samblanet. Others contributing included Mr. Randal L. Egan, Mr. Charles E. Kauffman, Mr. Thomas J. Misanik, Mr. Robert L. Sausman, Mr. Thomas L. Sluss and Mr. Robert H. Vandervaart along with Mr. John F. Erme, Ms. Jo Ann Klingaman, Mr. Kenneth J. Kushner, Mr. Jason H. Saragian and Ms. Judy L. Schrock.

The Timken team received direction and support from a management steering committee during the project. The cooperation of plant associates was uncommon for a technology placement project and was a key factor in making the deployment such a glowing success; most notably the gaugers, Mr. Charlie Albright, Mr. Bruce Giffen, Mr. Bill Lewis and Ms. Sue Clark.

Dr. Marc Choquet led the project at IMI, although during the latter stages of the project as a sub-contractor through Tecnar Automation Ltee., the commercialization partner. The IMI team was directed by Dr. Jean Bussière and Dr. Jean-Pierre Monchalin with Dr. Abdelhakim Bendada, Dr. Alain Blouin, Dr. Benjamin Campagne, Dr. Guy Lamouche, Dr. Daniel Lévesque, with Dr. André Moreau, and Dr. Lionel Pujol. Others contributing included Mr. Christian Corbeil, Mr. Mario Lamontagne, Mr. Martin Lord, Mr. Christian Néron, Mr. Christian Padioleau, Mr. Antoine Pelletier and Mr. Richard Talbot.

The ORNL project leader was Mr. Roger A. Kisner. The team included Dr. Steven W. Kercel, Dr. Philip R. Bingham, Dr. Brian Damiano, and in the early stages Dr. Martin A. Hunt. Others at ORNL contributing included Mr. Richard Crutcher, Mr. Michael Emery, Mr. T. F. Gee, Mr. J. E. Hardy, Mr. Michael Hileman, Mr. Roberto Lenarduzzi, Mr. Wayne W. Manges, Mr. Michael R. Moore, Mr. R. W. Tucker, and Mr. Kenneth Weaver.

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TASK 1

Project Management

A management system was developed to monitor the costs and progress of the project versus plan. The original project budget was increased first when a wireless task was added, then on two occasions when the complexity of installation caused costs to exceed estimates. A final adjustment was made to accept unfulfilled national lab costs. The total project costs will be about 10% above budget, although the DoE share has been capped at 60% of the $3.1 million project budget. Additional costs were borne by the project partners.

The project was originally scheduled to end in July 2001. The most significant schedule delays were for the laboratory investigation of the effect of grain size, for the delivery of the detection laser, and for problem-solving efforts related to window clouding and mirror fouling. The schedule was managed to include a long-duration online demonstration as the final task. Through no cost extensions, the project was extended through July 2002.

Technical reviews were held on bi-weekly with the Timken project team leaders and monthly with the management steering committee. Progress was reported to the DoE at Sensors and Controls updates each year from 1999 through 2002 and at the DoE 2000 Showcase and 2001 Expo. Project review meetings have been held at each partner location and Timken hosted four update meetings for the DoE and project partners.

TASK 2

R&D BACKGROUND WORK

This section describes the R&D background work done to determine the characteristics of major components of the LUT system for the online, non-contact measurement of wall thickness and eccentricity of steel seamless mechanical tubing during manufacturing. The section is presented following the sub-tasks as described in the project proposal.

2.1: Generation/Detection Experiments and Fiber Coupling

2.1.1: Laser-based ultrasonic data collection for signal processing

The purpose of this sub-task was to collect data to evaluate the signal processing function developed in the program and to determine the calibration factor to be used to predict the tube wall thickness at room temperature from the time-of-flight (TOF) measured by the LUT system at tube processing temperatures. Data were taken on steel samples as function of temperature, using a Gleeble™ thermo-mechanical simulator. The room temperature data were used to test the efficiency of the signal processing software modules as they were being developed. The high temperature data were used to determine the effect of temperature on the velocity of ultrasound in steel, i.e., on the factor to convert TOF measurement to wall thickness values.

Each steel sample with known thickness was cycled through a heating and cooling phase, with TOF data collected during both cycles. Calibration factors were determined as function of temperature. Some difference was observed between the values obtained from heating and cooling, probably caused by variation in the grain growth and texture modification of the sample as it is heated. The differences were not deemed to be so significant as to warrant more study.

The high-temperature data were also taken for different grades of steel. However, following an analysis of the data and discussions with metallurgists at Timken Research, it was decided to use a single calibration factor for all grades of steel for the initial setup of the LUT. The robustness of the calibration factor was verified by comparing wall thickness data taken at temperature using a contact ultrasonic probe system with room temperature measurements made at the same location using a calibrated ultrasonic system.

2.1.2: Development of fiber delivery for generation laser beam

Often, laser-ultrasonic systems have the lasers, which are used to generate and detect the ultrasonic probing pulse, placed in close proximity to the target. Such a configuration significantly limits the locations where a laser-ultrasonic system can be installed on a production line. To add mobility to the system, the LUT project proposed using optical fibers to deliver both the generation and detection laser beams to the surface of the tube, thus allowing flexibility in system placement. Delivery of the detection laser beam with an optical fiber has been demonstrated in numerous laser-ultrasonic systems in the past. However, reliable delivery of the high power generation laser had not been demonstrated prior to this program.

Initially, it was proposed to develop and test an optical setup that would robustly inject a high power Nd:YAG laser beam into a large core optical fiber. During the initial stages of the project, a laser supplier was found who was already selling such a system. Therefore, the work was redirected to test the commercial setup in order to evaluate its robustness and to determine the optical characteristics of the fiber output required for proper operation in the LUT system. After discussions with the laser supplier, a configuration that gave the required optical characteristics was achieved. The commercial laser has four output optical fibers. A new system for the focusing and collecting optics in the inspection head was designed to allow for simultaneous generation on four different spots and detection in the center of the four spot pattern.

2.1.3: Selection of laser interferometer

In laser-ultrasonics, the ultrasonic information is encoded in the phase of the backscattered light of the detection laser. There are numerous optical systems that can extract the phase information. The standard system used at IMI is a confocal Fabry-Perot (CFP). The LUT was initially designed using a CFP. While collecting data on steel samples at high temperature, it was observed that the grain growth significantly increased the effective attenuation of ultrasound at frequency above 1 MHz. The current standard configuration of the CFP has a low sensitivity at ultrasonic frequencies below 1 MHz.

Recently, a new laser-ultrasonic detection device based on two waves beam mixing in a photorefractive crystal (TWM) has been developed at IMI. The TWM is a compact active unit that adapts to ambient vibrations and temperature fluctuations, and is more sensitive to low frequency ultrasonic signals than the CFP. However, the trade-off for the low frequency gain is a greater sensitivity to the motion of the target.

A test setup was built to simulate the online velocity of the tube where the LUT was to be installed. Tests were made to determine if a TWM should be used instead of the CFP. Collected data showed that the sensitivity of the TWM is reduced by a factor of 2 for an in-plane velocity of 5 m/sec. Such a decrease could be compensated for by an increase in sensitivity at low ultrasonic frequencies, by using signal processing or by increasing the overall sensitivity of the photorefractive device by applying a high electrical field to the crystal.

The TWM is not only sensitive to in-plane motion of the target's surface, but also to out-of-plane motion, i.e., motion in the direction of detection axis. Effective out-of-plane motion would be recorded if the detection axis were tilted with respect to the tube's surface (non-normal incidence). The collected data showed that, for an incidence angle of 10º, the photorefractive signal would be reduced by approximately a factor of 2 for a velocity of 3 m/sec, indicating that the device would be relatively insensitive to non-normal incidence.

Since the maximum expected velocity of the tube on the production line is 5 m/sec, a TWM could be made with a response time fast enough for online wall thickness measurements. Its higher sensitivity to tube movement, when compared to the CFP, could be compensated by appropriate measures. However, the TWM has yet to be tested in a plant environment. Hence, despite the advantages of the low ultrasonic frequency response of the TWM, the CFP was kept in the final design of the LUT.

2.2: Coordinate Measuring System

2.2.1: Velocimetry with detection laser beam

In addition to measuring the wall thickness, a project objective was to develop a system that could calculate an eccentricity profile along the tube length. The LUT was to be installed on the production line at locations where the tube is both rotating and moving forward. Hence, data would be recorded following a spiral path on the surface of the tube. Determination of the location, where data are taken, is made by time integration of the velocity. The intent was to make those velocity measurements using laser-velocimetry.

Commercial laser-velocimeters (LVs) are currently used in the metals industries to make non-contact length measurements on sheets and tubes on the process line. Unfortunately, such systems are costly and bulky. Since the LUT already was to contain a number of lasers, the proposal was to use part of the detection laser to make the laser-velocimetry position measurements.

The principle of laser velocimetry involves overlapping two laser beams on the surface of a target in order to create an interference pattern. Any motion of the target in the direction of the interference pattern will generate an amplitude modulation of the back-scattered light which can be recorded by a photo-detector. The modulation frequency of the recorded signal is directly related to the target's velocity. Velocity is measured in the direction of the interference pattern. Using two LVs, both amplitude and direction of the velocity can be measured.

2.2.2: Use of commercial velocimeters

In a first step, an LV was designed and built with an integrated laser source (direct beam LV). Various optical setups, with various angles of incidence of the illumination beams, were tested on a controlled rotating wheel test setup to determine the appropriate characteristics for system needs. The test setup allowed the direct comparison of the velocity measured by the LV to the true velocity of the target. Comparisons were made between data collected with the LV, data collected using a commercially available system, and published data from another commercial system. The accuracy of the constructed LV was found to be equivalent to that of commercial systems.

In a second step, a LV was designed and built with a fiber-delivered laser source. The objective was to confirm the viability of the detection laser's seed as the laser source. The new design used single mode fiber to preserve the required beam quality. The new LV was also designed to measure simultaneously the velocity of the target along two different axes. Preliminary analysis of the design showed that cross talk between the four outputs from the two-axes LV did not allow it to measure simultaneously along both axes. A frequency shifter was added to shift the wavelength for one of the two axes to eliminate the problem.

In the last step, the final design of the LV was made. An optical system was developed and built to sample a portion of the seed laser from the detection laser, split the sampled beam into two, shift one of the two beams, and provide mechanical adjustment for injection of the beams into fibers. A second optical system was designed to split the output of each fiber into two beams and overlapped the beams on the surface of the target at an angle of ~10º to create the interference pattern. The same optical system is used to collect the backscattered light and inject it into a large core fiber; the fiber brings the amplitude-modulated beam to the photodetector inside the processing unit. A LabView™ module was designed to process the signal of the velocimeter and extract the velocity along both axes from the LV signal.

2.3: Signal Processing and Data Analysis

For determination of wall thickness, signal processing is needed in order to get TOF data from the acquired laser-ultrasonic waveforms in the presence of ultrasonic backscattering noise. To get the TOF, it was suggested to try a simple approach using numerical cross-correlation (CCR) either between two successive ultrasonic echoes, when available, or between the first ultrasonic pulse and a reference pulse, either measured or modeled.

In essence, the CCR technique can be viewed as an optimal matched-filter, which determines the affinity between two components as a function of time. Traditionally, CCR techniques have shown success and robustness in determining TOF from waveforms with signal-to-noise ratio (SNR) typically larger than 2 (or 6 dB). However, for hot seamless steel tubes, waveforms with very low SNR are expected to occur, especially for larger wall thicknesses. The challenge is then to extract TOF data from laser-ultrasonic waveforms with SNR under 0.5 (or -6 dB), i.e., with signal buried in the noise. For that, more advanced signal processing would be required.

2.3.1: Improvement of signal-to-noise ratio by signal processing

The technical teams at IMI and ORNL took on the challenge to develop a method that delivered the desired signal processing while meeting the processing time requirements. The signal criteria included a high rate of signal detection, i.e., correctly seeing a very high percentage of real signals present, with minimal false calls, i.e., minimal introduction of non-real signals. As the repetition was 100 Hz, the system had to capture and process the signal and reset before the next signal was generated. An 8 msec target was set.

The first method investigated was the use of over-sampling to improve SNR. Over-sampling consists of acquiring the data at a sampling rate exceeding the Nyquist criterion and averaging the over-sampled data prior to the CCR calculation. Tests done at IMI with laser-ultrasonic waveforms from steel tube samples have shown the potential benefit of this approach. However, the improvement is limited by hardware capabilities of high throughput digitizers. At the present time, the maximum sampling rate available for a 12-bits digitizer is 10^8 samples per second. This means that, at best, an averaging of 5 over-sampled data is possible for a signal with an ultrasonic frequency content below 10 MHz. Presently, the observed gain does not justify the use of over-sampling.

The possibility of increasing the SNR by reducing the noise with the use of split spectrum processing (SSP) was also studied. The SSP consists of the decomposition of an initial waveform into multiple waveforms by applying a set of narrow band Gaussian filters. The set of waveforms is then processed with a nonlinear operator to yield a composite waveform. The composite waveform has a generally better SNR than the initial waveform. The SSP has been shown to produce a large increase in SNR.

For a given nonlinear operator, the efficiency of SSP depends on three parameters: filter width, filter separation and the number of filters. It has been shown that optimum values of filter width and filter separation can be calculated knowing the total sampled time interval of the waveform. The optimum value for the number of filters is more complicated, but is related to the effective frequency bandwidth of ultrasonic echoes, which is generally not known. Recently, the reported method to calculate the optimum number of filters automatically has proven to be not robust. This does not mean that SSP is not efficient in increasing SNR of the laser-ultrasonic waveform, but rather that automatic calculation of the optimum number of filters is not currently possible.

Experience at ORNL suggested that three signal-processing methods might be able to enhance the determination of the TOF. Those included high-speed processing with dedicated hardware, wavelet analysis, and Bayesian parameter estimation.

Compared to the conventional practice of analyzing full optical receiver output with the CPU of the laser-ultrasonic system control computer, a dedicated DSP chip offers many advantages at comparatively low cost. First, there is a dramatic reduction in the volume of data flowing into the CPU. For each shot of the excitation laser, the CPU would receive a vector of 1 to 12 numbers as a result of signal processing as opposed to the 2800 to 3000 numbers for full waveform analysis. Second, since the DSP chip handles the computationally costly function of feature extraction, CPU resources are freed up for other functions. Third, the DSP chip is fast enough to perform feature extraction in real-time; for each shot of the excitation laser, the chip will produce the output feature vector before the system is ready to fire the next shot.

These advantages can be realized with a single DSP chip on a PCI board. This board increases the cost by $4800 for each laser-ultrasonic system, uses one PCI slot in the control computer, and does not increase the exterior size of the system. For this system, the speed of the processor permitted the necessary calculations to be complete within the sampling interval; therefore, a separate DSP board was unnecessary. If a greater time margin becomes necessary, it can be achieved through an upgrade of the processor as CPU speed continues to increase to 2 GHz and beyond.

Compared to the conventional practice of split spectrum analysis (also known as Gabor analysis), wavelet analysis is computationally more efficient. The split spectra of Gabor analysis are non-orthogonal and their outputs are over-determined; the resulting redundant data inherently imposes inefficiencies on the analysis process. In contrast, recently discovered wavelet algorithms produce orthogonal and critically sampled output data; these data represent information with the mathematically required minimum number of data points. Although the application of wavelets to laser-ultrasonic signatures was investigated a decade ago, most of the dramatic advances in wavelet analysis have been made since then.

Compared to the conventional practice of cross correlation with a matched filter, Bayesian parameter estimation extracts more and better information from the data in a noisy signal. Matched filtering requires *a priori* knowledge of both the model and parameters of the desired signal, and has no capability for exploiting other prior knowledge. Bayesian parameter estimation requires only the model, and then provides an estimate of the desired parameter values, and a mathematical measure of the goodness of the measure (a confidence factor). If the noisy data include the desired signal plus undesired non-random signals, Bayesian will still reliably detect the desired signal; matched filters can be confused by unexpected non-random signals. Finally, Bayesian analysis can exploit prior information to improve the goodness of the estimate.

The output of the Bayesian process enables flexibility in subsequent processes that was not previously available. The resolution of the estimated parameter values is at least an order of magnitude finer than that of conventional methods. Where conventional analysis reliably detects perhaps two pulses (reflections from the back surface of the tube of the laser generated ultrasonic probing pulse) in the laser-ultrasonic receiver output, with subsequent pulses buried in the noise, it is expected that Bayesian can reliably detect an additional pulse compared to other methods. Furthermore, instead of just the time of flight, Bayesian can provide time of flight, strength, dispersion and a confidence factor for each detected pulse. This is a wealth of information that can reveal many details of the properties of the tube being examined by the laser-ultrasonic system. For further details on advanced signal processing, please refer to Appendix A.

2.3.2: Time of flight calculation

The approach proposed to achieve TOF measurements for waveforms with SNR below 0 dB consists of a double strategy. First, proper windowing of the two portions of signals is used as a very effective and simple improvement to CCR (the back-wall echo and the reference). Windowing the data minimizes spectral leakage involved by using Fast Fourier Transform (FFT). Second, SSP could be optimally applied after the process of CCR on the resulting output. Indeed, the CCR is considered as a matched-filter, the result of CCR should strengthen the coherent part of the signal as compared to the initial ultrasonic echo in the waveform. The use of SSP would then identify the enhanced coherent signal and allow for a better location of the maximum in the CCR function.

To evaluate the proposed approach, laser-ultrasonic waveforms at room temperature were collected from a sample with known thickness. Data were obtained on a single steel bar nearly 25 mm thick, using different generation laser energies (20, 25, 30, 35, 40 and 50 mJ). In each case, nearly 75 measurements were made to get a good statistics. The raw laser-ultrasonic waveforms were numerically filtered with a band-pass filter in the frequency range 2.5 to 8.5 MHz to remove laser noise and time shifted to correct for any laser jitter present. Valid waveforms were then used to establish a synthetic reference signal. The reference signal was used for calculation of the CCR. The laser-ultrasonic data from all the different levels of excitation were analyzed and statistics for the thickness estimates calculated.

One important aspect in the analysis was to simulate eccentricity in the data set. The portion of the waveform selected for CCR with the reference signal was made using a "dancing window." The position of the "dancing window" was set using a random Gaussian distribution, with a mean corresponding to the nominal thickness (25 mm, 8.7 μs between roundtrips) and the 2σ variations of 8% of the nominal thickness. Such thickness variation is expected to represent an extreme case for online data.

Statistical comparison was made of results using CCR alone with results using CCR combined with SSP. The role of SSP is to identify cases for which the maximum of the CCR output would lead to incorrect thickness estimates. While the advantage of SSP in the presence of low SNR was demonstrated, its use showed a detrimental effect of having a large number of rejected values in conditions where direct CCR yielded a good answer. Both approaches were implemented into the data analysis software, with "soft-switches" for selection of the processing method. Final determination of the method to be used would be done online.

TASK 3

PROTOTYPE DESIGN AND IMPLEMENTATION OF SIGNAL PROCESSING

Following the R&D phase of the program, several modifications to the initial proposed system design of the LUT were made. These modifications were made to accommodate final designs of components and to adapt to plant restrictions. The following section describes the final prototype of the LUT system.

3.1: System Design

The LUT gauge is a non-contact thickness measurement gauge based on laser-ultrasonic technology. In laser-ultrasonics, the output of a high-powered, short-pulse generation laser is focused onto the surface of the target. The energy at the focus point is such that a small volume of the target material is vaporized. Matter is expelled from the surface and, by recoil effect, an ultrasonic compression wave is sent into the bulk of the material, in a direction normal to the surface. The amount of material removed from the target is generally very small and, in the case of hot steel, consists only of the metal oxide layer, which is rapidly renewed. Hence, the laser generation of ultrasound does not affect the ultimate surface quality of the product.

A frequency-stabilized detection laser is focused simultaneously near the point of impact of the generation laser. Any motion of the surface of the target will be recorded as a phase change and/or as an optical frequency shift of the back-scattered laser light beam. Available photodetectors do not have fast enough response time to allow a direct recording of the phase changes or frequency shifts. To detect them, the signal light beam from the sample is made to interfere or "beat" with a reference beam. The interference of both beams transforms the phase variations into amplitude variations, called demodulation of the signal beam. Such amplitude variations can then be recorded with a standard photodetector. In the LUT, the demodulator unit consists of a CFP interferometer with appropriate stabilization electronics and signal amplification.

Wall thickness measurements are made by determining the time of propagation of ultrasonic compression waves within the wall of the tube. Knowing the velocity of compression waves within the material, very precise measurement of the wall thickness can be obtained. Measurements of the TOF are made using numerical signal processing developed in the R&D phase of the program.

The velocity of compression waves will depend on different parameters such as steel grade, grain size, and temperature. Previous work indicated that the velocity variation is attributed principally to variations in temperature. Since temperature will vary between production lots, between tubes in a given lot, as well as within a single tube, temperature is an important parameter to measure. The LUT records the temperature of the tube with a two-color optical pyrometer. Temperature recordings are used to correct velocity variation and also to provide a temperature map of the tube. The light collection optics of the optical pyrometer are integrated with the collection optics of the laser-ultrasonic components. Numerical signal processing is used to achieve a high degree of precision in the temperature measurements.

The non-contact nature of laser-ultrasonics allows the LUT to generate and detect the ultrasound at a distance, independent of the temperature and orientation of the tube. However, since both the detection and the generation lasers are Class IV lasers, standard laser safety procedures require that the beams be encased in an enclosure to prevent human exposure to the beams. The focusing and collection optics are placed inside an enclosure, called the inspection head, which is placed on the production line.

All laser beams are delivered to the inspection head through optical fibers, which are encased in a protective flexible conduit umbilical cable. Safety measures that limit firing of the lasers to only when a hot tube is present in the propagation path of the laser beams have been integrated in the system. A laser shield, integrated into the production line, provides an opening large enough to allow a hot tube to pass thought it, while limiting exposure of any personnel near the system to diffuse or reflected laser light.

The intent of the project was not only to measure wall thickness, but also to gain an estimate of tube eccentricity. To accomplish this, the LUT is positioned at the exit of one of the rotary operations of the tube mill. As the tube is rotated and translated past the inspection head, measurements will be taken over a helical path. The laser-ultrasonic and pyrometer sensor data collected thus provide temperature and wall thickness profiles over the entire tube surface.

To provide maps of the data collected, positional information is required. A two-axis laser-velocimeter system has been designed and integrated into the LUT to provide the velocity along the axis of the tube and around the circumference. The location of each thickness and temperature measurement is determined by integrating the recorded velocities.

The LUT is the integration of the previously described functionalities and is composed of the generation and detection lasers, a demodulator unit, and an inspection head linked to the other units by optical fibers. The demodulator contains the interferometer, the two-color pyrometer and the electronics for the dual-axis velocimeter. The inspection head contains the focusing and collection optics of the laser-ultrasonic system, the pyrometer and the dual-axis velocimeter. The fourth component of the LUT system, the control unit, has three PCs for signal processing, a fourth PC for control, and a fifth PC for data transfer and user interface.

The initial concept of the LUT was that the lasers and control systems would be located remotely from the process line and inspection head. Those components would be installed on the production floor in a protective cabin with a controlled environment. The concept included provisions to place the inspection head at different locations and relocate the cabin if necessary.

To provide a mobile system, a decision was made to use the trailer section of a standard 8 m semi-tractor trailer as the control cabin. The trailer was modified with heating and air conditioning to produce a controlled environment. An internal electrical supply and chiller to provide liquid coolant to the laser components were added in an utility section. The section of the cabin containing the lasers was designed to be a light-tight laboratory to allow for on-site servicing of the lasers. The cabin is linked to the inspection head by a 20 m long umbilical cable housing the optical fibers and electrical links between the cabin and the inspection head.

A remote control station placed near the inspection head allows full control of the LUT at the process line. The station allows the operator to view the real-time data and to assess the operation of the sensors. A screen was added during online installation to provide real-time viewing of the data by the plant gauger (Figure 1) to be used to provide rapid feedback to correct production problems.

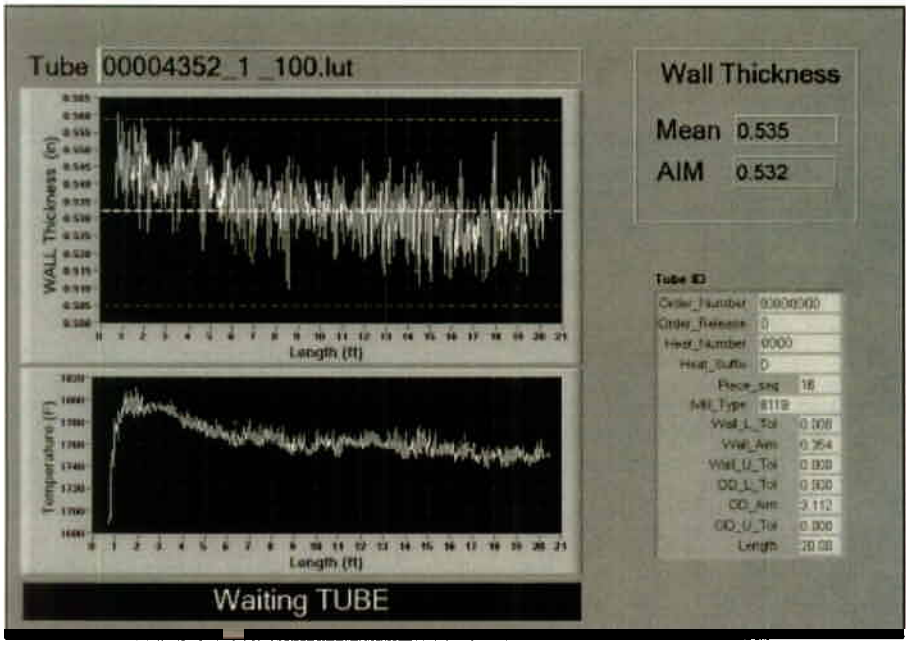

Figure 1. LUT gauger display of wall and temperature.

The LUT is linked to Timken's computer network to permit access for more extensive data analysis and storage. The operator can access the LUT data either with the remote control station or with a network link.

A software module, LUTDAS, was built to allow real-time viewing of the LUT data from anywhere within the Timken network. This tool was contemplated for use by process improvement engineers. Using LUTDAS, the tube data can be viewed in a format identical to the remote control station, with more detailed analysis and statistics. The data can also be viewed as a wall variation mapping as shown in Figure 2. The LUTDAS information has now been placed at several locations within the mill including several points along the tube making production line so that operators can monitor the effects of their adjustments.

The schematic in Figure 3 shows the positioning of the LUT components, notably the mobile cabin and the inspection head. The next sections contain details of the system components.

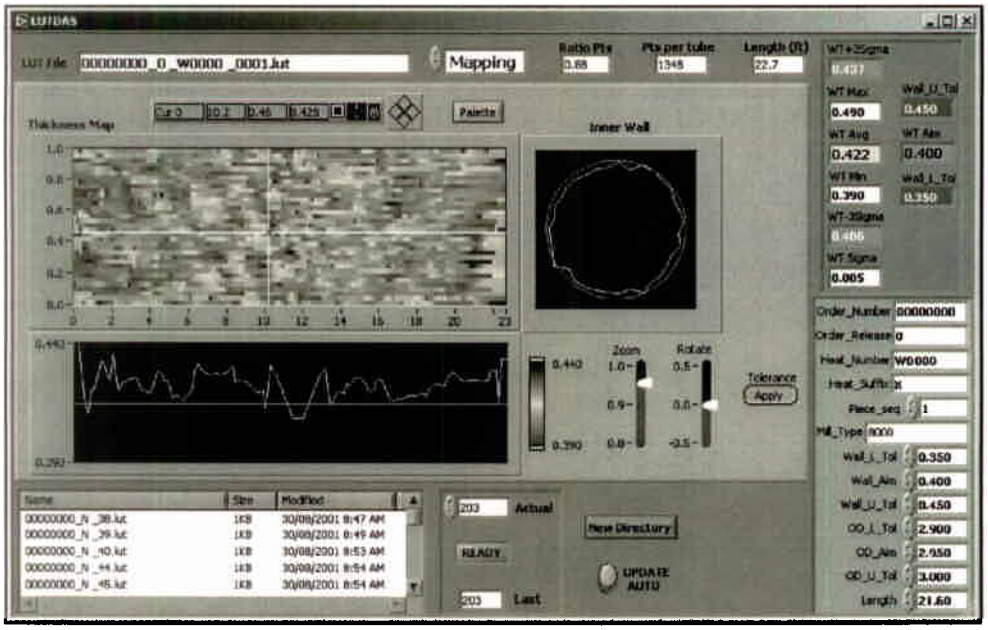

Figure 2. LUTDAS display of tube wall variation mapping.

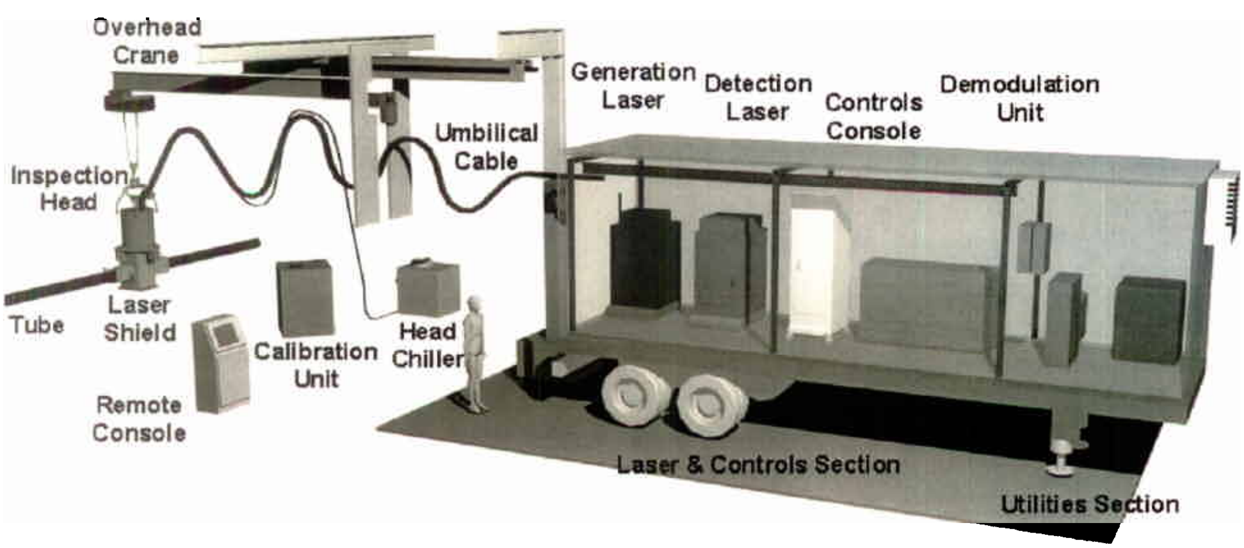

Figure 3. Schematic drawing of the LUT gauge in the tube mill.

3.2: Generation Laser Unit

The generation unit is a Nd:YAG laser, operating at a wavelength of 1064 nm, with an output of 320 mJ per pulse. The repetition rate is 100 pulses per second. The pulse width of the output laser beam is less than 10 nsec. An ultrasonic compression wave is generated in the steel with a bandwidth above 100 MHz.

The beam is delivered to the target using four large core optical fibers, imaged onto the surface as a spot approximately 3 mm in diameter. Large core optical fibers are used to reduce the possibility of fiber breakage due to concentration of the high energy density inside the fiber. However, large core fibers are brittle and can break easily if they are forced into too small radius. To protect them, the fibers have been encased in flexible protective tubing

The generation laser is an industrial grade laser, and is therefore equipped with standard laser safety interlock features, as required by the ANSI Z-136.1 standard and CDRH regulations for laser products. The laser has an industrial light-tight enclosure which is "hard-mounted" to the cabin floor. No other fixture is required in preparation for moving the LUT to a new location.

The laser is fully controlled by an external computer and is linked directly to the control computer of the LUT, where all of the generation laser parameters can be set. Since it is an industrial product, the laser is packaged for easy maintenance and periodic servicing, such as flash lamp replacement. The laser also contains an internal cooling unit, which cools the flash lamp inside the pump chamber of the laser, that has been connected to an external chiller.

3.3: Detection Laser Unit

The detection laser unit is a long-pulse Nd:YAG laser, which uses flash lamp technology. It has an output of approximately 100 mJ per pulse with a repetition rate of 100 pulses per second. This rate is limited by the flash lamps used to amplify the frequency-stabilized seed laser inside the detection laser. The pulse width is 60 μsec, thus providing an inspection window of approximately 40 μsec. Based on the velocity of sound in steel, this window allows the LUT to measure the full range of wall thickness specified in the project, i.e., from 6 to 76 mm.

Since the LUT gauge uses a laser velocimeter to determine the position where data is acquired on the tube, a portion of the seed laser of the detection laser is used as the laser source for the velocimeter. Hence, a beam is sampled from the seed frequency-stabilized laser and delivered, via two optical fibers, to the optical head of the velocimeter.

The output of the detection laser is delivered to the target using a medium-core size optical fiber. The output of the fiber is imaged onto the target surface as a 2 mm diameter spot. A visible HeNe laser tracer beam is injected in the output fiber of the detection laser to visualize the point of impact on the surface of the target.

Unlike the generation laser fiber, the detection laser fibers are sufficiently flexible with regard to curvature. However, since these fibers will be used in the plant environment, they are placed in flexible metal tubing to protect them from the environment as well as from mechanical damage.

While the fibers of each laser are encased in protective tubing, an additional measure has been taken to prevent breakage during positioning and handling. The protected fiber cables have been placed in a multi-directional flexible channel shielding system.

The detection laser is housed in a light-tight mechanical enclosure and is equipped with safety features as required by the ANSI Z-136.1 standard and the CDRH regulations for laser products. The laser enclosure is "hard-mounted" to the floor of the mobile cabin. No other fixture is required in preparation for moving the LUT to a new location. The detection laser is fully controlled by an external computer and is linked directly to the control computer of the LUT, where all of the detection laser parameters can be set. The detection laser was also designed for easy access and maintenance.

3.4: Pyrometer Unit

In order to achieve target precision for wall thickness measurements, the temperature of the tube is measured at each location of data acquisition. Initially, a commercial two-color pyrometer was included in the system to measure the surface temperature of the hot tubing. Unfortunately, no supplier was found capable of satisfying the requirement of a 20 m long fiber coupling between the mobile cabin and inspection head. Also, the optical pyrometer had to be designed to withstand the illumination by the generation and the detection lasers. It was decided to build an optical pyrometer within the scope of the project. Since the pyrometer is integrated in the LUT, it can use the same collection optics as the laser-ultrasonic detection sub-system. This allowed maximized collection efficiency without having to increase the size of the inspection head.

The pyrometer unit was assembled and tested using available calibrated blackbody and met the target performance specifications. The pyrometer unit was field-tested by viewing hot tubing on the production line at Timken using a simplified optical setup.

The detection and signal-processing module of the pyrometer unit is enclosed in a metallic box and housed inside the demodulator unit. The module can be removed easily from the demodulator unit for calibration or servicing. A software module was designed to process the signal from the two photodetectors and output the corresponding temperature. The module measures the temperature at a rate of 100 Hz, between successive firings of the generation and detection lasers. For each wall-thickness measurement, the temperature data are transferred to the main computer via the internal network of the LUT system.

3.5: Velocimeter Unit

Commercial laser-velocimeters are currently used in industry to perform non-contact length measurements of metal sheets and tubes. Unfortunately, such systems are costly and bulky. Since the LUT already contains a number of lasers, a portion of the detection beam is used as the laser source for the measurement of velocity. A two-axis laser-velocimeter with compact optical setup for the focusing and collection optics was designed, fabricated and tested in the course of the program. A software module was designed, implemented and tested to measure the velocity along both axes simultaneously.

The two-axis velocimeter was fully tested using a calibration device developed at IMI. The device consists of a large metallic wheel mounted on a frame and driven by an electric motor. A high-precision encoder is attached the main shaft of the wheel. By tilting the wheel with respect to the axis of the velocimeter, the velocity ratios can be varied and recorded. This device was used to calibrate the output of the software module. The calibration module was supplied at Timken with the LUT so that this procedure can be repeated and verified periodically during servicing.

3.6: Demodulation Unit

The demodulation unit is the heart of the laser-ultrasonic sub-system. Its function is to extract the ultrasonic pulse-echo information from the detection laser beam backscattered from the target's surface. After the R&D phase of the program, it was determined that the demodulation function would be made best with a CFP interferometer. A commercial 1 m long CFP was purchased for the project and placed in the demodulator unit. The output of the CFP photodetector is sent to a PC digitizer card for numerical signal processing.

Given the reflectivity of the mirrors, the CFP has a demodulation bandwidth of approximately 12 MHz, with a peak response at 5 MHz and a 3 db high-pass cut-off frequency of approximately 2 MHz. These characteristics meet the requirements for wall-thickness measurement. However, the present configuration has a limited bandwidth and would not be fully appropriate for direct use in spectral analysis of the ultrasonic attenuation in the hot mechanical tube.

The distance between the two mirrors of the CFP must actively be stabilized in order to achieve efficient demodulation. Stabilization of the CFP cavity generally is done by comparing the intensity of the input light to that of the output. However, since the generation and detection lasers both operate at the same wavelength, generation laser light collected by the collection optics of the laser-ultrasonic sub-system may perturb the stabilization. A new stabilization feedback-loop using computer control (instead of the standard analog electronics) and fast photodetectors was designed. The new feedback-loop takes into account the possible presence of the generation laser beam in the stabilization signal.

3.7: Inspection Head & Laser Shield

A mechanical support structure was designed and built to contain and protect the optical elements of the system. The design of the inspection head was made to minimize the volume of the probe while still providing access for alignment of the optical elements, and a robust protective enclosure.

The casing was designed with 20 mm steel walls to dampen vibration and resist impact. This resulted in a heavy structure that cannot be manipulated by an operator without assistance. A gantry was built inside the mobile cabin for manipulation of the inspection head and optical probe during servicing operations. A traveling beam crane was installed at Timken to manipulate the inspection head on the plant floor.

Since the inspection head is placed near hot metal tube, a significant rise in temperature inside the inspection head was expected. The base of the inspection head includes a coolant circuit which connects to an external chiller located on the plant floor. A heat sensor was installed inside the inspection head. If the inspection head temperature were to exceed a given temperature, an alarm would be triggered to alert the operator to remove the inspection head from the production line and allow it to cool before damage could occur.

The LUT uses lasers classified as Class III and Class IV by federal regulations. These types of lasers require specific safety measures to protect personnel. The LUT was designed to fulfill all of the safety requirements as defined by the ANSI-136.1 standard and is in compliance with the CDRH laser product guidelines.

In particular, the guidelines state that the laser beams must be enclosed in a protective housing so as to preclude any direct human exposure. To comply with this requirement, all laser beams are delivered to the target through optical fibers. A set of mechanical shutters controls the open-air transmission of the laser beams from inside the inspection head to the tube's surface. A hot-metal detector triggers the opening of the mechanical shutters only when a tube is present in the path of the laser beams, hence insuring that all laser beams are intercepted by the tube.

A laser shield was designed to serve as a positioning mount for the inspection head, to convey the tube as it moved past the LUT, and to contain fugitive light emissions. It was designed for strict adherence to calculated nominal hazard zones (NHZ) and built to contain all possible reflections of the lasers from the tube's surface. No direct or reflected beams can propagate outside of the laser shield.

For Class IV lasers, the laser shield must also provide protection against diffuse light, i.e., laser light scattered by the tube's surface. The laser shield must sufficiently enclose the tube as to limit the viewing angle of the point of impact of the lasers onto the tube surface. However, the aperture must also be large enough to allow passage of the tube, while guiding the tube through the laser shield. These conflicting requirements led to construction of a set of laser shields, each used for a range of outside diameter tube dimension.

Dimensions of each laser shield were adapted to follow production group range. As with the inspection head, the laser shield is a steel structure that is able to survive a contact with the hot metal tube. An audit conducted by an outside agency concluded the fully assembled LUT system to be equivalent to a Class I installation, eye-safe for plant personnel.

3.8: Control Unit

The LUT gauge system makes extensive use of computers to automate most of the functions of the gauge. All the computers used are housed in the control unit, placed inside the mobile cabin. The control unit contains the user interface computer, the control computer, the laser-ultrasonic data acquisition and signal processing computer, the pyrometer data acquisition and signal-processing computer, and the velocimeter data acquisition and signal-processing computer.

All five computers are standard off-the-shelf industrial PCs mounted in a rack connected to a water-cooled heat exchanger linked to the chiller. The control unit also houses the PLC, which enables monitoring of the status of the gauge and allows control of non-computer interfaced components and the system synchronization unit.

The following section details the function of the different components of the control units.

3.8.1: Control computer

The process control computer (PCC) performs the startup and shutdown functions, verifies operational status, and regulates the communication between the different computers. The PCC is linked to a programmable logic controller (PLC) through which it receives status of components that cannot be directly linked to the computer network, such as the laser safety interlock and power interruption status. The laser safety features, such as the emergency stops and laser interlocks, are not controlled by the PLC nor the PCC, but instead are directly linked to the power supplies of the lasers, as required by federal regulations.

At startup, the PCC checks and resets the parameters of the lasers, the demodulator and synchronization units, and checks the status of the other computers. The PCC controls the shutdown sequence to prevent data loss, even if the shutdown results from an emergency condition. It is programmed to deactivate the laser flash lamps during a delay in order to extend their life. The PCC resets the laser when a message of "in-coming tube" is received from the wireless tube detection device and/or the Timken network.

3.8.2: User interface computer

The user interface computer (PCUI) links the LUT to the remote control station and Timken's computer network. The main task of the PCUI is to receive data from the network which identify the incoming tube, and to collect and store the data transferred from the other data acquisition and signal-processing computers.

The PCUI receives the TOF data, rotational and linear velocities, and temperature. The PCUI combines the information into an indexed storage array for each inspected tube. The data for a given tube is stored in a single file through the network. The data file can be viewing by any user connected to the Timken network through the LUTDAS interface software. The PCUI displays real-time data, such as wall thickness profile, temperature profile and statistical analysis, for each inspected tube on the remote control station. The PCUI also displays messages from the control computer when operator action is required.

3.8.3: Laser-ultrasonic data acquisition and signal-processing computer

The laser-ultrasonic data acquisition and signal-processing computer (PCLU) digitizes the signal from the CFP and determines the TOF of the ultrasonic pulse. The signal is digitized using a commercial 12-bit PC based digitizer up to a rate of 10^8 samples per second. The digitized signal is then processed using numerical algorithm to extract the TOF.

3.8.4: Pyrometer data acquisition and signal-processing computer

The pyrometer data acquisition and signal-processing computer (PCPyro) digitizes the signals from the pyrometer photodetectors and calculates the tube surface temperature. In order to achieve a high precision in the temperature measurement, the pyrometer signals are collected over a period of 8 msec. Since the PCPyro is generally idle due to short computation time, it is also used to initialize stabilization of the CFP, periodically verify its status, and make an orderly shutdown.

3.8.5: Velocimeter data acquisition and signal-processing computer

The velocimeter data acquisition and signal-processing computer (PCVel) digitizes and processes the photodetector signal to get the velocities along two axes. The optical amplitude modulation frequency is directly related to the velocity of the moving tube. For a two-axis velocimeter, there are two interference patterns, and therefore, two modulation frequencies. The software module developed isolates the two dominant modulation frequencies by applying a spectral analysis to give the velocities along the two axes. Since the rotation velocity is much larger than the linear motion of the tube, the module always assumes that the lower velocity is the linear velocity.

The precision of the frequency measurements, and therefore the velocity, is determined by the length of the data array acquired. The velocimeter data acquired for a time period of 8 msec produces velocity measurements averaged over that period. Since the velocity of the tube is not expected to vary rapidly in normal operation, such averaging does not distort the maps produced by the LUT.

TASK 4

PROTOTYPE CONSTRUCTION

The LUT prototype system was assembled and tested at IMI and then moved to Timken. All individual components were tested independently for their functionality and then integrated into the full system. The integrated system was tested in laboratory conditions and then placed in the mobile cabin. No major modifications were needed during the integration phase of the LUT.

The assembled system was fully tested in the large-scale laboratory facility at IMI. This allowed the utilities section of the mobile cabin to be tested. Approval by Timken management and the appropriate safety officials was obtained during those tests, and the system was transported to Timken. The following section describes the construction of the prototype and required changes that have been made to the mill.

4.1: Mobile Control Cabin

One of the objectives of the program was to develop a gauge that could be used at different locations in a steel mill. The LUT is composed of several large components that must be moved to each new location where the gauge is to be used. Initially, the gauge was envisioned in the form a several inter-linked blocks, which would be detached and re-attached at the different locations. This approach requiring that each component be individually connected with power, environmental protection and computer networking was determined to be too costly and difficult to implement.

A more versatile and cost effective approach was to bring together the components into a single unit. A modified 8 m long trailer was purchased to house the components and provide a controlled environment. The mobile cabin is separate into two sections. The back section houses the generation laser, detection laser, demodulator and the control unit. The section is equipped with standard laser safety measures allowing the lasers to be serviced and maintained. A gantry structure is provided to manipulate the inspection head inside the cabin for off-line servicing. The forward section contains all utilities, including a power distribution unit and an internal chiller. The mobile cabin requires only one electrical supply to power the entire system.

4.2: Remote Control Station

The mobile cabin is located at some distance from the inspection head, outside the mill building. A remote control station is provided to allow the operator to control the LUT gauge and view the data on the plant floor. The remote control has the same control capabilities as in the mobile cabin for operation of laser products, as required by the CDRH guidelines.

4.3: Operator Interface

The communication interface design specification (IDS) documents communication between the LUT system's main computer and two Timken systems. The LUT receives tube identification and product specifications from Timken's tracking system. The LUT combines this information with the tube analysis data and sends it to the Timken network. When the tube exits the mill, the tracking system sends a statistical summary of the LUT gauge information along with numerous other tube records and mill parameters to a server for storage in a SQL database. If requested by the operator, the entire set of data can be viewed or saved on the LUT computers for later retrieval and analysis.

4.4: Calibration Unit

To provide for verification of TOF, wall thickness at room temperature, temperature, and position, a laser light-tight calibration unit has been constructed. Standards and/or devices can be placed in this calibration unit to test specific features of the LUT. The inspection head can be moved by traveling beam crane onto the unit, which is located on the mill floor near the gauge site, to perform these verifications. The calibration unit also acts as resting location for the inspection head when repairs or maintenance on the production line is done or when maintenance or repairs are needed inside the inspection head.

4.5: Mill and Facility Alterations

The Rotary Sizer outlet table at Timken's #4 Tube Mill was selected as the site for the in-plant trials. The outlet table conveyor rolls and tube guiding systems were modified during an outage to accommodate and allow installation of the hydraulic clamp base and the laser shields. The laser shields supports the LUT inspection head during operation, guides the moving tube from the Rotary Sizer through the area where the measurements will be taken, and serves as the primary shielding of the reflected and diffuse light from the lasers.

A spare set of laser shields was built, should ready replacement be needed due to wear or damage caused by a wreck in the mill. To this point, the design has been robust and no shields have been damaged by wrecks. Continuous use has caused wear of the sides and inner base of the shield; this wear is rapid during initial hours of use, and slows as the tubes contact other support surfaces. A replacement schedule has been established for the laser shields taking into account the rate of wear of the shields. A harder steel has been prescribed for use in base plate when the laser shields are refurbished. This wear is a critical parameter as it changes the effective tube height causing the laser's beam to be out of focus, reducing the generation and detection efficiency of the laser-ultrasonic sub-system, as well as reducing the accuracy of the laser-velocimeter.

A double-hoist jib crane was installed at the Rotary Sizer for expeditious changing of the laser shields. A traveling beam crane and building wall doorway were installed adjacent to the Rotary Sizer to move the LUT inspection head during laser shield size changeovers and to transport the inspection head to the mobile cabin for any required diagnostic work. A water chiller for cooling the inspection head was also installed on the plant floor near the calibration unit.

TASK 5

IN-PLANT TESTS

5.1: Mill and Facility Alterations

In the implementation phase of the project, the LUT was moved from IMI to Timken and installed at #4 Tube Mill in the late spring of 2001. Figure 4 shows the system in position for measurement with a tube passing from right to left out of the Rotary Sizer into the laser shield on which the inspection head is sitting.

Once installed, the performance of each measuring unit was tested online to determine the impact, if any, of the plant environment. Minor problems were identified and corrected. In particular, a slight modification of the inspection head casing was needed to correct the focus of the velocimeter. Also, the network communication protocol was modified to provide a more robust link. The full system acquired the first online data in September 2001.

In the fall of 2002, the LUT was used in parallel to the manual size checks performed by the plant gauger. The gauger generates limited data at the leading and trailing sections of selected tubes based on micrometer readings taken on cut samples. In nearly all cases, systematic comparison showed that the LUT data was consistent with the gauger data.

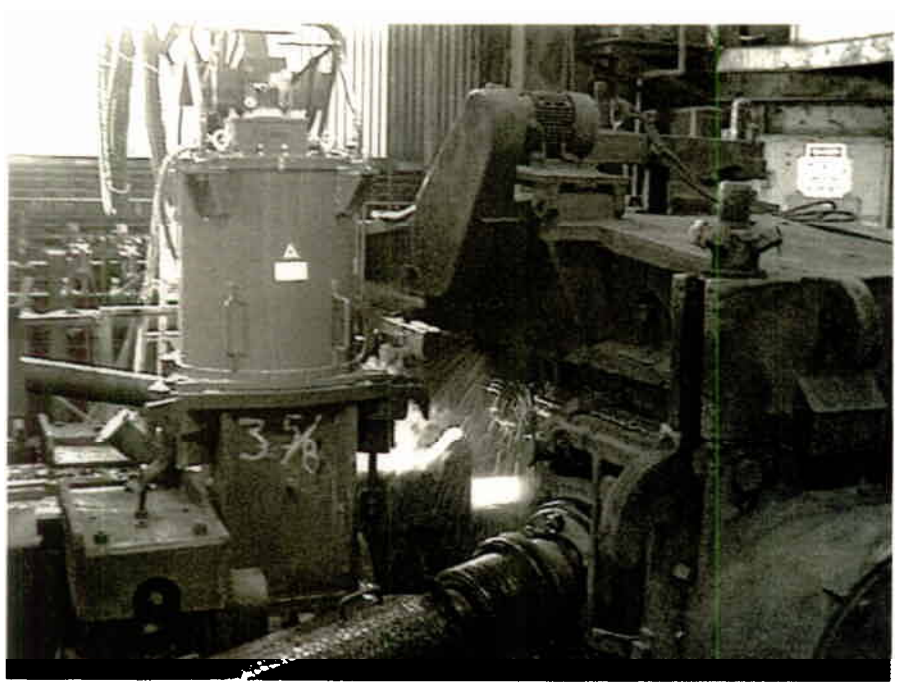

Figure 4. Picture of LUT online.

5.2: Data Acquisition and Comparison to γ–ray Gauge

During the early implementation period, cold-tubes with known thickness were inspected with the LUT. The thickness profiles were compared to data obtained with a non-destructive testing (NDT) system which uses conventional contact ultrasonic wall thickness gauging. The results showed an excellent match between the LUT data and that from Timken's NDT system.

As proposed, the LUT was to be implemented on the same mill as a γ–ray gauge, allowing direct comparison of wall measurements. Early in the project, it was decided to place the LUT on a different mill – one with no gauge system. Instead of using the γ–ray gauge as a comparator, plans were made to compare the LUT projected wall data to measurements made using a calibrated, conventional contact ultrasonic gauge measuring tubes at room temperature.

A calibration verification study was conducted by comparing wall data obtained on five tubes from one order measured hot with the LUT, with assumed accurate walls measured cold using the NDTs. Comparison of data sets showed an average difference less than 0.5%, verifying that the calibration equation was generally accurate. In addition, the LUT pattern of wall variation was a strong match to the NDT trace.

Those excellent results indicated that the calibration equation was adequate for the wall size and steel grade combination represented by the selected order. In order to show broader capability, a sampling plan was designed to cover the range of O.D., wall thickness and steel grade made on #4 Tube Mill.

The plan used an orthogonal design space covered by seventeen combinations of O.D., wall and grade - carbon levels. When a candidate order was found in the production line-up, instructions were given to capture the LUT data on nine tubes and route those same pieces for cold tube inspection. All but two of the desired combinations have been satisfied.

When the data for an experimental set were generated, a visual match was done and data representing similar sections of the tubes was retained for inclusion in the analysis. This was important to do as considerable wall variation can be encountered at tube ends.

It should be noted that the temperature measurement in the LUT, specifically the accuracy of the pyrometer, has been under refinement during the course of the experiment. It can be stated that the current best estimate of the temperature was made and that test conditions generated later should be the most accurate.

Data for fifteen of the seventeen planned conditions were generated. The remaining conditions did not appear in the production schedule. In order to complete the study, artificial data with three levels of assumed variation were used to populate the remaining conditions.

Analysis of study data indicated an 0.8% average difference in wall between LUT and NDT, with the LUT predicting a thinner than actual wall. That accuracy error is the conservative and favored condition as errors would to produce thicker than expected tubes, rather than the opposite where thinner than expected tubes could compromise machining tolerances.

The analysis using the difference between the LUT and the NDT readings indicated that tube wall thickness may be a significant parameter in predicting the observed difference. The difference increased with increasing wall thickness. The O.D. of the tube was found not to be a significant predictor.

The carbon level in the steel grade was found to be significant with the higher carbon tubing having less difference. This may be indicative of the thinner and tighter scale layer formed on the tubes prior to measurement.

The variance of the wall readings was also used as an assessment response variable. The results indicated that there was no difference between the LUT and NDT as they each captured the same amount of wall variation.

A subjective assessment of the pattern match between the respective traces indicated that the larger O.D. tubes had a poorer fit. In addition, there did not seem to be any effect of the improving temperature measurement during the course of the study.

The accuracy error could be corrected by implementing a regressed formula that accounts for wall thickness and carbon level effects. If the regression were integrated into the calibration formula, the bias would become zero. If that were done, the remaining error would be associated with the measurement method, i.e., its precision.

After determining the 95% confidence band for the difference and dividing by the average wall thickness in the experiment, that value is estimated to be 1.66%. The actual value probably is slightly less because the thicker walls have the larger errors. In general, the precision of the LUT measurement is to within 1.5%. Comparing the measurement precision with the allowable tolerances for tubing suggests that the measurement uncertainty would consume 20% of the allowable variation represented in the manufacturing tolerance.

The LUT system has proven to be capable of measuring wall thicknesses from 5 to 25 mm in tubes from 6 to 14 cm O.D. on most steel grades representing the full production capabilities of #4 Tube Mill. The grades more prone to rapid formation of a loose, non-uniform scale layer have been observed to be the most difficult to measure. This is consistent with difficulty in coupling to the steel tube. For the combination of thick wall and difficult grade, strong signal conditions produced by fresh flash lamps, and with clean windows and mirror are required. For more difficult conditions, scale removal or the advanced signal processing may be required to generate wall readings on those difficult wall-grade combinations.

In March 2002, the LUT gauge was put in full production mode. Since then, LUT data have been used to make production decisions, i.e., signaling to proceed with order as set-up pieces were in tolerance or to make necessary size adjustments, and to diagnose production problems. Given the improved assessment of wall variation provided by the LUT data, Timken's manufacturing organization has rapidly adopted and come to depend on the LUT gauge. The LUT has become a key tool for process improvement engineers, allowing wall scrap levels to be reduced to near record low levels on #4 Tube Mill.

5.3: Reliability and Mobility Tests

As noted earlier, the LUT was designed to be mobile and the original project scope included a task to relocate the system within the designated mill or to another mill. Since the cabin evolved into a truck trailer and because the system was tested at IMI and then deployed at Timken, it can be argued that the ability to move the lasers and control system has been proven.

Similarly, the original design included an inspection head that would be placed on the process line and left for long periods of time. Since it became necessary to exchange laser shields based on tube size, an appropriate handling system was developed and successfully implemented as evidenced by the fact that the head is removed and replaced almost every day.

Further, analysis of the data has indicated that it is not necessary to have the LUT located directly after any one process to determine which step is contributing to wall variation in the tube. A knowledge book is being assembled to identify patterns of variation and suggest proper adjustments that could be made to reduce the variation. As a result, the relocation task was dropped.

Since the LUT became an integral part of the production process, efforts have been made to maximize system availability. Upgrades and maintenance have been scheduled, when possible, during non-production periods, on weekends and holidays. The replacement of flash lamps, a consumable element of each laser, has been rendered a routine task, which can be accomplished during a downtime or even during larger orders once proper size is achieved.

A number of problems were encountered during the first six months online. Surprisingly, many were electronic component failures and not a reflection of the technology employed, which has been impressively robust. A short list of those problems includes a signal generator failure, a bad laser baseboard heater controller, a shorted coolant heater and a sticking laser shutter.

Problems constraining system availability were attacked and many solved. One example is the clouding of the external surface of the window on the inspection head due to moisture from the water applied to the Rotary Sizer rolls for cooling. A purge of plant air flowing inside a removable cone was installed which allowed operators to remove the cones and clean the windows as needed between orders.

The most glaring problem is the fouling of a flat, gold-coated folding mirror by 0.5-1.0 μm silica particles that build-up forming a spot that reduces beam strength. The origin of the particles remains unknown, but steps have been taken to allow rapid replacement of the fouled mirror. A portal access panel has been incorporated into the inspection head casing and a slide holder implemented to facilitate proper positioning of the replacement mirror. The mirror exchange can be done in less than 30 minutes and the fouled mirrors chemically cleaned for reuse. A new design of the inspection head has been developed to eliminate the need of a horizontally placed mirror and therefore reduce the possibility of particles fouling any folding mirror.

During the six-month period of March to September 2002, the system measured 76% of production, or a total of over 225,000 tubes. Of the 24% downtime, 14% consisted of maintenance or upgrades of the system. The remaining 10% was divided equally between tracking data problems, system component failures and periods of insufficient signal strength. Many of the reliability issues have been addressed and corrected, so that 95% availability should be easily possible. A semi-annual maintenance schedule has been planned to maximize system performance.

A good points ratio (GPR) has been added to the LUT display to represent the number of laser flashes turned into good wall readings. The GPR is being used to judge the health of the system as the value is reduced by weak signals or attentuation by a fouled mirror or clouded windows. The GPR can also be used to check the installation, as low values can indicate worn or misaligned mill equipment.

TASK 6

Documentation and Training

A comprehensive safety-training plan was developed based on thorough documentation of system safety features.

6.1: Safety Assessment Report

As a part of system documentation, which includes user manuals, a thorough report was assembled on the safety aspects of operation and conformance to industry and regulatory standards. The report was used to satisfy the CDRH for approval to import the assembled system from Canada and for safe usage of the laser system in the U.S. The document was also reviewed by Timken's Laser Safety Officer for acceptance of the system safety features in advance of the in-plant trials.

In order to assure the safety of the design, Rockwell Laser Institute was hired to review the design and installation and make light measurements of the LUT system to assess its safety. The results of their report indicated that adequate steps had been taken to ensure that the system operated as a Class I installation and required no special protection given the laser shield and safety interlocks provided in the system.

6.2: Safety Training

A three-step plan was executed to train Timken associates on laser and system safety. In the first step, associates working in #4 Tube Mill were given basic laser safety training. In a second step, operational training was given to personnel that need to interact with the system, such as for daily operation of the gauge or for changing of the laser shield. Finally, specific personnel were given training on maintenance of the LUT. Specifically, Timken personnel were trained for replacement of the flash lamps of the generation and detection lasers.

TASK 7

Feature Extraction and Online Tests

7.1: Test Plan and Setup

This task was included in the project to provide the operator with enhanced information to identify potential causes of observed wall variation. The expectation was that each cause of wall variation would produce a unique pattern that could be identified through pattern recognition. Identifying the patterns and their causes quickly would provide valuable information that could be used for feedback control.

7.2: Feature Analysis and Pattern Recognition

Preliminary studies conducted using data from existing NDT systems indicated that patterns of wall variation could be found. It was decided to determine if a classifier could be constructed by generating patterns caused by known conditions. An experiment was executed to control the tube making process to generate five common conditions expected to produce wall variation.

Data from the LUT on those conditions were analyzed by ORNL using sophisticated filtering techniques. Two of the five conditions produced recognizable patterns, while the other three did not. In fact, it was observed that significant variation was present even under the controlled conditions – suggesting more conditions would be needed for a robust classifier. Another limitation was that a metric could not be identified that would be useful in applying the classifier.

It was judged that the LUT's full-length tube display of wall variation would be such an improvement over the information generated from the few cut samples, that the gaugers and mill operators would soon be able to recognize the impact of the mill adjustments they would normally make based on their experience. The LUT thus became a valuable tool in the informal 'manual' recognition and adjustment feedback control loop. Two examples showing the reduction of variation relative to the aim wall and process limits are shown in Figures 5 and 6.

7.3: Test and Evaluate Algorithms

Rather than consume additional time and resources on such a difficult problem, it was decided to concentrate efforts and project resources on remaining tasks critical to deploying the system. Due to those circumstances, this task was cancelled. The task may be initiated at a later time outside the project.

7.4: Extension of Data Analysis

Due to circumstances explained in section 7.3, this task was cancelled.

7.5: Report and Recommendations

Due to circumstances explained in section 7.3, this task was cancelled.

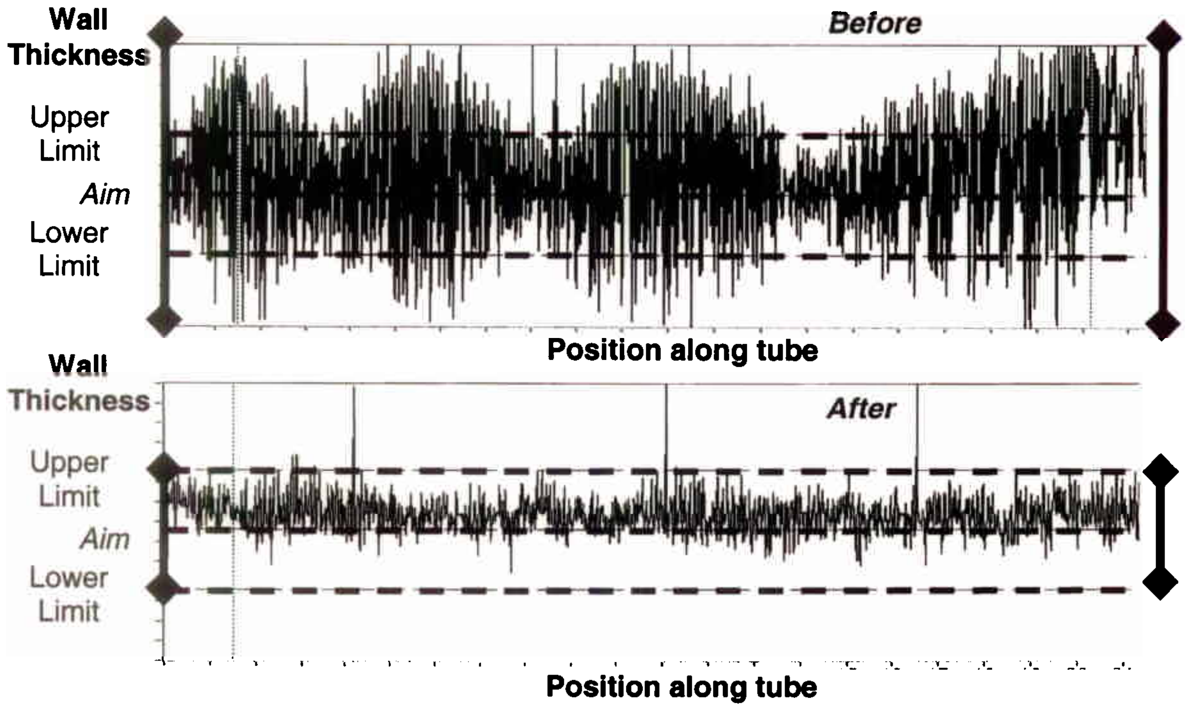

Figure 5. LUT traces showing reduction in variation after mill change.

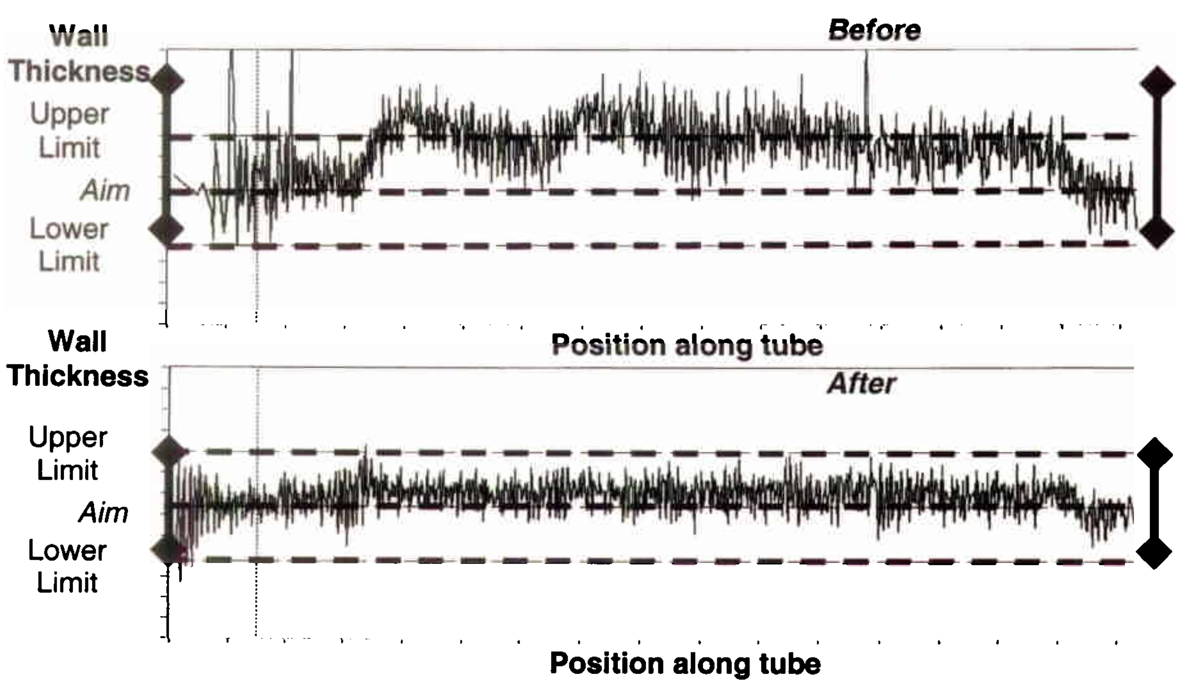

Figure 6. LUT traces showing reduction in variation after mill adjustment.

TASK 8

Wireless Sensing

The wireless sensing task was added to the project to demonstrate the capabilities of Direct Sequence Spread Spectrum (DSSS) technology and the advantages over hard-wiring in selected mill installations. A wireless tube detector (WTD) was developed to signal the passage of a tube at a point up the production line from the LUT. A tube approaching is one of the required components of the interlock system for safe laser firing.

The WTD would also be used to signal the system so that power could be re-applied to the lasers following a prescribed idle period. This approach would allow the system to reduce power to the laser flash lamps when no measurements were required, thereby extending lamp life. Use of this conservation approach could double the life of the flash lamps, which are a high-cost consumable with a finite duty cycle.

The sensor is based on detecting a local temperature increase. The presence of a hot tube would be transmitted via a 916MHz DSSS RF link to a repeater on the inside of the plant's wall and repeated via a 904 MHz DSSS RF link to an antenna and receiver at the LUT. The WTD circuitry was integrated into the LUT control circuitry so that the wireless information could be transferred using a 38.4 Kbaud RS232 serial link. An indicator was programmed in the interface to show the detection of an oncoming tube.

The WTD has proven to be unreliable for a variety of reasons: most are apparently unrelated to the wireless technology. The first problem was related to interference from a nearby antenna for a nationwide pager system. This was overcome by moving the center frequency of the direct sequence.The second problem resulted from an increase in the infrared radiation as the surrounding tube guides became increasingly hotter as more tubes were processed. Adding an optical filter reduced the background radiation and made it possible to discern a tube. A third problem was the fogging of the filter due to plant dust and debris. Reduction of the threshold allowed a tube to be detected properly. An additional problem encountered was related to the controller embedded in the receiver.

During the implementation, the WTD signal was periodically checked against a process control signal transmitted across the network that the next tube was processed upline from the LUT. The WTD would fail abruptly for no apparent reason. As a result of the WTD's unreliability, the decision was made to abandon the WTD and remove its function from the system software.

Diagnosis of the WTD system late in the project suggested that the radio link was robust and that other problems limited its reliability. An indicator light was installed to show that the WTD was detecting tubes. The continuing work on the wireless device will be done by ORNL and will be funded by DoE separate from the LUT project.

TASK 9

Conclusions, Final Reporting and Recommendations, and Commercialization

9.1: Conclusions

The LUT project has been a great success and showed the potential benefits for U.S. Department of Energy programs assisting industrial companies in developing and deploying new technology. The partnering has resulted in a technology flow from the laboratory to the production floor. The project demonstrated the applicability of laser-ultrasonics and met a specific technical need of the Timken Company, showing tangible benefits only six months after deployment.

The system design features largely have been realized. A commercial fiber-coupled generation laser has been modified and integrated with a custom-built detection laser. A portion of the detection beam has been used in a two-axis velocimeter for precise determination of measurement location. A high-precision pyrometer has been developed using the same collection optics as the detection laser, incorporating commercial photodetectors. The optics have been combined into an inspection head connected to the lasers using a fiber optic umbilical cable. A remote cabin has been used to house the lasers, processing optics and control computers.

9.2: Benefits and Energy Savings

The estimates developed for the proposal of this project claimed a potential for $0.85 million in annual savings through the implementation of the LUT at one Timken mill. That included $0.45 million for manpower costs through improved productivity, $0.30 million in material savings through reduced scrap and rework, and $0.10 million in reduced energy consumption. Those projections were based on historical data and projected tonnages for mill with higher throughput than #4 Tube Mill. Adjusting those savings by the ratio of projected tonnage would suggest that the overall savings expected should be $0.50 million annually.

Plant engineers were asked to estimate the savings after about three months of the deployment of the LUT. Having the customer conduct the analysis in itself insured that claimed savings would not be overstated. Confidence in the numbers was bouyed by the fact that actual cost tracking numbers were used to develop the estimates. Those estimates included savings for reduced time to get size on the mill, savings for reduced downtime because of improved decision making, savings due to fewer samples taken from production and savings because of reduced scrap and rework.

The annualized savings estimate totalled $0.53 million – 5% greater than claimed! The largest savings came from the time savings and the wall scrap reduction, each being 47% of the total. Rework was 3%, decision making 2%, and sample savings was 1% of the total. It is interesting to note that the savings due to reduced scrap levels may even be higher as recent trends in wall scrap have shown reductions to be 1/3 higher than projected.

The energy savings realized from the implementation of the LUT were estimated by noting that energy costs are roughly 1/3 of the total hourly costs to operate the tubing mill. The time savings noted above would translate into a 5% fuel savings based on 2001 data. As noted in the proposal, the tube mill uses 6.54 million BTUs to produce a ton of steel tubing. That savings applied to the tons produced would suggest 2.3×10^{10} BTUs will be saved in tube making costs alone by the first implementation of the LUT.

9.3: Commercialization

An evaluation process was used to identify important factors leading to successful commercialization. A scheme valuing interest, strategic fit and technical capability was developed. Six factors, each with five sub-factors, were given a weighting and the capabilities of a potential agent were rated. From the assigned values an overall desirability rating was determined.

The rating process suggested that Tecnar Automation, Ltee. was favored, reflecting that familiarity with the technology was beneficial in designing and optimizing LUT systems for subsequent applications. A commercialization agreement between Timken, IMI and Tecnar has been negotiated and signed. The first inquiries for systems have been received by Tecnar.

A cursory estimate of the market for an LUT system suggested possible applications in new equipment installations or retrofits in existing mills will total one to two dozen, perhaps three. That number could increase if multiple applications are justified along one production line.