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DEVELOPMENT AND EVALUATION OF A WORKPIECE
TEMPERATURE ANALYZER FOR
INDUSTRIAL FURNACES

Phase I

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EXECUTIVE SUMMARY

An instrument capable of measuring the bulk temperature of a workpiece while it is being heated could have a variety of applications. If such an instrument were reasonably priced, it would have a tremendous impact upon national energy usage. The Department of Energy has realized the importance of this type of instrument and has sponsored three concurrent programs to evaluate three different technologies for this type of instrument. In one of these programs, Surface Combustion is the prime contractor to develop a pulsed laser, polarizing interferometer based sensor to be used as a workpiece temperature analyzer (WPTA).

This program is divided into three phases leading to the field demonstration of this technology. This is the report of the first phase. The primary objective of Phase I was to investigate technical feasibility and economic attractiveness of the concept. The overall goal of the program is to develop a workpiece temperature analyzer for industrial furnaces to significantly improve product quality, productivity and energy efficiency. The project is being executed by the team of Surface Combustion Inc. and AVCO Research Laboratories. Surface Combustion is responsible for the overall project direction, market applications, and product specification. Surface Combustion will also be the commercialization company that will sell the final product. AVCO is responsible for the concept development, technical feasibility analysis, and preliminary cost estimates for the instrument. They will continue as the technical developer, building the necessary sensor apparatus and developing the necessary software to interpret the signals. This report is prepared by both companies with the complete AVCO report contained in appendix A.

The workpiece temperature analyzer as conceptualized has three primary elements:

1. Impulse laser which generates a sound wave in a workpiece.
2. Polarizing Interferometer which detects surface displacement from sound wave and determines "time of flight" for sound wave through the workpiece.
3. Microprocessor which converts the "time of flight" and initial workpiece thickness data into temperature readings.

The instrument in this development has three key features:

1. Measures the surface temperature of the work independent of the emissivity of the piece.
2. Measures the bulk average temperature of the work.
3. Measures the physical state of the work if the temperature is known.

With these features there are several types of applications where this unit can be used for non-contact measurement. The four metals heating process areas investigated during this phase for the application of this instrument are steel heat treat, aluminum heat treat, galvanneal and ion processing.

Fifteen industrial furnace users were surveyed by telephone and three industrial plants were visited to investigate the application of the WPTA system in the above four process areas. Potential users in all of the process areas expressed a desire to have such a sensor and many were willing to discuss potential uses in detail. It was determined that the most promising applications for the sensor would be for galvanneal and aluminum heat treat. The savings from the use of the WPTA system will be primarily from reduction of scrap, increased productivity, and improved energy efficiency. The total savings for these applications were estimated to be in the range of \$50,000 to \$500,000 per year with an average value of about \$125,000/year. The estimated sales price for the sensor is \$50,000 which represents a payback in less than 1/2 year.

The technical feasibility of the WPTA system concept was investigated through mathematical simulations for an impulse laser and a polarizing interferometer for a travel path through a workpiece of about 6". The parameters for an impulse laser system were determined for selected applications and were found to be within the range of reasonably priced commercially available off-the-shelf equipment. The simulation indicated that the sensor was technically feasible and actually exceeded expectations in some areas. The sensitivity was sufficient to attain the desired accuracy. It will be relatively insensitive to vibrations of the surrounding furnace. Measurements need only be taken on one side of the work, and the distance between the work and the sensor can vary without recalibration. But most important, it should be possible to measure the physical state of

the work if the temperature is known. This last feature opens the door to actually monitoring the metallurgical changes as they proceed in a heat treat operation and allow one to optimize the process.

Thus far all of the technical feasibility work has been done using a computer simulation. Future phases of this program will include testing and demonstration of the sensor features. The testing would include not only measurement of temperature, but also confirmation that one can measure the physical state of the work while it is in the heater chamber.

1.0 – INTRODUCTION

The traditional method of determining the workpiece temperature in industrial furnaces is to measure the surface temperature with a radiation pyrometer or a contact thermocouple. The contact thermocouples have a limited use because they scratch the workpiece surface in a continuous process or require drilling of a hole in the workpiece for a batch operation. Radiation pyrometers are used for non-contact surface temperature measurements, but suffer from inherent inaccuracies because of interference by radiation from furnace hot walls and gases in the furnace. Moreover, the accuracy of radiation pyrometers is adversely affected by varying emissivity of the workpiece during thermal processing. Table 1 summarizes the problems associated with the conventional temperature measuring instruments.

The traditional non-destructive temperature measuring instruments lack capability to measure temperature gradients in a workpiece. There are thermal processes where temperature uniformity ($\pm 5^\circ\text{F}$) from surface to core is critical for uniform phase transformation reactions in the bulk of the workpiece. Moreover, the knowledge of the time at which this uniformity is achieved is important to optimize process cycle time. Some specific examples for such processes are solution annealing and age hardening of aluminum and interrupted quenching of steels. There is a need for an instrument which can measure the surface temperature as well as the average bulk temperature to provide knowledge of temperature uniformity in the bulk of the workpiece. Such an instrument can be used to optimize process cycles and to improve product quality. It will have a major impact on saving of material and energy resources and U. S. competitiveness in the world market.

1.1–BACKGROUND

The Surface Combustion and AVCO Research team has conceptualized an impulse laser with a polarizing interferometer to be used as a workpiece temperature analyzer. A schematic of the concept with a laser beam hammer (for sound wave generation) and a detector on the same side of a workpiece is presented in Figure 1A.

Table 1

**PROBLEMS WITH CONVENTIONAL
TEMPERATURE MEASURING INSTRUMENTS**

TEMPERATURE MEASURING INSTRUMENT	PROBLEMS
1. Thermocouple	<ul style="list-style-type: none">a. Does not provide direct measurement of temperature of workpiece.b. Furnace cycle time calibration required.c. Sacrificial samples needed during cycle time calibration, as holes need to be drilled in sample to place thermocouple.d. Recalibration needed at regular time intervals as the system dynamics change (burner performance and insulation degradation).
2. Radiation Pyrometer	<ul style="list-style-type: none">a. Does not provide bulk or core temperature. It measures only surface temperature.b. Inaccurate due to emissivity changes in material and interference from furnace walls and gases.

1.2-OBJECTIVE

The development program at Surface Combustion was divided into three phases as follows:

Phase I: Define market, approximate value, instrument specification and proof of concept.

Phase II: Bench tests, assemble unit, hot tests on laboratory furnace, software package and cost estimates.

Phase III: Field test of unit on commercial furnace, verify costs and economics.

This report is for the activities carried out during Phase I of the program. This phase was started in August, 1989. The following tasks were completed during this phase.

Task 1-Application Selection

Task 2-Operational Requirements Definition

Task 3-Preliminary Concept Development

Task 4-Economic Analysis

Task 5-Phase I Report

The primary objective of the workpiece temperature analyzer program is to develop a bulk temperature measuring instrument for industrial furnaces to significantly improve:

- a. Product quality
- b. Production rate
- c. Energy efficiency

The specific results to be achieved in Phase I of the program were:

- a. Determination of technical feasibility of the concept
- b. Evaluation of economic attractiveness
- c. Selection of industrial application
- d. Specifications of the instrument

Figure 1A

**SCHEMATIC DRAWING OF THE
WORKPIECE TEMPERATURE ANALYZER
(SINGLE-SIDED)**

1.3-BENEFITS

The workpiece temperature analyzer concept in this program uses a pulsed laser polarizing interferometer (PLPI) for measuring sound velocity through a workpiece. This type of instrument has a high resolution and could detect surface motion of as small as 10 picometer. The sound velocity measurement can be converted to an average workpiece temperature through a mathematical equation programmed into the microprocessor used for control. The major benefits from this type of instrument are:

1. The instrument is non-contact and measurements are non destructive. The measurements are made from one side of the workpiece (Figure 1A), but also can be done from both sides (Figure 1B).
2. The temperature readings are independent of the emissivity of the surface of the workpiece. Thus, this instrument can be effectively used for processes where emissivity changes during processing (as in the process like galvanneal).
3. The instrument provides remote sensing with long stand-off distance (1 to 2 meters).
4. It provides an average bulk temperature as well as surface temperature of the workpiece rather than only surface temperature provided by a radiation pyrometer or contact thermocouple.
5. A single instrument can be used to measure temperature at various points on a workpiece through mirror arrangement for temperature uniformity determination.
6. The instrument readings are not affected by a glow discharge as encountered in ion-processing.
7. The readings are not affected by low frequency vibrations as encountered in normal industrial furnaces.
8. Less costly system can be used to measure surface temperature in thin materials.

Figure 1B

ADVANCED WORKPIECE TEMPERATURE MEASUREMENT SYSTEM

2.0-DISCUSSION

The workpiece temperature analyzer concept under this program utilizes the idea of using sound waves to monitor the interior temperature of a workpiece in an industrial furnace. To make measurements, one can apply an impulse to one side of a workpiece by a high energy pulsed laser beam. This laser beam acts like a hammer and generates a sound wave. The wave propagates through the workpiece and arrives after a time lapse to the interferometer sensor. The sensor can be on the same side or opposite side as the impulse laser as shown in Figure 2. If the sensor is on the same side as the impulse laser, the wave can be detected after it is reflected from the far side (Figure 2B). Knowing the time of impact and the time of arrival of the incident sound wave at the other side or reflected sound wave on the same side, the velocity of sound in the workpiece can be calculated if the thickness is known. The velocity of sound in a workpiece is directly related to the average bulk temperature. A mathematical model can be used to convert the measured sound velocity into bulk temperature of the workpiece. Similarly, measurement of surface sound wave (Figure 2A) velocity can provide surface temperature. Thus, a temperature gradient in a workpiece can be measured. For thin materials, only surface wave measurements are required, because temperature gradients are very small. A low energy impulse laser can be used for this purpose to reduce the cost of an instrument significantly if the instrument is to be used for only surface temperature measurements.

2.1-WORK PLANNED

Phase I of the workpiece temperature analyzer program was divided into the following tasks:

- Task 1-Application Selection
- Task 2-Operational Requirement Definition
- Task 3-Preliminary Concept Development
- Task 4-Economic Analysis
- Task 5-Phase I Report

Figure 2

SOUNDWAVE PROPAGATION AND DETECTION MODES

Work planned in each task was as described below:

Task 1--Application Selection:

Industrial processes will be surveyed to find furnaces suitable for acoustic temperature measurement systems (WPTA). Aluminum heat treating, steel heat treating, galvanneal furnaces, and ion processing applications will be included. A minimum of 15 industrial contacts covering these four process areas will be made to determine current state-of-the-art temperature measurement techniques. Energy savings potential, expected product quality improvements, reduction in environmental pollution, and other improvements made possible by an WPTA will be estimated for each of the four process areas. Limitations which would be placed on a WPTA by these processes will also be determined. A preliminary assessment will also be made of the economic advantages of an improved temperature measurement system based on the expected improvement in accuracy of the WPTA over temperature measurement systems now commercially available. A particular furnace type will be selected for further study by mutual agreement between the participant and DOE.

Task 2--Operational Requirements Definition for the WPTA:

Preliminary specifications for the ATMS defining the required features of the system (including component accuracy requirements, target selling price, target installation costs and target operating costs) will be prepared.

Task 3--Preliminary Concept Development:

A literature survey will be conducted and a data base compiled of previous and current research on acoustic wave transmission as it pertains to temperature measurement.

A conceptual design will be developed. The concept design will include equipment identification, operating limitations, techniques to calculate distance through the workpiece, calculations of laser excitation requirements, and field installation requirements.

An analytical model of the WPTA will be generated which will include all laser parameters, and detection system parameters, workpiece properties, and furnace characteristics. The analytical model will be used to evaluate technical feasibility and potential system performance. Vendors will be

contacted to determine availability of individual system components. Identification will be made, if required, for any component level or system level developments that are needed to assemble a prototype system. Any other major uncertainties will be defined and lab testing necessary to eliminate or quantify the uncertainties will be identified. Descriptions of the testing will be sent to DOE for approval.

Task 4--Economic Analysis:

Development time and costs will be estimated for the WPTA. Preliminary cost estimates at various production volumes will be generated. Economic benefits will be determined in terms of cost savings versus added cost. The simple payback approach to capital amortization will be used. Credits given for increased production, reduced down time, and improved product quality will be defined.

Task 5--Final Report:

A final report will be prepared which summarizes the work conducted in Tasks 1 through 4. The report will make recommendations for continued project support and direction.

2.2--WORK PERFORMED

2.2.1--APPLICATION SELECTION

There are a variety of processes where the WPTA system can be used effectively. A list of major process applications is summarized in Table 2. Four process areas were investigated in more detail for the application of the WPTA system during this phase of the program. These areas are:

1. Steel Heat Treat
2. Aluminum Heat Treat
3. Galvanneal
4. Ion Processing

The applications of the workpiece temperature analyzer within the process areas fall into three general categories:

1. Measurement of the surface temperature for thin materials as in continuous annealing lines.
2. Measurement of bulk and surface temperature for thicker materials such as plates, and slabs for temperature uniformity determination and cycle time optimization. The processes such as solution annealing, precipitation or age hardening and interrupted quenching are some of the specific examples where such an analyzer is an ideal instrument.
3. Measurement of the phase change or micro structure change under isothermal conditions. This type of measurement can revolutionize the heat treatment industry.

The specific applications of a WPTA system are grouped in the following three categories:

1. Processing of thin strips ($< 0.10''$) in continuous annealing of steel, aluminum, and brass, and galvanizing and aluminizing of steel.
2. Semi-continuous processing of sheets, plates or slabs in a single layer rather than a stack (e.g. solution annealing furnaces for aluminum plates).
3. Batch or continuous processing of regularly stacked pieces as shown in Figure 3. The workpieces can be gears, bearings, crank shafts, tool dies, etc.

The temperature measurement problems with the currently used instruments are described in Table 3. The advantages of the WPTA system are also summarized in this table.

Table 2
APPLICATIONS

STEEL MANUFACTURE

- Galvanizing
- Aluminizing
- Galvannealing
- Continuous Annealing
- Reheating
- Continuous Casting

ALUMINUM

- Reheating
- Solution Annealing
- Strip Processing
- Continuous Casting

CERAMICS

- Fired Ceramics
- Composites

STEEL HEAT TREAT

- Hardening Tool Steels
- Annealing
- Mar-Quenching
- Ion Processing

PETROLEUM

- Fired Heater Tubes

2.2.1.1-STEEL HEAT TREAT PROCESSES

There are a variety of processes in the steel heat treatment area. These include annealing, quenching, carburizing, carbonitriding and several others. The steel heat treat furnaces vary in size and shape. Some are batch and some are continuous furnaces. The parts processed through these furnaces have a variety of shapes. Some typical examples include plates, slabs, bars, gears, bearing races, etc. The parts could be randomly loaded in a tray for some applications or they may be regularly stacked in other applications. The WPTA system application is primarily geared for the processes using regular stacking, but can be applied for the randomly loaded trays if the trays are modified. A fixture can be attached to the tray and a workpiece can be placed in it to assure position and orientation. The WPTA system can monitor the workpiece on this fixture.

The batch furnaces are normally controlled by a thermocouple in a gaseous environment. The furnace cycle times are based on initial testing with the contact thermocouples. The cycle time is rechecked by commercial heat treaters at regular intervals to allow for any changes in burner and insulation performance characteristics. Captive heat treaters run bar samples regularly along with the load and analyze the samples for carbon content after completion of process cycle. The cycle times include a conservative allowance for soak time to assure product quality as they do not have means to measure bulk temperature of a workpiece.

Figure 3

REGULARLY STACKED WORKPIECES FOR HEAT TREATMENT

Table 3
WPTA APPLICATIONS

APPLICATIONS	PROBLEMS WITH CURRENT TEMPERATURE MEASURING SYSTEMS	ADVANTAGES OF WPTA
<ol style="list-style-type: none"> 1. Continuous processing of thin strips. (<0.1") 2. Semi-continuous processing of sheets, plates and slabs up to 6" thickness in non-stacked fashion. 3. Batch processing of regularly stacked workpieces as in ion-nitriding. 	<ol style="list-style-type: none"> a. Thermocouple in gas-phase does not provide temperature of solid surface. b. Contact thermocouple not practical as it causes mark on surface and may not stay in good contact with solid surface to provide accurate measurements. c. Optical/radiation pyrometer does not provide accurate measurements because of emissivity changes and interference from furnace walls and gases. d. Furnace certification required every 3 to 6 months which interferes with regular production. e. Conservative residence times are used to assure product quality. This approach results in higher capital cost and/or production rate is lower than furnace capability. f. Verification records for temperature of solid surface are not feasible. g. Glow discharge in ion processing does not permit use of radiation pyrometers. Thermocouples with ceramic insulators to avoid arcing are used, but are major maintenance items. 	<ol style="list-style-type: none"> a. WPTA provides average bulk temperature of solid for thicker materials. b. Lower cost WPTA can be used for surface temperature measurement of thin materials (<0.1"). The temperature gradients in thin metallic materials is negligible and can be considered as bulk temperature. c. WPTA is a non-contact instrument and not affected by furnace walls and gases. d. Furnace certification may not be required, as it provides direct measurement of solid temperature. e. Conservativeness in residence time can be significantly reduced as solid bulk temperature is measured rather than inferred. This feature can either reduce cost for new furnaces or increase production for existing furnaces. f. Temperature verification records can be easily obtained, which may have significant value from liability view point. g. WPTA is not affected by glow discharge in ion-processing.

There are about 700-800 commercial heat treaters in the U.S.A. The number of heat treating furnaces at these commercial heat treaters is estimated to be about 5000. There is a considerable market potential for the workpiece temperature analyzers in the heat treating industry. The demand for improvement in product quality and productivity is growing. The ability of a WPTA to obtain real-time measurement data permits better process control and thus, allows to improve product quality, reduce manufacturing cost and enhance competitiveness.

The processing rates in steel heat treat furnaces can vary from 200 lbs/hr in a small batch furnace to 20,000 lbs/hr in a large continuous furnace. A typical processing rate can be considered to be in the range of 1000 to 2000 lbs/hr. Energy consumption in these furnaces is about 1.5 to 2.0 mm Btu/ton of steel. A typical steel heat treat furnace line is depicted in Figure 4.

Importance of the WPTA system in the heat treating of steels can be explained by a specific example of the heat treatment called "marquenching" or "interrupted quenching". This process is depicted in Figure 5. During direct quenching, severe stresses are generated due to temperature gradient between the surface and core of a workpiece. The surface cools faster, so martensite formation starts earlier at the surface. The microstructural differences between the surface and core during quenching results in severe stresses and cracking. In marquenching (or interrupted quenching), the workpiece is cooled at a temperature slightly higher than the temperature (M_s) at which martensite formation starts. The core temperature is allowed to equilibrate with the surface temperature for a certain length of time. An instrument that can measure the temperature gradient from the surface to the core is needed for this process to minimize the time allowed for temperature equilibration and to avoid bainite formation which results when the temperature equilibration is continued for longer than necessary. The WPTA system is well suited for this process to improve product quality and increase productivity.

Figure 4

TYPICAL STEEL HEAT TREAT FURNACE LINE

Figure 5
INTERRUPTED QUENCHING PROCESS

2.2.1.2-ALUMINUM HEAT TREAT PROCESSES

Aluminum heat treat furnaces are either batch or continuous. They are used for annealing, solution heat treatment, aging and reheating. The materials processed through these furnaces have a variety of shapes and sizes. Some typical examples include ingots, billets, coils of strips, plates and sheets. The typical processing rates for continuous furnaces are in the range of 10 to 20 tons/hr and batch loads are 50 to 150 tons with cycle times varying from 10 hours to 40 hours depending upon the type of process. The processing temperature can be as low as 650°F for aging process to as high as 1050°F for reheating furnace. Energy consumption per ton of aluminum heat treatment can vary from 0.6 to 1.0 mm Btu/hr depending upon process temperature. A typical reheat furnace for aluminum is presented in Figure 6.

The problems encountered for measuring temperature during heat treatment of aluminum are more severe than steel heat treatment. The emissivity of the workpieces is low and varies as the surface gets oxidized during processing. Usually, radiation pyrometers are not used because of the changes in emissivity. Since the heat treating temperatures are close to the melting temperatures, the thermal head is limited. The heating rate, which is proportional to the thermal head, could be increased with a WPTA system, as it allows to measure surface and bulk temperature. The higher thermal head increases production rate.

Figure 6
ALUMINUM REHEAT FURNACE

Two Surface chairback furnaces, with a capacity of 120,00 pounds each, reheat aluminium ingots for rolling as they are conveyed continually and automatically through the heating cycle.

In this Surface chairback furnace installation, there is less than 5° F. total temperature variation in a five-hour cycle, and total temperature uniformity throughout each individual ingot. The ingots move through the furnace leaning against "chairbacks" made of heavy structural steel on an endless conveyor belt powered by a hydraulic mechanism. All operations in the Surface-engineered installation are automatic, including removal of the ingots from the conveyor mechanism at the end of the cycle. The ingots are brought from cold to 925° F.

The WPTA sensor can have a dual function in processing aluminum. In addition to measuring the temperature, it will be able to sense the time that the metallurgical reactions are complete and the metal is ready to be removed from the furnace. There are two specific types of furnaces in use today.

1. Aluminum mill homogenizers - typically high tonnage continuous operation with extremely rigid temperature specifications.
2. Solution annealing and age hardening furnaces at the end user facility (e.g. aircraft manufacturers that have banks of furnaces to age harden the aluminum "skins of airplanes").

The real result of using the new sensor is that manufacturers will be able to monitor the process in a way that they will be able to produce a better quality product at a more competitive price. Saving a few pounds of aluminum on an aircraft is worth many thousands of dollars in fuel during the life of an aircraft. We estimate that there are 500 aluminum furnaces of the types listed above in the US. On the average each sensor in this service could save about 1.3 billion Btu/sensor/yr. There would be a corresponding increase in the productivity of the particular furnaces resulting in a large savings.

Importance of the WPTA system in heat treatment of aluminum can be explained by the specific example of the process called age hardening or precipitation hardening. During this process an aluminum alloy is initially heated to form a single phase solid solution. It is quenched to form a super saturated solution and then reheated to an intermediate temperature to form submicroscopic precipitate. This submicroscopic precipitate increases the hardness of the alloy. The alloy needs to be cooled down again to avoid overaging or growth of precipitate particles. The time at age hardening temperature is a critical factor. Insufficient time does not achieve desirable hardness properties and too much time at age hardening temperature causes the alloy to soften due to growth of precipitate particles.

The solution treatment of aluminum-copper alloy containing about 5% copper is depicted in Figure 7. It should be noted along the line CD in the figure that the temperature band for a single phase (K) solid solution is very narrow. Controlling the temperature in this narrow band ($\pm 5^\circ\text{F}$) and achieving uniform temperature in bulk of the workpiece are essential for better product quality. The WPTA system can measure surface and bulk temperature and can determine when the desired temperature uniformity is achieved. Thus, excessive soak time can be eliminated from process cycle time, resulting in increased productivity.

The WPTA system can also be applied to measure microstructural transformation reactions at a constant temperature. During the age hardening process as shown in Figure 8, microstructural changes occur as a function of time at a constant temperature. An optimum time for age hardening process can be determined by the WPTA system. Improvements in product quality and productivity can be easily achieved through the use of the WPTA system for the age hardening process.

2.2.1.3-GALVANNEAL SYSTEM

The galvannealing is the transformation of the zinc coating into an alloyed coating consisting of various iron-zinc alloy phases. In order to obtain a ductile coating without powdering, brittle phases such as δ and τ (in iron-zinc phase diagrams) should be limited. Various parameters such as aluminum content of the coating, processing temperature and time, coating thickness, etc. need to be considered for controlling this system. The galvannealing is a continuous process with a typical processing rate of about 50 tons/hour. The process temperature ranges from 850° to 1100°F .

The galvanneal system comprises primarily of three components, viz. a molten zinc pot, a furnace for heating and a cooler. A continuous steel strip passes through the molten zinc pot to the cooler via the furnace (see Figure 9). The strip gets coated with a thin layer of zinc in the pot and when it passes through the furnace, the zinc transforms into various alloys with iron. The furnace has a holding zone to provide adequate time for diffusion of iron into zinc for transformation reactions. Typical residence time for the strip in the reaction zone is about 15 seconds.

Figure 7
**ALUMINUM-RICH END OF THE
ALUMINUM-COPPER EQUILIBRIUM DIAGRAM**

Line AB represents the increase in solubility of copper in solid aluminum with increasing temperature.

Figure 8

AGE-HARDENING PROCESS (95.5Al-4.5 Cu)

Maximum hardness occurs when the clusters of CuAl_2 which constitute the pre-precipitate are still submicroscopic.

Figure 9

STRIP TEMPERATURE EVOLUTION DURING GALVANNEALING

After the strip is soaked the desired time, the strip is cooled to a temperature below 700°F so that the strip can come into contact with the mill rollers. The heating process is intended to cause a diffusion of the iron in the base metal through the zinc coating. This diffusion process results in a matte surface finish which is more desired for painting than the standard galvanized coating surface. There has been a move by the automotive industry toward the use of galvanneal products for exterior panels.

Alloyed coatings present a dull surface texture which readily takes paint. The alloying must be uniform. No bright unalloyed regions must remain. At the same time, over alloying must be avoided. Thus, time and temperature control play a significant roll in the galvanneal process. Sophisticated computer algorithms are used to set these parameters. Emissivity of bright zinc coating is very low, but emissivity of dull alloyed coating is high and therefore, use of a radiation pyrometer is not suitable for temperature measurement. Contact thermocouples cannot be used for this application because of surface damage.

The transition band from a bright zinc coating to a dull alloyed coating is narrower in length and fluctuates along the length of the strip. Visual observation of this band by an operator and adjusting the operating parameters manually, requires constant operator attention. Sometimes the strip can be bright on one side and dull on the other side, which makes control by radiation pyrometer almost impossible. The WPTA system, which is not dependent on emissivity of material, may be ideal for this application.

Increasing the strip heating rate and thermal efficiency of gas fired galvanneal lines through a WPTA control system will increase the competitive advantage of gas fired lines. If the heating rate in the heating zone of the galvanneal line can be increased, the height (galvanneal lines are vertical) of the heating zone will be reduced. The effect of a reduced heating zone is that the production rate of the galvanneal line can be increased or the overall height of the line can be decreased. Decreasing the line height also reduces the length of the unsupported strip which reduces clearance requirements around the strip and the amount of cold air entrained with the strip.

One of the most promising areas of the WPTA system application is continuous strip processing of steel. There are about 125 continuous annealing and galvanizing lines in the USA. Each line would require about 4 WPTA systems to control the entire process. Thus, there is a market potential of 500 WPTA systems in continuous strip processing of steel.

2.2.1.4--ION PROCESS

A vacuum vessel is used for ion processes such as ion-nitriding and ion-carburizing. The workpieces are stacked in a regular pattern in an ion-processing unit. The working pressure varies between 1 to 10 torr. In this vessel, the workpiece becomes the cathode and the vessel wall, the anode (see Figure 10). Application of DC power under vacuum conditions cause the gas to ionize and the workpiece to glow. Impingement of ions on the workpiece causes a temperature rise in the workpiece. Ion nitriding is conducted at a temperature level of 850°F to 1200°F and ion carburizing at 1550°F to 1950°F. Typical cycle times for ion-nitriding is 10 to 12 hours and for ion carburizing, 5 to 6 hours, and average processing rate is about 150 lbs/hr.

Contact thermocouples cannot be used in this process because of an arcing problem and radiation pyrometers are not practical because of the glow discharge from workpieces. Embedded thermocouples with ceramic insulator are currently used as sacrificial pieces. This approach is time consuming and requires frequent replacement of ceramic inserts and thermocouples.

The WPTA system is a non-contact instrument and therefore, eliminates arcing problems in an ion-processing furnace and is not influenced by a glow discharge. Thus, ion-processing could be a good application for the WPTA system. At present, the number of ion processing units in the USA is estimated to be about 100. The materials processed through these units are normally finished products such as gears, bearing races, injector nozzles, etc., and have high product value. If the WPTA system can reduce off-quality product by 1%, the savings would be in the range of \$50,000 to \$100,000 per year for a 6000 hour operation per year.

Figure 10
ION PROCESSING FURNACE

2.2.1.5-INDUSTRIAL SURVEY

A systematic approach was followed to conduct the industrial survey for application of the WPTA System in the following four industrial processes:

- a. Steel Heat Treating
- b. Aluminum Heat Treating
- c. Ion Processing
- d. Galvanneal Process

A questionnaire as shown in Table 4 was prepared for this survey. The product managers at Surface Combustion for the products associated with each of the above four industrial processes were asked to contact about 4 industrial users for each process. The questionnaire was used by them as a guide during phone conversation with industrial users. A list of the companies contacted by them is presented in Table 5. This list included companies from steel, aluminum and brass industries. The following industrial companies were visited as part of the industrial survey work:

COMPANY	PROCESS
1. Inland Steel, East Chicago, IN	Galvanizing, Aluminizing and Continuous Annealing Strip Line
2. Reynolds Metal, Chicago, IL	Aluminum Heat Treat
3. Furn-Tech, Inc., Perrysburg, OH	Steel Heat Treat and Ion Processing

Most of the surveyed parties either use an embedded thermocouple or a radiation pyrometer to measure the workpiece temperature. Some use inferential approach by prior calibration of workpiece temperature from furnace temperature and time measurement. One of the industrial contactees mentioned the use of polar radiometry (a proprietary technique for workpiece temperature measurement).

Table 4

QUESTIONNAIRE FOR WORKPIECE TEMPERATURE MEASURING DEVICE

Person Contacted:— Name:

Title:

Phone:

INFORMATION REQUIRED	ANSWER			
	A	B	C	D
Process	Ferrous Heat Treat	Non-Ferrous Heat Treat	Ion Process	Galvaneal
Temperature Measuring Instr.	Contact Thermocouple	Optical Pyrometer	Gas-Phase Thermocouple	Other
Location of Sensor	Furnace Side Walls	Furnace Roof	External to Furnace	Other
Furnace Atmosphere	Oxidizing	Neutral	Reducing	Other
Temperature Range	Up to 1000°F	1000-1500°F	1500-2000°F	Above 2000°F
Instrument Cost	< \$2000	\$2000-5000	\$5000-10,000	> \$10,000
Maintenance Time/Yr.	< 8 hours	8-16 hours	16-40 hours	> 40 hours
Accuracy Required	± 5°F	± 20°F	± 1% Full Scale	Other

Problems: List what problems they have with current temperature measuring instrument for the process

Need: Do they have a need to measure bulk temperature (average temperature) of workpiece?

Benefits: What benefits do they see if this need for bulk temperature measurement is satisfied?

- Energy savings
- Production increase
- Product quality improvement
- Reduction in waste
- Pollution abatement

What kind of temperature information would they like to have?

Why is it hard to obtain this information from current instruments?

What problems do they foresee with our approach?

Would they be interested in becoming a host site?

How many furnaces do they have where the proposed temperature instrument is applicable?

Table 5

LIST OF INDUSTRIAL COMPANIES SURVEYED

COMPANY	TYPE OF PROCESS
1. Advanced Heat Treat Corporation	Ion Process
2. Hansen-Balk Steel Treating Company	Ion Process
3. Surface Combustion	Ion Process
4. Alcan	Non-Ferrous Heat Treat
5. Kaiser Aluminum	Non-Ferrous Heat Treat
6. Reynolds Metal	Non-Ferrous Heat Treat
7. American Brass	Non-Ferrous Heat Treat
8. Bethlehem Steel	Galvanneal
9. Midwest Steel	Galvanneal
10. Armco Steel	Galvanneal
11. Inland Steel	Galvanneal
12. Hansen-Balk Steel Treating Company	Steel Heat Treat
13. Horsburgh-Scott	Steel Heat Treat
14. Dana Corporation	Steel Heat Treat
15. American Steel Treating, Inc.	Steel Heat Treat

The industrial companies using embedded thermocouples and radiation pyrometers are not completely satisfied with the current temperature measurements, as they do not provide the necessary workpiece temperature data for process optimization. Some of these industrial parties were very much interested in real time measurement of micro-structural changes and completion of transformation reactions.

The comments from industrial companies during this survey are summarized as follows:

- Can use temperature gradient measurement device for process improvement.
- This type of instrument can be very useful for improving product quality.
- Can get better documentation of workpiece temperature data to defend liability suits.
- Would also be interested in other than temperature measurement applications. For example, measurement of phase transformation reactions.
- See considerable potential for production rate increase and energy savings.
- Can reduce waste products.
- Would be interested in discussing possibility for being a host site.

The results of the user survey are quantified in Table 6.

Table 6
QUANTIFIED RESULTS FOR SELECTED PROCESSES

	Production Rate Increase (%)	Energy Reduction (%)	Waste Reduction* (%)
Aluminium Heat Treat	5	3 to 5	N/A
Continuous Strip Processing (Galvanneal, Galvanizing, Aluminizing, Etc.)	1 to 2	2 to 5	1 to 2
Steel Heat Treat	5 to 20	5 to 10	N/A
Ion Processing	1 to 2	1 to 2	N/A

N/A – Not available

** Based on percent of production rate.*

2.2.1.6—PRELIMINARY ECONOMIC ASSESSMENT

A preliminary economic assessment for the four processes investigated in this program is presented in Table 7. Even though the production rate for steel heat treat and aluminum heat treat furnaces vary over a wide range, the process rate is taken as a typical value for this analysis.

The following assumptions were made for this analysis:

1. An increase in product value by each process is:
 - a. \$100/ton for continuous steel strip processing.
 - b. \$1,000/ton for aluminum or steel heat treatment.
 - c. \$4000/ton for ion processing.
2. Operating cost is 25% of the added product value by the thermal process.

The following conclusions can be derived from this economic assessment:

1. Scrap minimization significantly increases the amount of savings for continuous strip processing.
2. Savings in operating cost is considerably higher than energy savings for all four processes.
3. Application of a WPTA System in these four process areas has a potential to save 4 to 5 trillion Btu/year on a national basis for the USA.
4. The savings in operating cost is more than adequate to justify use of a WPTA System in all four process areas. The savings from scrap minimization will have an added advantage.
5. The operating cost savings for each process is dependent on the processing rate for the furnace. The larger capacity (± 1000 lbs/hr.) furnaces can very easily justify use of the WPTA System.

Table 7
PRELIMINARY ECONOMIC ASSESSMENT

Economic Factor	Steel Heat Treat	Aluminum Heat Treat	Ion Processing	Continuous Steel Strip Processing for Galvanizing, Aluminizing and Annealing
1. Typical Production Rate	1000 lbs/hr	1000 lbs/hr	150 lbs/hr	50 tons/hr
2. Energy Consumption Per Year* in a Typical Furnace	6000-8000 MM Btu	500,000 KWH	90,000 KWH	120,000 MM Btu
3. Energy Savings Per Year* in a Typical Furnace	600-800 MM Btu	20,000 KWH	1000-2000 KWH	4000 MM Btu
4. \$ Savings from Energy Reduction	\$3000-\$4000	\$1000	\$50-100	\$20,000
5. Production Rate Increase Potential in a Typical Furnace	10%	5%	5%	1.5%
6. Operating Cost Savings Potential Per Year in a Typical Furnace	\$100,000	\$50,000	\$30,000	\$150,000
7. Number of Furnaces in the U.S.A.	~5000	~ 500	~ 100	~ 125
8. National Energy Savings Potential Per Year	3 to 4 trillion	10 MM KWH	100,000 to 200,000 KWH	0.5 trillion
9. Savings from Scrap Minimization/Furnace	N/A	N/A	N/A	\$2,500,000/Year

* Based on 8000 hours production per year.
N/A – Not applicable

2.2.1.7-SELECTION OF FURNACE

All four process areas were reviewed for selection of a furnace type for further investigation. The preliminary economic assessment (Table 7) had revealed that the economic benefits were higher for higher production rate units. Thus the furnace selection was focused on higher production rate continuous furnaces. Additional criteria used for this selection were as follows:

1. Difficulty of temperature measurement in current practice.
2. Potential for increased production rate and energy savings.
3. Additional advantages as in product quality, reduction in scrap, reduced operating cost.
4. Compatibility of WPTA System with furnace and workpiece.
5. Number of similar furnaces in the United States.

The pulsed laser polarizing interferometer for WPTA System uses an impulse laser for generating sound waves in a workpiece. The energy required for the impulse laser is proportional to thickness of the workpiece. The low energy impulse lasers are considerably less expensive (\$1000-2000) than the high energy impulse lasers (\$20,000-25,000). Thus the furnace selection was categorized into two groups. One group included the furnaces processing thin workpieces (< 0.1" thick) which would require a low energy impulse laser for the WPTA system. The other group includes the furnaces processing thicker workpieces, which would require a higher energy impulse laser.

The choice for the first group is a continuous steel strip process line for galvanneal process, and for the second group, a roller hearth furnace for solution heat treatment of aluminum sheets and plates. Ideally both of these choices should be investigated, but monetary and time constraints may not permit the investigation for both choices. If only one furnace is to be selected for further investigation, then the choice is a roller hearth furnace for solution heat treatment of aluminum sheets and plates.

This selection of furnace for further study is based on wider application of higher energy impulse laser. A plan view of a fraction of a furnace is shown in Figure 11. The furnace has a total of 14 zones. Only three zones are shown in Figure 11. The furnace is 210 feet long, 16 feet wide and nominally processes 16,000 lbs/hr. of aluminum plates in 1/4" to 6" thickness range. An economic assessment for the furnace is presented in Table 8.

A cross sectional view of the furnace is shown in Figure 12. The temperature sensor is shown to be mounted at the top. The impulse laser and detection laser are both at the top. Alternatively, the impulse laser can be at the top and the detection laser can be at the bottom. The furnace has view ports at the top and bottom. A typical mirror arrangement for multi-point temperature uniformity measurement is also presented in Figure 12.

Figure 11

TYPICAL PLAN VIEW OF ALUMINIUM HOMOGENIZING FURNACE

Table 8

ECONOMIC ASSESSMENT FOR SELECTED FURNACE

Process	Solution Heat Treatment of Aluminum
Capacity	60,000 Ton/Yr
Workpieces	0.25" to 6" Thick Plates
Increase Productivity (3% Increase)	1800 Ton/Yr
Value of Increased Productivity	\$1 MM/Yr, Furnace
Operating Cost Savings	\$0.25 MM/Yr, Furnace
Energy Savings	\$20,000/Yr, Furnace
Similar Furnaces in U.S.A.	25
Total Value of Increased Productivity for U.S.A.	\$25 MM/Yr
Total Energy Saved in U.S.A.	0.1 Trillion Btu/Yr

Figure 12

**SCHEMATIC CROSS SECTION OF FURNACE WITH
SINGLE SENSOR MEASURING MULTIPLE POINTS**

2.2.2-OPERATIONAL REQUIREMENTS DEFINITION

The primary features required for the WPTA System were determined through industrial survey. These features are:

1. Emissivity independent.
2. Should not be affected by glow discharge on workpieces during ion processing.
3. Changes in furnace gas composition should not influence temperature readings.
4. The instrument should be able to tolerate typical vibrations in industrial furnaces without affecting temperature readings.
5. It should be rugged and compatible for industrial environment.
6. The maintenance requirement should be low (less than one hour per week)
7. Accuracy for temperature measurement should be $\pm 10^{\circ}\text{F}$. for steels, but $\pm 5^{\circ}\text{F}$. for aluminum.
8. Should have capability to measure temperature uniformity.
9. Should allow to measure surface as well as average bulk temperatures.

The major components for the WPTA System are as follows:

- a. Impulse Laser
- b. Detection laser
- c. Data Processor
- d. Optical Process Unit

The most expensive component in a high energy impulse laser WPTA System is the impulse laser. The specifications for this impulse laser unit are as follows:

Type:	Pulsed Dye Laser (Coax Flash)
Wave Length:	335 - 850 nanometer
Pulse Energy:	150 millijoule
Pulse Duration:	250 nanosecond

Pulse Rate: 10 pulse per second

Beam Diameter: 5 millimeter

The targeted equipment selling price, operating cost and installation for the WPTA System using high energy impulse laser are summarized in Table 9.

2.2.3-PRELIMINARY CONCEPT DEVELOPMENT

The concept development work was primarily performed by our subcontractor, AVCO Research Laboratories. This work included literature review to compile a data base related to transmission of acoustic waves for measurement of workpiece temperature. A semi-empirical model for ultrasound generation and propagation was developed. The model predictions for surface displacement were compared with literature data and were found to be in good agreement.

An analytical model was developed for a polarizing interferometer. The minimum detectable displacement was found to be 10 to 15 picometers ($1 \text{ pm} = 10^{-12} \text{ meter}$). This type of high resolution for detection of surface displacement enhances the instrument sensitivity and accuracy in temperature measurement.

2.2.4-ECONOMIC THRESHOLD ANALYSIS

The economic viability of the sensor (and as the development project) depends upon the price a potential user would pay for the sensor, the cost of manufacturing the sensor and the savings that the sensor offers the user.

Cost- Dollars that the sensor supplier would pay to purchase the various components

Price- The dollars a user would pay to purchase a sensor from the supplier

The most expensive component in the workpiece analyzer system is the high energy impulse laser. Several impulse laser suppliers were contacted for prices and availability of the components. The impulse lasers are commercially available in large quantities. The cost Surface would pay to the off-the-shelf impulse lasers are summarized in Table 10. This laser

would be integrated into a total package and resold as a complete sensor. The off-the-shelf impulse lasers include some unneeded features. Once the demand for a larger quantity of WPTA System is generated, the laser supplier will be asked to change the configuration of the impulse laser to eliminate unneeded features from the current off-the-shelf units. This approach is expected to reduce cost of the impulse lasers to be used for the WPTA System from \$17,300 to \$15,000.

Table 9

HIGH ENERGY IMPULSE LASER WPTA SYSTEM TARGET

Capital Equipment Cost:	\$25,000
Selling Price Without Installation:	\$40,000 (Temperature Application)
	\$60,000 (Temperature Plus Micro- Structural Application)
Installation Cost:	\$ 5,000
Operating and Maintenance Cost/Year:	\$10,000

Table 10

**COST OF IMPULSE LASER
WHICH IS ONE COMPONENT OF THE WPTA**

QUANTITY	COST/UNIT	
	Off-the-Shelf	Modified
1	\$20,225	—
10	\$19,550	—
50	\$18,800	—
100	\$17,300	\$15,000

The cost of the major components to be used in the WPTA Systems are summarized in Table 11. It should be noted that the cost of the WPTA System for thin materials (using low energy impulse laser) is significantly lower than the WPTA System for thicker materials using high energy impulse laser. The cost analysis for these two WPTA Systems is presented in Table 12.

The savings from using this sensor results from several sources. One of the primary benefits of the sensor is that there would be a substantial improvement in the product quality and corresponding reduction in the amount of scrap or off-spec product produced. The result is that more product of a higher quality can be produced from a given furnace (capital investment). In addition, reduction in scrap reduces the problems associated with disposal and/or reuse of the scrap. Secondly, application of the sensor allows one to control the given process more accurately and reduce the "safety margins" built in to assure acceptable product. This results in shorter processing times and less energy per pound of product. The third benefit comes from more efficient operation allowing the product to be manufactured at a lower cost and be more competitive on the world market.

Table 11
COST FOR THE SYSTEM COMPONENTS
(NOT SELLING PRICE)

COMPONENT	COST (DOLLARS)	
	HIGH ENERGY IMPULSE LASER	LOW ENERGY IMPULSE LASER
Impulse Laser	\$15,000	\$1,000
Detection Laser	\$500	\$500
Data Processor	\$1,000	\$1,000
Lenses, Photodiodes, Bridges, Etc.	\$1,000	\$1,000
Hardware Mounting, Electrical Connections, Etc.	\$1,000	\$1,000
T O T A L	\$18,500	\$4,500

Table 12

ECONOMIC ESTIMATES FOR WPTA SYSTEM

	HIGH ENERGY IMPULSE LASER	LOW ENERGY IMPULSE LASER
Cost of Major Components ⁽¹⁾	\$13,500	\$ 4,500
Cost of Assembled System ⁽²⁾	\$25,000	\$10,000
Selling Price ⁽³⁾	\$40,000	\$15,000
Installation Cost	\$ 5,000	\$ 4,000
Operating and Maintenance Cost/Year	\$10,000	\$ 5,000

(1) Cost of individual components

(2) Includes cost of enclosure and assembly of components.

(3) Selling price includes general and administrative expenses and profit.

One of the most promising areas of savings is strip steel processing, annealing and galvanizing. The automotive industry is the biggest user of processed steel strip. The steel mills are currently increasing and upgrading the capacity to meet the future need for galvanized steel for auto bodies. We estimate that the units can reduce waste by about 1.5% or 5000 ton/yr (Table 13). The value of that steel (sell price - scrap cost) is about \$2.5 mm/yr per furnace. We also estimate that the fuel efficiency can be increased by about 1.5% which amounts to a savings of 650,000 mm Btu/yr for the 125 furnaces in the US. We see no reason that there would not be 100% penetration of this market which would result in a sale of about 500 sensors (at four per furnace). The average energy savings are 1200 mm Btu/sensor/yr.

The sensor can have a dual function in processing aluminum. In addition to measuring the temperature, it will be able to sense the time that the metallurgical reactions are complete and the metal is ready to be removed from the furnace. There are two specific types of furnaces in use today:

1. Aluminum mill homogenizers - typically high tonnage continuous operation with extremely rigid temperature specifications.
2. Solution annealing and age hardening furnaces at the end user facility (e.g. aircraft manufacturers that have banks of furnaces to age harden the aluminum "skins" of airplanes).

The real result of using the new sensor is that manufacturers will be able to monitor the process in a way that they will be able to produce a better quality product at a more competitive price. Saving a few pounds of aluminum on an aircraft is worth many thousands of dollars in fuel during the life of aircraft. We estimate that there are 500 aluminum furnaces of the types listed above in the US and a market penetration of 250 units is possible. On the average each sensor in this service could save about 1300 mm Btu/sensor/hr. There would be a corresponding increase in the productivity of the particular furnaces resulting in savings of about \$400,000 worth of aluminum per year per furnace.

Table 13

ECONOMIC ANALYSIS FOR GALVANIZING/ANNEALING FURNACES

Nominal Capacity	350,000 Ton/Yr
Energy Used	0.35 Trillion Btu/Yr, Furnace
Total Waste Strip	50,000 Ton/Yr, Furnace
Waste Due to Temperature Measurement Problems	10,000 Ton/Yr, Furnace
Saving With WPTA (1/2 of Above)	5,000 Ton/Yr, Furnace
Value of Saving (Annealing at \$400/Ton)	\$2 MM/Yr-Continuous Annealing Fce.
(Galvanizing at \$500/Ton)	\$2.5 MM/Yr Per Galvanizing Fce.
Furnaces in U.S.	50-Galvanizing 75-Continuous Annealing
Energy Savings (Going from 85 to 86.5% Efficient)	0.65 Trillion Btu/Yr
Annual Value of Saved Product	\$275 MM/Yr

There are many other applications in metals heat treating that are more difficult to quantify. We estimate that there are more than 3000 integral quench batch furnaces, 1500 vacuum furnaces, and 500 continuous furnace where this sensor could be applied. The sensor would allow one to monitor the actual metallurgical process and optimize the control to reduce waste and energy consumption. At a twenty five percent penetration of these furnaces another 1250 sensors could be sold...

There are about 150 continuous casters in the US which could use this sensor to determine the amount of melt remaining in the center of the cast as it leaves the casting machine. With this information they can operate the caster nearer its ultimate capacity without fear of liquid metal breakthrough. At fifty percent penetration there would be another 75 units. The total potential market is about 2000 units for retrofit applications. After ten years there would be replacement business for old sensors. In addition there should be a market for about 30 units per year in new furnace applications.

The sales price of the unit would depend upon the application and the configuration. When it is configured in the temperature measuring mode, it can be sold for about \$40,000 each but when configured in the "physical properties" mode the sale price could be increased to \$60,000 to include the cost of some application engineering and additional software. For the purposes of this analysis assume that one half of the units sold would be configured in each mode. The result would be an average sell price of \$50,000 per unit.

In order to quantify the impact of WPTA System, it has been assumed that the "AVERAGE" savings can be derived as a composite of several typical applications. The average values for non-fuel and fuel savings are as follows:

Non-fuel savings/year per WPTA System = \$125,000

Fuel savings/year per WPTA System = \$ 5,000

An economic impact for a period of 10 years from the product introduction in 1992 is presented in Table 14. The return on investment is estimated to be 218% and a payback period is 0.46 years.

Table 14
ECONOMIC IMPACT BY WPTA SYSTEM

YEAR	92	93	94	95	96	97	98	99	00	01
Unit Sales	15	100	150	175	200	200	200	200	200	200
Cumulative Units	15	115	265	440	640	840	1040	1240	1440	1640
Annual Sales @ \$50 K/Unit (mm Dollars)	0.75	5	7.5	8.75	10	10	10	10	10	10
Annual Profit @ 10% (mm Dollars)	0.075	0.5	0.75	0.875	1	1	1	1	1	1
Energy Savings @ \$5000/ Unit (mm Dollars/Year)	0.075	0.575	1.325	2.2	3.2	4.2	5.2	6.2	7.2	8.2
Non-Energy Savings @ \$125 K/Unit (mm Dollars/Year)	1.875	14.375	33.125	55	80	105	130	155	180	205

Return on Investment = 218%

Payback Period = 0.46 Years

2.2.5-COMMERCIALIZATION

The workpiece temperature sensor functions on the principle of measuring the speed of sound as it travels through the workpiece and determining the temperature from a mathematical relationship characteristic of the material. The sound wave is induced by "pinging" the work with a laser. An interferometer which senses the sound wave at a different location measures the time required to travel the known path length. By analysis of the various times and velocity of the sound waves one can also determine the physical properties of the work if the temperature is known. The apparatus of this development has three key features:

1. Measures the surface temperature of the work independent of the emissivity of the piece.
2. Measures the bulk average temperature of the work.
3. Measures the physical state of the work if the temperature is known.

With these features there are several types of applications where this unit can be used for non-contact measurement. There are situations (e.g. galvanizing steel strip) where the surface emissivity is a variable so traditional optical pyrometers are not applicable. There are situations where the work temperature must be controlled very accurately and it is necessary to know the uniformity of the piece temperature more accurately than is presently possible with optical pyrometers (aluminum solution annealing and age hardening). In many metallurgical heat treating applications, there are multiple phases (crystal structures) that have different physical properties. If the temperature is known, it is possible to measure the differences caused by phase structure (examples include carburizing, annealing, and homogenizing). In a related application, the sensor can be used to determine the amount of liquid material remaining in the extrudate of a continuous caster, thus allowing better control of the metal quality and production rate.

As a typical example, a unit is chosen that is capable of measuring all three of the items listed above. It is also assumed that the basic software required to interpret the data from the interferometer has been developed and debugged as a part of the research program. The last phase of the research

program will include a field demonstration of the sensor and incorporation of any features that are discovered during the testing. The product will be introduced at a modest pace to allow "fine tuning" after the first few units have been in operation for several months. The costs of the first fifteen units will be more because of the potential for change. Subsequent units will be manufactured in a cost effective manner. It is assumed that the markets will start in the areas of maximum return and expand into the other less obvious areas as the reputation is enhanced.

Surface Combustion, Inc. intends to commercialize this development for metals heating applications. They are a major manufacturer of high temperature industrial furnaces and a supplier of instruments specially tailored to the particular furnace application. Both retrofit and new applications will be pursued.

It can be handled through the current agents who are located throughout the United States. These agents call on most of the metal heat treaters and steel mills. There would be a need for special coverage in the nonferrous plants since there is a very good application. Applications outside the traditional Surface markets will be addressed by assigning one salesperson the responsibility of finding new applications in markets e.g. plastics, paper, ceramics and composites, waste disposal, and glass. It is anticipated that most of the early sales will be of the "special" variety and that application engineering will be required to assure proper results. Eventually, there will be a backlog of applications that are proven and can be repeated without application engineering.

The manufacturing of these sensors will be through a special license with one or more laser and electronic assemblers. As they become more skilled in the assembly and are able to utilize the built-up common components, the cost will be further reduced. The first fifteen units will be made by assembling commercially available components purchased at low volume prices, which may include unneeded features. The components for the next fifty will be less costly since they will be purchased at high volume prices. The next fifty units will be manufactured using integration of the components and without the unneeded features or components.

The sale of the first unit is scheduled for soon after the end of the field demonstration in early 1992. Prior to this time technical papers will have been given in conferences and some preliminary advertising will have been done. The steel strip lines and aluminum homogenizing furnaces will be the first targets and the sales will be done by sales engineers who understand the metals industry. After the first units are in operation, additional sales can be handled by less technical salespersons. We estimate that only fifteen units would be sold in the first year. The sales should increase very rapidly in the second year after the sensors have been in successful operation for a year. We estimate that about 200 units would be sold each year as the product becomes established.

3.0-CONCLUSIONS

1. The overall technical feasibility of the sensor has been established using a computer simulation of the components.
2. It is predicted that the three features of surface temperature measurement, bulk temperature measurement, and determination of the work pieces physical state can be achieved with this approach.
3. There is a high potential for application of the "physical state" measurement, since no other sensor exists today with this capability.
4. The economical analysis indicates that the sales price objectives can be met and that there is a substantial impact on the national energy use and economy.
5. The sensor can be made compatible with being placed in a dirty industrial environment.
6. Use of the WPTA allows the furnace operator to take better control of the overall heating process.

4.0-RECOMMENDATIONS

Mathematical simulations of a pulsed laser polarizing interferometer has indicated technical feasibility of the WPTA System to measure temperature as well as transformation reactions. Up to this point there has been no laboratory work to confirm the applicability of the polarizing interferometer for the above claims. The specific results to be obtained from the laboratory work are answers to the following questions:

1. Can the ultrasonic vibrations be sensed in sufficient detail to allow one to determine the "time of flight" of the wave?
2. Can the ultrasonic vibrations be sensed in the presence of other vibrations typically found in an industrial environment?
3. Can the polarizing interferometer also be used to determine the difference in physical state of the material?

These are key feasibility questions that greatly affect the applicability and usefulness of this sensor. Therefore, it is recommended that further work be directed toward the resolution of these issues prior to embarking into the full development program.

A detailed description of the further work is given in the following five tasks:

Task 1-Assembly and Testing of Polarizing Interferometer:

The components for a polarizing interferometer will be assembled and tested to assure that it performs as expected. The tests will include limits of sensitivity and the ability to measure the "characteristics" of the vibrations rather than just the time of arrival. These will be preliminary tests with more complete evaluation in Task 2.

Task 2-Testing of Impulse Laser:

An impulse laser will be selected and purchased so that all of the critical components can be tested. The impulse laser will be integrated into the system. There will not be sufficient software to totally interpret the results, but there will be sufficient data gathering equipment (recorders, oscilloscope, etc.) that differences can be observed. The system will be tested on material samples supplied from Task 4. At the end of the testing

It will be possible to tell which of the desired industrial applications (identified in the phase report) are indeed feasible with the system that was selected. Testing will also be done to determine the effect of other vibrations on the sensitivity of the sensor.

Task 3--Temperature Testing:

Metal samples will be heated in a furnace and the readings will be made of the sensor response to the impulse laser. Comparisons of the responses will be made to assure that it will be possible to sense the differences are due to temperature and physical state.

Task 4--Sample Preparation:

Samples of various materials will be collected and analyzed prior to testing with the interferometer. These samples will be of two types. First there will be samples of steel, aluminum, brass, and stainless steel (two grades) of various thicknesses. Secondly, there will be samples of the same materials in different physical states including aluminum fully homogenized and unhomogenized, steel uncarburized and carburized to two different depths, and steel with and without retained austenite. The physical samples will be prepared by Surface Combustion using their furnaces in their laboratories. There will be a microscopic examination to confirm the physical state.

Task 5--Reporting:

There will be a report prepared documenting the feasibility of the approach and detailing the characteristics of the proposed sensor and any market implications of these findings. If the results are favorable there will be a proposal for additional development of this system.

APPENDIX A

PRELIMINARY CONCEPT DEVELOPMENT

REPORT BY AVCO RESEARCH LABORATORIES, INC.

**REPORT ON
PRELIMINARY CONCEPT DEVELOPMENT
FOR WORKPIECE TEMPERATURE ANALYZER**

**Prepared For
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EXECUTIVE SUMMARY

A sensor to measure the bulk (internal) and surface temperature of a workpiece as it is being heated in an industrial furnace has been investigated.

The operation of this Workpiece Temperature Analyzer (WPTA) is based on the laser generation and then propagation of ultrasound waves on the surface and through the body of the workpiece. The speed of ultrasound is determined by measuring the time-of-flight of the waves, through a polarizing interferometer. Since, in general, the speed of sound (or ultrasound) is a function of the temperature of the workpiece, the bulk and surface temperatures can be determined by using self-contained calibration curves.

The WPTA presents a number of advantages over other similar systems:

- o Use of ultrasound is conceptually simple.
- o Ultrasonic flow detection is a widely known and accepted technology.
- o Ultrasound is directly related to bulk and surface temperature.
- o Use of laser to generate ultrasound provides precise timing for accurate temperature reading.
- o Lasers can generate higher signal levels for stronger ultrasound.
- o Ultrasound excitation with lasers is remote with large standoff.
- o Use of interferometer provides remote detection and large standoff (instrument outside the furnace).
- o Polarizing interferometer not sensitive to external vibrations of the workpiece in the furnace.
- o Polarizing interferometer has low threshold for signal detection.
- o Optical system is reliable and simple.
- o Cost of components is moderate (inexpensive detection laser and moderate cost impulse laser).

Several tasks have been undertaken towards the development of the WPTA. First, a detailed literature survey was completed in order to determine the uniqueness of the WPTA. Second, a conceptual design was developed, which included equipment identification, operating limitations, techniques to calculate distance through the workpiece, calculations of laser excitation requirements, and field installation requirements. Third a semi-empirical model of the WPTA was generated, which included all laser and detection system parameters, workpiece properties, and furnace characteristics. The model validity was verified by comparing its predictions to available data from the literature. Then this model was used to evaluate the technical feasibility and potential performance of the WPTA. Both came out to be satisfactory and very promising. Fourth, vendors were contacted to determine availability of individual system components.

After completion of all the program tasks, the following conclusions can be made:

- o The semi-empirical model for the WPTA provides reliable predictions for ultrasound displacement.
- o Minimum detectable displacement as low as 15 pm.
- o Concept of bulk and surface temperature measurement is quite feasible.
- o A preliminary configuration for the WPTA has been developed and its potential performance has been assessed.
- o All applications selected are feasible with a wide margin.
- o Vendors have been contacted for price and availability of components.
- o All components are commercially available items with a total cost of less than \$20,000.
- o WPTA concept appears to be feasible and very promising.

Our future plans include assembly of a prototype analyzer and laboratory scale tests, aimed at demonstration of the concept and proof of predicted performance. A number of issues and possibilities for expanded use raised during Phase I will also be addressed.

Issues:

- o Repeatability and reliability of calibration.
- o Maximum workpiece thickness as determined by ultrasound attenuation (including temperature effect).

Other Uses:

- o Determination of internal workpiece condition (grain structure) after and/or during heat treatment.
- o Detection of carburization depth.
- o Ultrasonic tomography for internal temperature distribution.

1.0 INTRODUCTION

1.1 PROJECT OBJECTIVE

The objective of this project was to develop a sensor that can measure the bulk (internal) temperature of a workpiece as it is being heated in an industrial furnace. Currently, the traditional method of determining the workpiece temperature in industrial furnaces is to measure the surface temperature with optical pyrometers. There are a few applications where thermocouples can be attached or contact the work, but these applications are limited and the reliability is generally poor. Measurements using optical pyrometers depend upon the emissivity of the workpiece. If the workpiece has low or varying emissivity, the accuracy of the optical readings is adversely affected.

Several examples of good applications for this sensor can be given:

- o Control of a galvaneal line where the emissivity of the steel strip depends strongly upon the condition of the zinc coating (molten or solid).
- o Heat treatment of aluminum, where the emissivity of the workpiece changes as the oxide layer varies.
- o Ion nitriding and carburizing where the created "glow" in the gases surrounding the piece makes optical temperature measurements impossible.

As it is apparent from the examples given above, the sensor under development must be noncontact, with large standoff, and must not be sensitive to workpiece emissivity changes. A sensor like that could provide substantial

cost savings and payback. Increases in the production rate from existing furnaces offers the highest payback from increasing production, especially if the increase is caused by a reduction in scrap. In addition, the substantial improvement in product quality that can be achieved with this sensor can lead to more reliable and safe materials.

1.2 PRINCIPLE OF OPERATION

The operation of the Workpiece Temperature Analyzer (WPTA) is based on the generation and propagation of ultrasound waves on the surface and through the body of the workpiece (Figure 1). A laser beam (impulse laser) is used to generate the waves. The arrival of the waves at an appropriately selected location (backside of the piece or at an offset point on the same side) is monitored using a polarizing interferometer. Its operation is based on the fact that any deflection on the surface of the workpiece can lead to phase shifts of the interferometer beams. By using conventional polarizing techniques, this phase shift is detected as a change in the polarization levels. Once the time-of-flight (TOF) is determined, the speed of the ultrasound can be calculated. The speed of sound or ultrasound is a function of the temperature of the workpiece. Therefore, the temperature is determined by using self-contained calibration curves.

1.3 BACKGROUND

Generation and detection of ultrasound in solids have been investigated for many years. The field is quite broad and numerous applications of this technology can be found. Physical description of the phenomena involved requires contributions from many areas, like laser-solid interaction, elastic waves in solids, optical detection of ultrasound, thermal stresses in solids, absorption of laser radiation, etc. In our survey, we received approximately 500 paper titles, 250 abstracts, and 90 full papers. We discuss here the most relevant ones (65 references) to the Workpiece Temperature Analyzer (WPTA).

Figure 1: Schematic Drawing of the Workpiece Temperature Analyzer (Single-sided)

We begin the literature survey with the field of laser-solid interaction.⁽¹⁻⁹⁾ These papers represent only a small selection from among hundreds. In general, three interaction regimes can be identified, namely thermoelastic, plasma formation, and surface melting. The type of interaction depends on the strength and wavelength of the laser, the properties of the material, and the condition of the surface. The first regime is that of thermal absorption. The laser beam heats the surface with no apparent damage. In the second regime, plasma is generated by vaporization of a small amount of solid from defects on the surface. This vapor is ionized by the laser light and consequently the air is ionized. The air plasma achieves very high temperature and pressure. Because the plasma is at high pressure for a relatively long time, a significant impulse can also be generated. A parametric, analytical model for this regime is formulated in Ref. 3 in order to account for two-dimensional effects arising from the rarefaction structure within the laser-heated gases. In the surface melting regime, the melting point of the solid is reached, and hence surface damage is unavoidable. The review paper by Woodroffe⁽¹⁾ is a good source of general information in the field.

Most of the work in the area of laser-solid interaction is based on the use of infrared lasers. However, with a UV laser,^(8,9) where the photons are more energetic and where the absorptivity of the surface is much higher, the interaction is different. In fact, high thermal coupling and significant impulse even at low laser fluences were observed in that regime.^(8,9)

The absorption of laser radiation on metal surfaces has aroused considerable interest, because of the numerous applications of this technology in laser welding and surface heat treatment areas.⁽¹⁰⁻¹⁶⁾ These papers are

only a small but still representative sample of the hundreds that were found. Ready⁽¹⁰⁾ describes methods by which one may calculate the effects of pulsed laser radiation absorbed at opaque surfaces. In Refs. 13 and 14, and especially Ref. 16, a more mathematical approach to the heat conduction problem is given.

Many thousands of articles and reports have been published on the generation of elastic waves in solids. Since it is necessary to understand the basic theory of elastic waves, a number of key textbooks on this subject⁽¹⁷⁻²²⁾ are included in the reference list. In this survey, we will primarily focus on the phenomena associated with ultrasonic waves, which are only a small part of the spectrum of elastic waves.

When transient changes in the structure of a solid (rapid heating, sudden impact, etc.) occur, elastic waves are generated on the surface and in the bulk of the piece. In general, there are four types of waves that can propagate in solids, namely longitudinal (L), shear (S), Rayleigh or Surface (R), and Lamb waves.⁽¹⁷⁻²²⁾ The first two travel through the bulk of the solid with the L-waves being almost twice as fast as the S-waves. The R-waves travel only on the surface of the solid with speed slightly less than the S-waves. The Lamb waves propagate only through very thin plates (less than 0.030"), and have been used to measure the thickness of these plates.⁽²³⁻²⁵⁾ However, we are not going to expand on these waves, since their application is limited only to very thin pieces.

Laser pulses are one of the most actively developed methods of ultrasound generation in solids. In particular, many papers deal with the generation of R-waves (Rayleigh) and their application to detect surface flaws or defects.⁽²⁶⁻³²⁾ The literature body is quite extensive and these papers

are only representative samples. Aindow, et al.⁽²⁶⁾ generated ultrasonic R-waves with well described directional characteristics, using laser pulses in the thermoelastic regime. A more mathematical approach to the propagation and damping of these waves is given in Refs. 29, 30, 20. Ledbetter and Moulder⁽²⁷⁾ reported generation and detection of all three types of waves, including R-waves, in their experiments. The generated waves were detected using piezoelectric transducers mounted on the specimens.

L- and S-bulk waves have also been extensively used for detection of flaws, measurement of elastic properties of solids, and monitoring of steel solidification.⁽³³⁻⁵⁰⁾ These publications are again only a selection among hundreds that were found. In all these papers, the ultrasound waves were generated using various methods, including laser pulses. Most of the laser beams used in these papers were strong enough to deliver substantial impulse to the test pieces, followed by some surface mass removal. However, it should be pointed out that plasma formation is not necessarily associated with metal vaporization and surface melting. In the UV regime, most of the metals might reach their melting point before any plasma is formed, while the opposite is true in the IR regime.

The Workpiece Temperature Analyzer (WPTA), under development at ARL, should ideally operate in the thermoelastic regime to eliminate surface mass removal. Work in this area has been very limited. We were able to locate only one paper by Aindow, et al.⁽⁴¹⁾ from University of Hull, England, that deals with the same situation. This paper presents very important data, since it demonstrates the generation of all three types of waves (L, S, and R) in aluminum, brass, and various types of steel without any surface damage. The thickness of their test specimens was about one inch. In addition, no

coatings⁽³³⁻³⁹⁾ or acoustical constraints^(38,42) were used to increase laser radiation absorption and ultrasound amplitude. The laser was simply focused on a bare metal surface. It is also important to notice that in the thermoelastic regime, the amplitude of the L- and S-waves increases linearly with the laser energy per pulse, if the pulse duration and spot diameter are kept constant. This indicates that problems of material yield due to the high thermal strain at the laser spot are of secondary importance. The R-waves exhibit a more complicated behavior, but their amplitude still increases continuously with laser energy in the thermoelastic regime. In the plasma formation regime, things are totally different and some very surprising nonlinearities can be observed. However, since we do not plan to operate the WPTA in that regime, we will concentrate only upon the data from the thermoelastic regime. It should be pointed out again that in all these tests, the ultrasound was detected using conventional piezoelectric transducers mounted on the specimen, rather than optical techniques like the polarizing interferometer that will be used in the WPTA.

A very good theoretical and analytical approach of the generation of elastic waves by transient surface heating is given by White.⁽⁴⁰⁾ This work is not limited to surface heating only by laser pulses, but includes cases of electron bombardment and RF absorption. The problem of an input energy flux varying harmonically with time is treated in detail, since this problem is easily solved and the result shows clearly the nature of the wave generation process.

The dissipation of acoustical energy in polycrystalline metals, like steel, can, in general, be attributed to elastic hysteresis, thermoelastic relaxation, and scattering.⁽⁴³⁾ The elastic hysteresis is caused by the

time-independent nonlinear stress strain relationship. Loss due to thermoelastic relaxation is caused by the fluctuations in the stress distribution, which results in irreversible heat currents. Scattering of sound waves takes place whenever there exists regions of varying density or elasticity. Darbari, et al.⁽⁴³⁾ give theoretical background and experimental results on sound attenuation at elevated temperatures. They report strong dependence of the attenuation on temperature and magnetic properties of steel. For nonmagnetic steel, the attenuation remains practically constant with respect to temperature. Ultrasound attenuation at high temperatures has also been investigated by Papadakis, et al.⁽⁴⁴⁻⁴⁶⁾ and Fairand, et al.⁽³³⁾ Papadakis⁽⁴⁴⁾ shows that the solution and precipitation of carbides affect the sound velocity drastically, while the attenuation is affected by at least one of the following; magnetism, recrystallization, carbon solubility, and grain growth at elevated temperatures. In Ref. 43, the ultrasound was generated using the momentary contact pulse-echo method. In the second paper,⁽³³⁾ valuable data are given on the attenuation of the pulse strength in the specimen, along with some computer predictions. The laser used was very powerful and all the tests were performed in the plasma regime. The waves were monitored using transducers mounted on the specimen.

Alternative techniques for ultrasound generation are given in Refs. 54-58. In Refs. 55-57, piezoelectric materials driven by high frequency electronic oscillators have been used. However, they generally produce low amplitude waves which are undesirable in highly attenuating materials. High velocity gas guns firing flat plate projectiles at specimens have also been used,⁽⁵⁸⁾ but they suffer from slight alignment variations from shot to shot

resulting in nondesirable stress loadings. In Ref. 54, Electromagnetic Acoustic Transducers (EMAT) have been employed to generate elastic waves in metals by applying electromagnetic forces in the test metal block. The EMAT concept can also be used in a reverse manner to detect surface vibrations of the piece, which are directly related to the arrival of the ultrasonic acoustic wave. However, the EMAT technique has major drawbacks since it cannot generate strong enough ultrasonic pulses above the magnetic transition point (approximately 770°C), leading to large errors in the temperature measurements.

Although not directly related to the WPTA, Refs. 47-53 give important information about the application of ultrasound to measure the rate of solidification of steel during casting, based on the dependence of through-transmission transit time upon the extent of solidification.

Ultrasonic tomography has been investigated as a method to give temperature distribution in steel pieces.⁽⁵⁹⁻⁶²⁾ Wadley, et al.⁽⁶⁰⁻⁶²⁾ generated ultrasound waves in relatively thick steel specimens (at least 6" thick) using strong laser pulses (with some surface damage), and used an EMAT system or specimen mounted piezoelectric transducers to detect the arrival of the ultrasound. No noncontact optical techniques were implemented in their detection system. Although their reconstruction accuracy needs some improvement, their results are very encouraging in terms of future use of ultrasonic tomography for internal temperature measurements. It is also important to point out that they were able to generate strong ultrasound waves, in thick steel pieces (15.2 cm in diameter) using relatively small lasers (30 mJ). As shown later in Section 2.1 of this report, this is consistent with our model predictions and the data from Ref. 71. In Ref. 59,

some more detailed work on the temperature profile reconstruction schemes is reported. However, most of these systems are built for a specific application and geometry, leading to major necessary modifications of the software and hardware for the new configuration. On the other hand, the major advantage of the ultrasonic tomography is its ability to give temperature distribution, rather than average bulk temperature. We believe that the existing ultrasonic tomography software is developed well enough to be directly incorporated into our system as part of Phase 2 of the current program.

The detection of ultrasound using optical techniques has been motivated by the need of noncontact, nondestructive techniques to visualize and image the ultrasonic field. Recently, the generation of ultrasound using laser pulses led to a perfect coupling of these two techniques in order to make a powerful tool to either inspect or measure properties of materials from large distances (more than 1m). Monchalin⁽⁶³⁾ provides a good review of the techniques that have been used to detect ultrasound in opaque solids also (Refs. 73-76). These techniques can be classified into noninterferometric and interferometric, the latter being more general and currently more actively developed. It is important to notice⁽⁶³⁾ that a displacement of only a few Angstroms, due to the ultrasound waves, is large enough to be detected by most of the interferometers. Some of the techniques described in that paper are quite sensitive to vibrations of the workpiece, while others are not. In addition, most of these techniques do not require polished metal surfaces. Surprisingly, the polarizing interferometry concept used by the WPTA is not mentioned in this paper. The basic principles of operation of a polarizing interferometer can be found in Ref. 64. The concept is widely known and has been applied in numerous applications. It should be pointed out that this

technique eliminates the need to mount all the optics so that they stay fixed to within a wavelength, using heavy optical tables or steel beams, which are necessary for most of the other interferometric measurements. All that is needed here is to keep the reference and signal path lengths approximately equal and to keep the optics aligned well enough to properly combine the beams. Vibrations are quite acceptable as long as they are at a lower frequency than one wishes to observe. The signal from the interferometer will primarily detect rapid phase changes, rather than the absolute phase difference of the beams. Despite all these advantages, polarizing interferometry has never been used before for the detection of ultrasound in opaque solids. However, similar systems⁽⁶⁵⁾ have been developed for other applications, and a good sensitivity of $1/10,000$ of the wavelength of the laser beam are reported.

In conclusion, we believe that the concept of the WPTA proposed by ARL is unique, although its individual components have been successfully used before for various other applications.

1.4 ADVANTAGES OF THE WPTA

The WPTA has many advantages over other similar systems:

- o Use of ultrasound is conceptually simple.
- o Ultrasonic flow detection is a widely known and accepted technology.
- o Ultrasound is directly related to bulk and surface temperature.
- o Use of laser to generate ultrasound provides precise timing for accurate temperature reading.
- o Lasers can generate higher signal levels for stronger ultrasound.
- o Ultrasound excitation with lasers is remote with large standoff.
- o Use of interferometer provides remote detection and large standoff (instrument outside the furnace).

- o Polarizing interferometer not sensitive to external vibrations of the workpiece in the furnace.
- o Polarizing interferometer has low threshold for signal detection.
- o Optical system is reliable and simple.
- o Cost of components is moderate (inexpensive detection laser and moderate cost impulse laser).

1.5 ACHIEVEMENTS

Several tasks have been undertaken towards the development of the WPTA. First, a detailed literature survey was completed in order to determine the uniqueness of the WPTA. Second, a conceptual design was developed, which included equipment identification, operating limitations, techniques to calculate distance through the workpiece, calculations of laser excitation requirements, and field installation requirements. Third a semi-empirical model of the WPTA was generated, which included all laser and detection system parameters, workpiece properties, and furnace characteristics. The model validity was verified by comparing its predictions to available data from the literature. Then this model was used to evaluate the technical feasibility and potential performance of the WPTA. Both came out to be satisfactory and very promising. Fourth, vendors were contacted to determine availability of individual system components. A preliminary estimate of components cost resulted in a low value of less than \$20,000.

2.0 MODEL DEVELOPMENT FOR THE WPTA

2.1 SEMI-EMPIRICAL MODEL FOR ULTRASOUND GENERATION AND PROPAGATION

The model developed by ARL, in order to describe the generation and propagation of ultrasound in metals, is a combination of theoretical and experimental results. At this stage of the development of the WPTA, this semi-empirical model can be reliably used to predict the motion on the surface of the workpiece, as the ultrasound waves arrive.

Two major regimes will be distinguished as far as the laser-solid interaction is concerned. The first is the thermoelastic regime, where the generation of ultrasound is simply the result of the expansion of the solid due to laser heating, without any surface damage or material removal. The second is the plasma regime, in which strong impulse is generated due to the vaporization of the material or the formation of plasma over the surface of the piece. In the case of plasma formation, some material is removed from the surface of the piece. In general, the impulse and the associated surface displacements are higher in the plasma regime.

Thermoelastic Regime

Consider the idealized geometry of a laser pulse of duration t_p of uniform and constant intensity Φ (W/cm^2) normally incident on a plane boundary of an absorbing material with an absorption coefficient α (Figure 2). The reflection coefficient at the surface is R . R and α characterize the optical properties of the material and are assumed to be independent of temperature. The thermal properties of the material are described by the specific heat per unit mass, C_v , the mass density ρ , and the thermal conductivity k . The heat diffusivity $K = k/\rho C_v$ determines a characteristic length $(2Kt_p)^{1/2}$, which indicates how much the temperature

Figure 2: Conceptual Drawing of Laser-Solid Interaction

profile is spread out during the laser pulse. To obtain an order of magnitude estimate of the attainable heating and cooling rates, the assumption is made that k , K , and C_v are independent of temperature and that no latent heat due to phase transitions is involved. The limiting cases may be distinguished, which are illustrated in Figure 2a and 2b.

Case a:

The optical absorption depth α^{-1} is small compared to the thermal diffusion length, $\alpha (2Kt_p)^{1/2} \gg 1$. In this case, the energy absorbed during the laser pulse $(1-R) \phi t_p$ is used to heat a layer of thickness $(2Kt_p)^{1/2}$. The average temperature rise in this layer is:

$$\Delta T = \frac{(1-R) \phi t_p}{\rho C_v (2Kt_p)^{1/2}} \quad (1)$$

After the laser pulse, the heat in this layer diffuses into the substrate.

Case b:

The optical absorption depth α^{-1} is large compared to the thermal diffusion length, $\alpha (2Kt_p)^{1/2} \ll 1$. The light absorption creates an exponential temperature profile, with characteristic length α^{-1} ,

$$\Delta T(z) = \frac{(1-R) \alpha \phi e^{-\alpha z} t_p}{\rho C_v} \quad (2)$$

The penetration depth at the light field in good conductors in the visible and near infrared frequencies lies in the range of 1 to 3×10^{-6} cm.

For most metallic conductors, the inequality of Case a, $\alpha (2Kt_p)^{1/2} \gg 1$ is satisfied for laser wavelengths between 0.2 and 2 μm and pulse durations longer than a few picoseconds (1 psec = 10^{-12} sec).

Therefore, the following model description in the thermoelastic regime will be based on Case a.

As the area of the laser spot is heated, the metal expands and some strain, ϵ , is generated equal to:

$$\epsilon = \delta \cdot \Delta T \quad (3)$$

where δ is the linear coefficient of expansion of the material. Consequently, at the point of impulse a displacement, Δl_1 , is formed, given as:

$$\Delta l_1 = \epsilon \cdot \delta \quad (4)$$

where

$$\delta = (2Kt_p)^{1/2} \quad (5)$$

is the penetration depth of heat.

The attenuation of the generated ultrasound wave is primarily due to the spherical spreading of acoustic energy as d_s/x , where x is distance from the point of impulse and d_s the laser spot diameter. In addition, the waves are attenuated as they propagate through the solid, because of elastic hysteresis, thermoelastic relaxation, and scattering. This attenuation is frequency dependent and scales with $e^{-N\Delta/C x}$, where N is the ultrasound frequency, Δ is the logarithmic decrement, C is the speed of sound, and x is the distance traveled. This model was selected despite its rather crude simplicity, because of serious lack of better models in the literature.

For simplicity, we define an attenuation coefficient, a , as:

$$a = - \frac{N\Delta}{C} \quad (6)$$

Theory⁽⁴⁴⁾ predicts that the attenuation coefficient for the shear waves, a_s , is related to that of longitudinal waves, a_L , as:

$$a_s = \frac{3}{4} \left(\frac{c_L}{c_s} \right)^3 a_L$$

where C_L , C_S are the sound speeds of the longitudinal and shear waves, respectively. Therefore, only one of the attenuation coefficients is needed for the calculation of the ultrasound attenuation.

The theoretical problem of calculating farfield displacement of both longitudinal and shear waves, along with their directivity patterns, was investigated many years ago.⁽⁶⁶⁻⁶⁹⁾ The key to the accuracy of these calculations is the representation of the acoustic source. Two types of acoustic sources are considered and are illustrated in Figures 3a and 3b. The first one is a disk source with uniformly distributed normal stresses (Figure 3a), and the second is an infinitely long line source with uniformly distributed shear stresses (Figure 3b). The theoretical asymptotic (large distance) behavior of the acoustic radiation pattern induced in an isotropic, linear elastic half space is described by the generated displacements,⁽⁶⁷⁾ as:

Disk Source:

$$\text{Longitudinal displacement: } U_R \sim \frac{F(\theta)}{\mu} \quad (8)$$

$$\text{Shear displacement: } U_\theta \sim \frac{G(\theta)}{\mu}$$

Line Source:

$$\text{Longitudinal displacement: } U_R \sim \frac{H(\theta)}{\mu} \quad (9)$$

$$\text{Shear displacement: } U_\theta \sim \frac{K(\theta)}{\mu}$$

where $\theta = 0^\circ$ is the direction normal to the surface and μ the Lamé constant or the modulus of rigidity of the material. The functions $F(\theta)$, $G(\theta)$, $H(\theta)$, $K(\theta)$ are given in⁽⁶⁷⁾ and describe the directivity pattern of the generated ultrasound. A thorough investigation of this pattern is presented in,⁽⁶⁹⁾

Figure 3: Theoretical Modeling of Acoustic Sources

where it is concluded that the directivity pattern of the ultrasound generated in the thermoelastic regime by a laser heated circular spot resembles that of a line acoustic source, while in the plasma regime the disk source is a closer representation of the corresponding acoustic source. Combining Eqs. (1), (3), (4), (5), (6), and (7), we obtain the displacement at the detection point for longitudinal and shear waves as:

$$\Delta \ell_2^L = \frac{\phi (1-R) \Phi \cdot t_p}{\rho C_V} \frac{d_s}{x} e^{a_L x} \frac{H_0}{\mu} \quad (10)$$

$$\Delta \ell_2^S = \frac{\phi (1-R) \Phi \cdot t_p}{\rho C_V} \frac{d_s}{x} e^{a_S x} \frac{K_0}{\mu} \quad (11)$$

where a_L , a_S are related through Eq. (7) and $H_0 = H(\theta=0)$, $K_0 = K(\theta=0)$, where $H(\theta)$, $K(\theta)$ appear in Eq. (9). This solution corresponds to a system where the detection laser is located at the epicenter of the impulse point or next to it. In both cases, $\theta = 0^\circ$, but in the latter the detector senses the arrival of waves reflected from the bottom surface of the workpiece.

The model was first fitted to the data from, ⁽⁷⁰⁾ by matching the directivity factors K_0 , H_0 , and the logarithmic decrement, Δ , for longitudinal waves, only for two data points on the curve for longitudinal waves in Figure 4 and one data point on the curve for shear waves in Figure 4. Then the laser intensity, Φ , was varied and the model predictions are compared to the rest of the data points from Ref. 70. The test specimen for these data was a 25 mm thick aluminum slab, the pulse duration was kept constant at 24 nsec, and the laser energy was varied from 10 to 60 mJ per pulse. The agreement is strikingly good, which is not surprising since the model was fitted to some of the data points. The important observation is that the model predicts very well the linear variation of displacement with intensity.

Figure 4: Comparison between data and model predictions of the ultrasound displacement in the thermoelastic regime for a 25 mm thick aluminum piece

The next step was to predict the displacement at the epicenter of the impulse point without changing any directivity patterns or logarithmic decrement values in the case of a steel piece. The only new inputs to the calculation are the necessary elastic thermal, mechanical, and optical properties of steel, along with the new laser characteristics (energy per pulse 5-40 mJ, pulse duration 17 ns, laser diameter 3.8 mm, slab thickness 25 mm). The data,⁽⁴¹⁾ along with the prediction for the longitudinal waves, are presented in Figure 5 and they are in excellent agreement. This comparison can be considered a good test of the validity of the thermoelastic model, since no data match was used for the model prediction.

As a final check of the model, we compared its predictions with data obtained under randomly selected conditions.⁽⁷¹⁾ Figure 6 summarizes the results of this comparison. The open symbols correspond to data (squares for L-waves and circles for S-waves), and the solid symbols are the model predictions (same convention for L and S waves). The size of the data symbols represents typical uncertainties. The agreement between model prediction and data is again very good.

In summary, the semi-empirical model for the thermoelastic regime gave predictions in excellent agreement with the available data. Therefore, it can be reliably used to determine the expected displacement due to the ultrasound waves under any conditions specified by the designer.

Plasma Regime

In this regime, the phenomenology of the laser-solid interaction is quite different from that of the thermoelastic regime. The formation of air plasma is one of the most characteristic and interesting features of the interaction.⁽¹⁾ This air plasma is generated by vaporization of a small amount of metal from defects on the surface. The metal vapor is then ionized

Figure 5: Comparison between data and model prediction of the ultrasound displacement in the thermoelastic regime for a 25 mm thick steel piece

Figure 6: Comparison between randomly chosen data points and model predictions in the thermelastic regime

by the laser light and, consequently, the air is ionized. The air plasma achieves very high temperatures and pressures, and it is a very efficient radiator. Since this air plasma is at high pressure for a substantial length of time, a significant impulse can be generated. Simple vaporization from the metal surface can also generate impulse,⁽¹⁾ but much less effectively. Data show⁽¹⁾ that with an air plasma, impulse values approximately ten times higher than those with vaporization can be achieved.

When laser flux, Φ_i (W/cm^2), impinges on the metal surface, some of it is reflected and some is absorbed Φ_a (W/cm^2). An absorption coefficient, f_a , is usually included in the calculations as:

$$\Phi_a = f_a \cdot \Phi_i \quad (12)$$

The absorption coefficient is a property of the metal and is a strong function of the wavelength of the laser light.⁽¹⁾ Most of the metals exhibit high absorption coefficients in the ultraviolet and low in the far infrared.

The generated air plasma achieves high pressures on the surface of the piece. These pressures have been measured in⁽¹⁾ as a function of laser flux, and Figure 7 presents some of the data. A simple curve fit gave us the functional dependence of the surface pressure as:

$$p = 1.79 \times 10^{-4} \Phi_a^{0.76862} \quad (13)$$

where p is in atms and Φ_a in W/cm^2 .

One of the dominant parameters in plasma-solid interaction is the plasma confinement time.^(1,5) Figure 8 is a schematic illustration of the detailed phenomena that occur during the interaction. The pulsed laser beam generates

Figure 7: Measured Plasma Surface Pressures vs. Laser Flux (from Ref. 1)

LASER PULSE LENGTH $= t_L$

PLASMA CONFINEMENT TIME $= \frac{R_s}{C_{PLASMA}}$

$$\tau = t_L / (R_s / C_P)$$

Figure 8: Schematic Illustration of the Laser-Solid Interaction in the Plasma Regime (from Ref. 1)

a laser supported combustion wave, which leaves a dense plasma behind it. The plasma is "inertially confined" for a time that corresponds to that for a rarefaction wave to travel from the edge of the spot to the center of the target. This time is the spot radius divided by the plasma acoustic speed. The parameter $\hat{\tau}$ is the ratio of the pulse length to the plasma confinement time and is a very important parameter as far as impulse delivery to the metal is concerned. The importance of $\hat{\tau}$ is illustrated in Figure 9.⁽¹⁾ In this figure, the ratio, σ , of laser produced impulse to the product of the initial surface pressure and pulse length have been plotted. Therefore, the pressure delivered to the piece, p_D , is:

$$p_D = \sigma p \quad (14)$$

where p is defined in Eq. (13). Following simple curve fitting techniques, the dependence of σ on $\hat{\tau}$ and initial surface pressure, p , is given as:

For $\hat{\tau} < 0.3105$

$$\sigma = 5.5823 (\hat{\tau})^{-0.3016} [1.3571 (\hat{\tau})^{-0.0670}] \log (p/10) \quad (15)$$

and for $\hat{\tau} > 0.3105$

$$\sigma = 3.0915 (\hat{\tau})^{-0.8069} [1.5062 (\hat{\tau})^{-0.0221}] \log (p/10) \quad (16)$$

The ratio σ can range from values higher than 100 to values below 1.

The next step in the model is the calculation of the ultrasound displacement at a distance x . As explained before, the data presented in⁽⁶⁹⁾ justify the representation of the acoustic source in this interaction regime as a disk source with normal stresses. Therefore, in this part of the model Eq. (8) will be used instead of Eq. (9) that was used for the thermoelastic

Figure 9: Air Plasma Impulse Delivery as a Function of Nondimensional Plasma Confinement Time (from Ref. 1)

regime. All the arguments about the attenuation of ultrasound are still valid in this regime and will not be repeated here. The only difference is that now the strain, ϵ , on the surface is:

$$\epsilon = \frac{p_D}{E} \quad (17)$$

where E is the Young's modulus of elasticity for the metal. Combining all the above, we derived the final expressions for the displacement for longitudinal and shear waves at the detection point, a distance x away from the point of impulse.

$$\Delta \ell_2^L = \frac{p_D}{E} \sqrt{\frac{2Kt}{\rho}} \frac{d_s}{x} e^{a_L x} \frac{F_o}{\mu} \quad (18)$$

$$\Delta \ell_2^S = \frac{p_D}{E} \sqrt{\frac{2Kt}{\rho}} \frac{d_s}{x} e^{a_S x} \frac{G_o}{\mu} \quad (19)$$

The parameters used have already been defined in Eq. (10), (11), and (8).

The model predictions will now be compared to the available data.⁽⁸⁾

As described in that paper and illustrated in Figure 10 from,⁽⁹⁾ the amplitude of the shear displacement decreased as air plasma was formed. On the other hand, the amplitude of the longitudinal displacement increased initially and, after reaching a peak, it decreased. Since the amplitude of the shear displacement decreased, we decided not to use these waves for our system, but concentrate on the prediction and detection of the longitudinal waves only. Figure 11 presents a comparison between the model prediction (solid line) and the data from Figure 10. For this set of experiments, the laser energy per pulse was kept constant at 33 mJ, the pulse duration was also constant and equal to 27 nsec, and the test specimen was a 25 mm thick aluminum disk. The laser intensity was varied by focusing the beam.

Figure 10: Variation in displacement amplitude as a function of laser intensity at constant laser energy of 33 mJ

Figure 11: Comparison between data and model prediction of the longitudinal ultrasound displacement in the plasma regime for a 25 mm thick aluminum piece with constant energy per pulse 33 mJ

The agreement is sufficient for the purpose of this simple model. High inaccuracies can be observed in the transition regime right before the plasma formation. These are probably due to the inability of the plasma model to predict thermoelastic effects. The model predicts a change in the slope of the displacement curve at about $26 \times 10^7 \text{ w/cm}^2$, but it doesn't show any decrease in the amplitude of the displacements.

These phenomena are a direct consequence of the interaction between two competing factors. The first is shown in Figure 7 where the surface pressure of the plasma increases with the laser flux. The second factor comes from Figure 9 in which the delivered pressure to the workpiece decreases as the nondimensional plasma confinement time $\hat{\tau}$ increases. A process of focusing the laser beam (like the one in Figure 10 and 11) corresponds to an increase of $\hat{\tau}$. Therefore, the reversal of the curve in Figures 10 and 11 might be attributed to the fact that at high laser fluxes the surface plasma pressure increases, but the impulse delivery to the piece becomes more and more inefficient. Previous work at Avco has identified such mechanisms and experimental and theoretical demonstrations of their existence have been achieved.

Another series of experiments was undertaken in⁽⁷¹⁾ to examine the effect of varying optical energy at constant laser intensity (w/cm^2). This was achieved by using selected combinations of lenses and neutral density filters to produce a chosen intensity of $180 \pm 30 \times 10^6 \text{ (w/cm}^2\text{)}$ at the aluminum surface. A comparison between these data and the model prediction (solid line) for the same conditions is presented in Figure 12. The agreement is within the experimental error and is considered satisfactory.

Unfortunately, we were unable to find data on ultrasound displacements for steel or other materials in the plasma regime. However, we believe that the model predictions for steel are accurate enough to serve the approximative

Figure 12: Comparison between data and model prediction of the longitudinal ultrasound displacement in the plasma regime for a 25 mm thick aluminum piece at constant intensity of $18 \times 10^{17} \text{ W/cm}^2$

nature of this model. Figure 13 presents the results of the model prediction for the longitudinal displacement at the epicenter of the impulse point. The material is steel 1" thick, the energy is kept constant and equal to 33 mJ per pulse, the pulse duration constant at 27 msec, and the intensity was varied by focusing the laser beam.

Some general comments on the results of this modeling effort are given below. First, it has been demonstrated that the model can predict very well the ultrasound displacement in steel and aluminum in the thermoelastic regime. In the plasma regime, the predictions are simply adequate for the purpose of this model, which is not more than an order of magnitude prediction of the displacement. The most important conclusion is associated with the value of the displacement amplitudes that are measured or predicted. The maximum displacement achieved through a 25 mm thick aluminum is about 1100 pm or 11×10^{-10} m in the plasma regime, while for a similar steel specimen this value drops down to 55 pm or 55×10^{-12} m. These values certainly introduce a challenge to the detection polarizing interferometer, which now must be sensitive enough to detect them. It should, however, be pointed out that the energy per pulse (30-50 mJ) and the pulse duration (17-27 msec) used for these tests correspond to characteristics of commercially available lasers with prices well under \$20,000.

2.2 ANALYTICAL MODEL FOR THE POLARIZING INTERFEROMETER

The purpose of this model is to determine the minimum detectable displacement due to the arrival of ultrasound waves. In describing the model of the polarizing interferometer, we will refer to Figure 14, where a schematic illustration of the system is presented.

Figure 13: Model prediction of the longitudinal ultrasound displacement in the plasma regime for a 25 mm thick steel piece with constant laser energy per pulse of 33 mJ

The signal beam from the workpiece and the reference beam from the detection laser are first linearly polarized and then combined to give a total intensity of I_t . The combined beam then goes through the 50-50 splitter into systems A and B (Figure 14). The resulting beams are then added and, probably, a square root operation gives the final signal.

Consider an acoustic wave of displacement amplitude Δ and frequency ω_s . Then the deviation, ξ , due to this wave is:

$$\xi = \Delta \cdot \sin \omega_s t \quad (20)$$

and hence the corresponding phase shift for the beam is:

$$\Delta\theta = 2 \frac{2\pi}{\lambda} \cdot \xi = \frac{4\pi\Delta}{\lambda} \sin(\omega_s t) \quad (21)$$

where λ is the light beam wavelength and the factor 2 is due to the double path traveled by the beam as it is reflected from the piece. Therefore, the electric field vector of the light beam reflected from the piece is in general given as:

$$\vec{A}_p = \hat{i} A_{p_x} \cos(\omega t) + \hat{j} A_{p_y} \cos(\omega t + \theta_p + \frac{4\pi\Delta}{\lambda} \sin(\omega_s t)) \quad (22)$$

where θ_p is a constant arbitrary phase, ω is the light angular frequency, and $\hat{i}, \hat{j}$ are the unit vectors in the x- and y-directions, respectively, z being the direction of wave propagation.

For the reference beam vector, we have:

$$\vec{A}_r = \hat{i} A_{r_x} \cos(\omega t + \theta_r) + \hat{j} A_{r_y} \cos(\omega t) \quad (23)$$

where again θ_r is a constant arbitrary phase. We designate the x-axis as horizontal and the y-axis as vertical.

SYSTEM A

Figure 14: Motion Sensing Polarizing Interferometer

The signal beam goes first through a vertical polarizer and becomes:

$$\vec{A}_p = \hat{j} A_{p_y} \cos(\omega t + \theta_p + \frac{4\pi\Delta}{\lambda} \sin(\omega_s t)) \quad (24)$$

while the reference beam goes through a horizontal polarizer and becomes:

$$\vec{A}_r = \hat{i} A_{r_x} \cos(\omega t + \theta_r) \quad (25)$$

The two beams are then combined through the Polarizing Beam Combiner to give:

$$\vec{A}_t = \hat{i} A_{r_x} \cos(\omega t + \theta_r) + \hat{j} A_{p_y} \cos(\omega t + \theta_p + \frac{4\pi\Delta}{\lambda} \sin(\omega_s t)) \quad (26)$$

or in a more compact form:

$$\vec{A}_t = \hat{i} A_{r_x} \cos(\omega t) + \hat{j} A_{p_y} \cos(\omega t + \theta) \quad (27)$$

where

$$\theta = \theta_p - \theta_r + \frac{4\pi\Delta}{\lambda} \sin(\omega_s t) \quad (28)$$

The light intensity, I_t , at this point is:

$$I_t = |\vec{A}_t|^2 \quad (29)$$

After the 50-50 splitter, the two beams become:

$$I_A = \frac{I_t}{2} \quad (30)$$

$$I_B = \frac{I_t}{2} \quad (31)$$

and hence the two beam vectors are:

$$\vec{E}_A = \hat{i} E_x \cos(\omega t) + \hat{j} E_y \cos(\omega t + \theta) \quad (32)$$

$$\vec{E}_B = \hat{i} E_x \cos(\omega t) + \hat{j} E_y \cos(\omega t + \theta) \quad (33)$$

where

$$E_x = \frac{A_r x}{\sqrt{2}}, \quad E_y = \frac{A_p y}{\sqrt{2}} \quad (34)$$

The two systems, A and B (Figure 14), will be described separately.

System A:

The beam I_A goes through a beam splitter and the emerging beams are linearly polarized through two $+45^\circ$ and -45° polarizers, giving beams I_1 and I_2 , respectively (Figure 14), as:

$$I_1 = \frac{E_x^2 + E_y^2}{2} + E_x E_y \cos \theta \quad (35)$$

$$I_2 = \frac{E_x^2 + E_y^2}{2} - E_x E_y \cos \theta \quad (36)$$

The two beams are then collected by the photodetectors, which generate currents i_1 and i_2 , respectively.

In general:

$$i_1 = n I_1 \quad (37)$$

$$i_2 = n I_2 \quad (38)$$

where n is the detector sensitivity or quantum efficiency (typically equal to 0.3 - 0.4 A/W). The two currents are then subtracted to give:

$$i_a = i_1 - i_2 \quad (39)$$

$$i_a = 2n E_x E_y \cos \theta \quad (40)$$

or using Eq. (34):

$$i_a = n (I_r I_p)^{1/2} \cos \theta \quad (41)$$

where

$$I_r = Ar_x^2 \quad (42)$$

$$I_p = Ap_y^2 \quad (43)$$

I_r , I_p represent the intensities of the reference and signal (reflected from the piece) beams.

System B:

The purpose of this system is to create two circularly polarized beams (left- and right-hand polarizations). This is achieved by taking the beam through a 1/4 wave plate and then through + 45° and - 45° linear polarizers. Finally, we obtain the two beams I_R (right-hand polarization) and I_L (left-hand polarization) as:

$$I_R = \frac{E_x^2 + E_y^2}{2} + E_x E_y \cos \sigma \quad (44)$$

$$I_L = \frac{E_x^2 + E_y^2}{2} - E_x E_y \cos \sigma \quad (45)$$

where

$$\sigma = \vartheta - \frac{\pi}{2} \quad (46)$$

or

$$I_R = \frac{E_x^2 + E_y^2}{2} + E_x E_y \sin \vartheta \quad (47)$$

$$I_L = \frac{E_x^2 + E_y^2}{2} - E_x E_y \sin \vartheta \quad (48)$$

Following similar procedure with that of system A, we obtain:

$$i_b = n (I_r I_p)^{1/2} \sin \theta \quad (49)$$

The two currents i_a , i_b are then taken through high-pass filters, squared, and added. A square root operation (not shown in Figure 14) completes the signal processing. The final current, i_s , is given as:

$$i_s = \left(\frac{I_r I_p}{2} \right)^{1/2} \left[\frac{4\pi\Delta}{\lambda} (RC) \omega_s \right] \cos(\omega_s t) \quad (50)$$

where RC is the time constant of the high-pass filter.

The minimum detectable displacement is determined by the level of photocurrent noise (shot noise) of the detector. The RMS value of this current noise, $\tilde{i}_N$, is generally given as:

$$\tilde{i}_N = (2enIf)^{1/2} \quad (51)$$

where f is the detector bandwidth, e the electronic charge, and I the average light on the photodiode ($= I_r + I_p$).

The RMS value of the signal, $\tilde{i}_s$, is given as:

$$\tilde{i}_s = n (I_r I_p)^{1/2} \frac{2\pi\Delta}{\lambda} (RC) \omega_s \quad (52)$$

By setting the RMS signal-to-noise ratio $\tilde{i}_s / \tilde{i}_N$ equal to 1, the minimum detectable displacement Δ_m can be calculated, as:

$$\Delta_m = \frac{(ef)^{1/2} \lambda (I_r + I_p)^{1/2}}{(2n)^{1/2} \pi (RC) \omega_s (I_r I_p)^{1/2}} \quad (53)$$

The intensities, I_r , I_p , can be related to the total power of the detection laser, I , as follows:

$$I_r = bI \quad (54)$$

where b is the fraction of the beam that is diverted and does not reach the workpiece (typical value 0.1). The light intensity, I_p , from the piece is a function of the diameter of the collection lens, d_c , the distance from the surface of the piece, L , and the reflectivity of the piece surface, r . Using solid angle geometry, we obtain:

$$I_p = \frac{d_c^2}{8L^2} r (1 - b) I \quad (55)$$

The number of pulses, N , reduces the minimum detectable displacement by a factor of $1/\sqrt{N}$, according to statistical theory.

Finally, if we take all these into account, along with Eqs. (53), (54), and (55), we obtain the final expression for the minimum detectable displacement, $\Delta_{\min}$:

$$\Delta_{\min} = \frac{(ef)^{1/2} \lambda}{(2n)^{1/2} \pi (RC) \omega_s (NI)^{1/2}} \left[\frac{8L^2}{rd_c^2 (1 - b)} + \frac{1}{b} \right]^{1/2} \quad (56)$$

A parametric study was performed to determine the typical range for $\Delta_{\min}$.

Figures 15-18 present the results of this study. Some of the parameters were kept constant for all the figures:

$$\begin{aligned} RC \omega_s &= 1 \\ r &= 0.4 \\ b &= 0.1 \\ \lambda &= 6328 \text{ \AA} \\ n &= 0.3 \\ e &= 1.6 \times 10^{-19} \text{ cb} \end{aligned}$$

In Figure 15, the effect of the collection lens diameter is shown. Figure 16 presents the effect of amplifier bandwidth throughout a typical range of values (50-200 KHz). Figure 17 illustrates the effect of distance from the piece (typically 1 to 3 m). Figure 18 shows how the number of pulses from the impulse laser (number of separate events) affects the minimum detectable displacement. According to this figure, a minimum detectable displacement of 10-15 pm ($1 \text{ pm} = 10^{-12} \text{ m} = 10^{-2} \text{ \AA}$) is feasible, if the amplifier bandwidth is 50 KHz, the collection lens diameter is 5 cm, the distance from the piece is 1 m, and the number of pulses is 100.

2.3 TEMPERATURE MEASUREMENT

In this section, the details of the temperature measurement will be given. Once the time-of-flight is determined, as described in Sections 2.1 and 2.2, the speed of ultrasound can be calculated.

In general, the speed of the longitudinal waves, C_L , is given as:

$$C_L = \left[\frac{E_Y (1 - \nu)}{\rho (1 + \nu) (1 - 2\nu)} \right]^{1/2} \quad (57)$$

and of the shear waves, C_S :

$$C_S = \left[\frac{E_Y}{2\rho (1 + \nu)} \right]^{1/2} \quad (58)$$

where E_Y is the Young's modulus of the workpiece and ν the Poisson's ratio.

For the surface (Rayleigh) waves, the speed of ultrasound, C_R , is:

$$C_R = K C_S \quad (59)$$

where K is calculated from the following equation:

$$K^6 - 8K^4 + (24 - 16\beta)^2 K^2 + (16\beta^2 - 16) = 0 \quad (60)$$

where:

$$\beta = \frac{1 - 2\nu}{2(1 + \nu)} \quad (61)$$

Figure 15: Minimum Detectable Displacement vs. Detection Laser Power, with Variable Collection Lens Diameter

Figure 16: Minimum Detectable Displacement vs. Detection Laser Power, with Variable Amplifier Bandwidth

Figure 17: Minimum Detectable Displacement vs. Detection Laser Power, with Variable Distance from the Piece

Figure 18: Minimum Detectable Displacement vs. Detection Laser Power, with Variable Number of Pulses

For steel, these equations yield:

$$C_R = 0.9258 C_S \quad (62)$$

A good empirical formula also exists for the speed of Rayleigh waves, given as:

$$C_R = \frac{0.87 + 1.12\nu}{1 + \nu} C_S \quad (63)$$

For steel, this yields

$$C_R = 0.9262 C_S \quad (64)$$

very close to the theoretical prediction above.

In all these equations, the speed of sound is a function of the Young's modulus E_y , density ρ , and Poisson's ratio ν . However, E_y and ρ are functions of temperature as shown in Figure 19. The Poisson's ratio is more or less constant. Therefore, changes in the temperature of the workpiece will be reflected as changes in sound speed through the variations of E_y and ρ . A calibration of sound speed versus temperature can provide a lookup table to calculate the temperature from the measurement of sound speed.

Figure 19: Material Properties as Functions of Temperature for Steel (from Ref. 72)

3.0 MEASUREMENT SCHEMES TO ACCOUNT FOR THICKNESS CHANGES

The thickness of the workpiece is quite important, since it is directly used to infer the speed of ultrasound from the time-of-flight measurement. During the heating process, the workpiece expands in all dimensions and hence its thickness changes. In the following, we describe how we plan to deal with this problem. Two major schemes can be distinguished. Both will be discussed in connection with their application only to strips and plates of simple geometry.

In the first scheme, the thickness of the cold piece is not known in advance. Therefore, the WPTA will first focus on the cold piece. The time-of-flight for the longitudinal and shear waves is given by Eqs. (65) and (66) below:

$$t_L = h F(\nu) (\rho/E)^{1/2} \quad (65)$$

$$t_S = h P(\nu) (\rho/E)^{1/2} \quad (66)$$

Similarly, the time-of-flight for the surface (Rayleigh) waves is given by Eq. (67):

$$t_R = x R(\nu) (\rho/E)^{1/2} \quad (67)$$

where, ρ the density, E the Young's modulus, h the thickness of the piece, x the known distance between the impulse and detection beams (see Figure 1 for details), and $F(\nu)$, $P(\nu)$, $R(\nu)$ known functions of the Poisson's ratio, ν . The left hand side of Eqs. (65) to (67) is measured. If we assume that the mechanical properties of the material in the cold workpiece are uniform, then Eqs. (65) and (67) yield Eq. (68), while Eqs. (66) and (67) give Eq. (69):

$$\frac{t_L}{t_R} = \frac{h}{x} \frac{F(v)}{R(v)} \quad (68)$$

$$\frac{t_S}{t_R} = \frac{h}{x} \frac{P(v)}{R(v)} \quad (69)$$

which in turn give Eqs. (70) and (71), respectively, for the unknown thickness, h:

$$h = x \frac{t_L}{t_R} \frac{R(v)}{F(v)} \quad (70)$$

$$h = x \frac{t_S}{t_R} \frac{R(v)}{P(v)} \quad (71)$$

Ideally, these two equations should give the same value for the thickness. If they don't, an average of these values is probably the best approach. It should be pointed out that both impulse and detection beams are perpendicular to the surface of the workpiece. If they are inclined, then a simple geometry calculation can take into account the path changes. The Poisson's ratio that appears in Eqs. (70) and (71) is a well known property of every material and remains more or less constant for a very wide range of temperatures.

This technique cannot be applied in the case of a hot workpiece, because the parameters in Eqs. (65) to (67) change. The surface waves do not penetrate into the solid for more than a few hundred microns, while the longitudinal and shear waves propagate through the bulk of the piece. Therefore, the density and Young's modulus that appear in Eqs. (65) to (67) are different, since the temperature of the surface layer is not necessarily equal to that of the bulk. Additional information is needed in order to obtain equations like (70) and (71).

In the second scheme, the thickness of the workpiece is not needed, but instead a calibration with a similar specimen must be available. In the case of a solid, the density change due to temperature is primarily due to linear expansion in all three dimensions. We are going to present the equations for the shear waves only, but the same arguments can apply to the longitudinal ones. Keep in mind that in this case the surface waves are not being used as explained in the previous paragraph. Equation (66) can be modified as:

$$t_S = P(\nu) (m/E)^{1/2} (h/lw)^{1/2} \quad (72)$$

where m is the mass of the piece, and l, w , are its length and width respectively. When the piece is heated, Eq. (72) becomes:

$$t'_S = P(\nu) (m/E')^{1/2} (h'/l'w')^{1/2} \quad (73)$$

where the primed quantities indicate the new value at a higher temperature. Notice that the mass, m , and the Poisson's ratio, ν , remained constant. If we take the ratio of Eqs. (72) and (73) and include the fact that all the linear dimensions expand by a factor of $(1 + \alpha \Delta T)$, where α the linear coefficient of expansion and ΔT the temperature change, then we obtain:

$$\frac{t'_S}{t_S} = (E/E')^{1/2} (1 + \alpha \Delta T)^{-1/2} \quad (74)$$

The only unknown quantity in Eq. (74) is the ratio E/E' which will be given by the calibration procedure. In particular, a similar procedure like the one leading to Eq. (74) will be followed for the calibration and the ratio E/E' will be calculated from:

$$\frac{E}{E'} = (1 + \alpha \Delta T) (t'_S/t_S)_{cal}^2 \quad (75)$$

The right hand side of Eq. (75) is known for the temperature range covered in the calibration. Therefore, substituting the ratio E/E' into Eq. (74), we can calculate the temperature level, since the left hand side of Eq. (74) is directly measured.

Since two measurements are needed (cold and hot piece), a set of mirrors might be necessary to focus the beams on the cold end of the furnace and then divert them to the hot interior. If the same point is being sampled in both measurements, then the sheet does not have to be uniform in the other two dimensions, otherwise such a uniformity is a necessary assumption.

Finally, a very simple approach to this problem should also be mentioned. If the thickness of the cold strip is known within certain dimensional uncertainties (small in general), then the change of thickness due to the heating process can be included as a simple additional uncertainty in the measurement of bulk temperature. In general the uncertainty in the measurement of the velocity of ultrasound, U_c , can be described as a function of the uncertainties in thickness, U_h , and time-of-flight, U_t , as:

$$U_c = \left\{ \left[\frac{\partial c}{\partial h} U_h \right]^2 + \left[\frac{\partial c}{\partial t} U_t \right]^2 \right\}^{1/2} \quad (76)$$

In order to estimate the error contribution from thickness only, we assume $U_t = 0$ in Eq. (76) and hence

$$U_c = \frac{\partial c}{\partial h} U_h = \frac{1}{t} U_h \quad (77)$$

The speed of ultrasound can be expressed as a function of temperature, or if we invert the function we can have:

$$T = f(c) \quad (78)$$

Assuming that the only contribution to the temperature uncertainty, U_T , is from the uncertainty in the measurement of the speed of ultrasound, U_c , then we have:

$$U_T = \frac{\partial f}{\partial c} U_c \quad (79)$$

or using Eq. (77):

$$U_T = \left(\frac{\partial f}{\partial c} \right) \frac{1}{t} U_h \quad (80)$$

If α is the linear coefficient of expansion, then Eq. (80) becomes:

$$U_T = \left(\frac{\partial f}{\partial c} \right) \frac{1}{t} \alpha (\Delta T) h \quad (81)$$

where ΔT is the temperature change and h the initial workpiece thickness before thermal expansion. Equation (81) can also be expressed as:

$$\frac{U_T}{\Delta T} = \left(\frac{\partial f}{\partial c} \right) c \alpha \times 100 \quad (82)$$

where c is the speed of ultrasound before expansion and the right-hand side is expressed in percentage. Using values from Ref. 54, we have:

$$\frac{\partial f}{\partial c} \approx 0.45^\circ\text{C}/\text{m}/\text{sec}$$

$$c \approx 2794 \text{ m/sec}$$

$$\alpha \approx 14.8 \times 10^{-6}/^\circ\text{C}$$

and hence Eq. (82) gives an error of 1.86 percent in the measurement of temperature. For $\Delta T = 100^\circ\text{C}$, this can be translated into a $\pm 1.86^\circ\text{C}$ uncertainty. If the uncertainties due to other error sources are higher than this, then it might be more efficient to avoid using any of the previously described schemes and simply accept the uncertainty associated with the thickness change.

In conclusion, we believe that the thickness change issue, can be effectively addressed. All the described schemes have their merits, and they should be chosen according to the specific application and ease of implementation.

4.0 SURFACE TEMPERATURE MEASUREMENTS

The generation of surface (Rayleigh) waves was described in Sections 1.3 and 2.3. One of the most important features of these waves is that they travel only through a thin layer near the surface of the workpiece. Figure 20 presents the amplitudes of the stresses and displacements associated with Rayleigh surface waves in steel. It can be noticed that for $z/\lambda = 1$ (where λ is the wavelength of the vibrations), all the amplitudes are almost zero. Typical depth of penetration ($z/\lambda \approx 1$) for these waves is a few thousandths of an inch. This property of the Rayleigh waves can be used to measure surface temperature, following a procedure similar to those of Section 2.3. For example, the speed of Rayleigh ultrasound waves C_R is given by Eq. (62) as a function of E_y and ρ , which in this case are the properties of the surface layer of the workpiece.

In addition to that, Rayleigh waves exhibit one more desirable property. Since they do not penetrate into the depth of the solid, their amplitude decays with distance as $1/\sqrt{r}$ (where r is the distance from the source) due to divergence of the wave beam emitted by the source. This decay is like that of cylindrical waves, i.e., it occurs more slowly than in the case of bulk (longitudinal and shear) waves, where the analogous decay law is $1/r$. This is precisely why Rayleigh waves are the principal type of waves recorded in earthquakes. Seismographic records of the waves observed some distance away from an earthquake show three separate groups of waves. The first to arrive are waves in which the vibrations are predominantly longitudinal, these being longitudinal waves which have the highest

Figure 20: Amplitudes of Stresses and Displacements for Rayleigh Surface Waves in Steel (from Ref. 17)

propagation velocity. Next come the shear waves, in which the motion is found to be mainly transverse, and the third group is of surface waves whose amplitude is large compared with that of the other two.

All the above lead to the conclusion that both surface and bulk temperatures can be measured with the WPTA, leading to a better estimate of the thermal gradients in the workpiece.

5.0 TECHNICAL FEASIBILITY AND POTENTIAL SYSTEM PERFORMANCE

In this section, a conceptual design of the WPTA is presented. The components of the system are identified and the model described in Section 2.0 is used to determine the feasibility and the potential performance of the system.

5.1 CONCEPTUAL DESIGN

A schematic illustration of the WPTA was given in Figure 1. This is a single-sided version of the system, which means that both impulse and detection lasers are mounted on the same side of the workpiece. However, in some cases (like thick pieces of steel, thickness more than 6 to 10"), the ultrasound attenuation is too strong. Therefore, in these cases we anticipate using an alternative configuration, where the impulse and the detection laser are on opposite sides of the workpiece. In this case, the waves will be detected when they arrive at the epicenter of the point of impulse.

One of the key components of the WPTA is the "Optical Processing Unit," which is shown in detail in Figure 21. This is a simplified version of the system shown in Figure 14, which was used to develop the analytical model for the polarizing interferometer.

5.2 COMPONENT IDENTIFICATION

The most expensive component of the WPTA is the impulse laser. For the applications considered, a pulsed dye laser (coax flash) with the following specifications would be more than adequate:

- o Wavelength Range: 335-850 nm
- o Pulse Energy: 150 mJ
- o Pulse Length: 250 ns
- o Pulse Rate: 10 pps
- o Beam Diameter: 5 mm

Figure 21: Schematic Drawing of the Optical Processing Unit

For the detection laser, according to the results of the model in Section 2.2, a continuous wave He-Ne with 1 mW power would be acceptable. Both lasers are commercially available and are produced by several manufacturers, like Candela, Phase-R, Lamda Physik, etc.

The collection lens in Figure 1 should be 5-10 cm in diameter and the distance from the piece can be 1-3 m or even more, depending on the focusing requirements of the impulse laser beam.

5.3 PERFORMANCE EVALUATION

A number of applications were considered in order to determine the feasibility and potential performance of the WPTA. In particular, steel and aluminum plates and strips of variable thickness (0.030" to 6") were input to the WPTA model. The results are presented in Figure 22, where the y-axis is logarithmic. It is clear that in all cases the WPTA with the components given in Section 5.2 generate signals much (at least one order of magnitude) stronger than the minimum detectable displacement predicted by the polarizing interferometer model. Therefore, we conclude that the use of the WPTA to measure bulk and surface temperature is feasible and the system has satisfactory performance.

5.4 UNCERTAINTY ANALYSIS

The uncertainty in the measurement of temperature is a strong function of the application in question. Thick workpieces lead to lower uncertainties than thin ones, since the time-of-flight in the latter is shorter and hence the percentage error higher. For a typical 2" thick steel, assuming an averaging procedure over 100 pulses, the speed of sound can be determined within ± 2 m/sec, which is equivalent to $\pm 1.5^\circ\text{F}$ at 1000°F . This calculation assumes that the change in thickness of the workpiece during heating is known. A linear coefficient of expansion (not a strong function of temperature) should be used to eliminate this problem.

Figure 22: Workpiece Temperature Analyzer Performance Evaluation

An issue related to the calibration of the WPTA was also raised during this Phase I of the program. Lack of available data prevented us from reaching conclusive evidence of possible calibration uncertainties.

Therefore, we plan to address this issue with high priority in Phase II.

5.5 COMPONENTS COST ESTIMATE

A number of vendors were contacted in order to determine availability and cost of the WPTA components. The following table gives an estimate of the components cost. All of them are commercially available, off-the-shelf items.

<u>Component</u>	<u>Price</u>
Impulse Laser	\$15,000
Detection Laser	500
Data Processor	1,000
Lenses, Photodiodes, Bridges, etc.	1,000
Hardware Mounting, Electrical Connections, etc.	<u>1,000</u>
	\$18,500

It should be pointed out that this estimate represents components cost only and does not include furnace mountings and other expenses associated with the preparation of a final and complete product.

6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONCLUSIONS

The following conclusions can be made:

- o The semi-empirical model for the WPTA provides reliable predictions for ultrasound displacement.
- o Minimum detectable displacement as low as 15 pm.
- o Concept of bulk and surface temperature measurement is quite feasible.
- o A preliminary configuration for the WPTA has been developed and its potential performance has been assessed.
- o All applications selected are feasible with a wide margin.
- o Vendors have been contacted for price and availability of components.
- o All components are commercially available items with a total cost of less than \$20,000.
- o WPTA concept appears to be feasible and very promising.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Our future plans include assembly of a prototype analyzer and laboratory scale tests, aimed at demonstration of the concept and proof of predicted performance. A number of issues and possibilities for expanded use raised during Phase I will also be addressed.

Issues:

- o Repeatability and reliability of calibration.
- o Maximum workpiece thickness as determined by ultrasound attenuation (including temperature effect).

Other Uses:

- o Determination of internal workpiece condition (grain structure) after and/or during heat treatment.
- o Detection of carburization depth.
- o Ultrasonic tomography for internal temperature distribution.

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