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**ADVANCED TEMPERATURE MEASUREMENT SYSTEM
FOR THE U.S. GLASS INDUSTRY MELT TANKS AND
DELIVERY SYSTEM**

Phase 1 Report

April 1997

Work Performed Under Contract No. FC07-95ID13367

**For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC**

**By
AccuTru International Corporation
Kingwood, TX**

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817 Russell Palmer Road
Kingwood, TX 77339-1644**

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1.0 Executive Summary

The U.S. Department of Energy has identified seven major industry groups as high energy consuming industries. The DOE has decided to assist these industries in reducing their energy consumption, thereby reducing pollution and increasing efficiencies that will allow for an improved competitive position in the world market. The U.S. glass industry is one of the seven industries consuming approximately 3.0×10^{11} BTUs of energy annually. One area identified by the industry and DOE where improvement will make a substantial contribution to the DOE's objectives is improved temperature measurement in the melting and delivery systems of the glass making process.

The Department of Energy became aware of conversations between AccuTru and Corning Incorporated concerning solutions to temperature measurement problems in the melting and forehearth areas and granted an award to AccuTru for research, development and demonstration of an advanced temperature sensor for the entire glass industry.

The initial statement of work was prepared using the best data AccuTru could secure from the DOE, available public literature, and limited access to the industry. As the project proceeded, a better understanding of the glass industry was obtained, regarding their real needs, wants, and future desires. AccuTru conducted a "Needs Analysis" survey among employees of the industry participants (Corning Incorporated, Owens-Corning, Libbey-Owens-Ford, and Anchor Glass Container) and developed a very close working relationship with plant furnace operators, systems engineers, technicians, and managers. The information gained as the project proceeded made it obvious that, in order to make a substantial impact on the glass industry's temperature measurement problems, more than an improved glass sensor was needed. The single greatest problem, according to the survey, and confirmed in follow-up discussions, is the inability to identify in situ decalibration (drift). Any Advanced Sensor that is more rugged and reliable still has the uncertainty of drift and, therefore, is only marginally more useful than what is being used by the industry today.

For this project to be considered a success by the glass industry, and to meet the original desires of DOE, the project required the development of an advanced sensor system that includes:

1. A more rugged, reliable sensor,
2. High quality inner protective sheath,
3. Improved data transmission that is hardened to the environment of the melt tank surroundings,
4. A system that reduces or eliminates in situ decalibration (drift),
5. An improved outer protection sheath.

During Phase I of the project, AccuTru pursued the advanced sensor development identified in the original "Statement of Objectives" and, at the same time, shifted resources to address the other problems identified by industry. All or most of these problems needed to be solved in order to make a major step forward in temperature measurement for the glass industry. The project is well on the way to meeting four of the five industry requirements as evidenced by this Phase I report. Three of the four provide breakthrough technologies for the glass industry. AccuTru has been updating our DOE Technical Advisor and our industry participants on the direction and progress of the product on a monthly basis.

Through Phase I, testing has determined the feasibility and preliminary performance characteristics that meet or exceed the project criteria. These results demonstrate that four of the five problem areas have been resolved. With the help of the University of Missouri-Rolla's materials group, it is possible that the project may be able to address the fifth. The project has demonstrated in the laboratory that the major identified problem, the inability to identify in-situ decalibration (drift) has been solved. Successful Beta testing of this solution alone, would be considered by the industry as a major breakthrough.

To meet the industry requirement for a major step forward in melt tank temperature measurement technology, it is recommended that an expansion of the "Statement of Objectives" Phase II, and a modification to the "Federal Assistance Budget Information" be considered.

2.0 INTRODUCTION AND OBJECTIVES

2.1 History of Project

AccuTru is a company rich in research, development and commercialization talents in temperature measurement components and systems, especially in very hot, hostile environments. The Department of Energy became aware of conversations AccuTru was having with Corning, Incorporated concerning temperature measurement problems in the melting and forehearth areas of the melting furnaces. In December, 1994, AccuTru was invited to Washington to discuss this project with the DOE. The DOE stated that they had identified temperature measurement in the melt tanks and forehearth portions of the glass making process as a problem that may be common to all four segments of the glass industry. DOE staff members noted that they had funded a proposed optical solution to the forehearth problem but the project was not successful. AccuTru reviewed its staff's accomplishments in similar situations and its talents in solving high temperature, hostile environment problems with DOE. The Department of Energy stated that they "...want(ed) a major advancement in temperature measurement that is the result of cooperative efforts of the glass industry, Office of Industrial Technology, and AccuTru."

After AccuTru was deemed by the DOE as having unique enabling technology to address the kinds of problems faced by the glass industry, and after AccuTru had received tentative commitments of involvement by a major company in each of the four segments of the glass industry, AccuTru was granted a fixed sum, two phase award. The project was launched in July of 1995, and is scheduled for completion in November of 1996.

2.2 Glass Manufacturing Temperature Needs

The manufacture of glass involves the high temperature conversion of raw materials into a homogeneous melt for fabrication into useful articles. The U.S. glass industry sells over \$10.6 billion (20.8 million tons) of glass products per year. The industry has approximately 500 melting furnaces located in various parts of the United States. It is a high energy consuming industry, using approximately 3.0×10^{11} BTUs of energy each year.

Of the total manufacturing costs of the U.S. glass industry, about 25% is for energy (natural gas and electricity). As much as 70% of the energy used is consumed in the melting and refining processes. Maintaining correct processing temperature is critical to product quality and energy efficiency. The very hot, corrosive nature of the molten glass and gasses cause rapid degradation (drifting of thermocouple signals), short life, and unreliable readings (optical pyrometry) using existing measurement technology.

Currently the glass melt and refining process is controlled by a combination of operator experience, interpretation of various temperature readings and down line quality reports. Over correcting in the melter results in energy wasted while under-correcting results in diminished product quality (increase in the scrap rate).

2.3 Benefits of Enhanced Temperature Measurement Technology in the Melt Tanks and Forehearth to the Glass Industry.

There are several areas of potential benefit to the glass industry through enhanced temperature measurement. They are: 1) Energy savings, 2) product quality improvement (reduced scrap rates), and 3) increased furnace life. AccuTru's research has not yet been able to quantify the economic value of the advanced temperature measurement system. There is a consensus regarding the three areas of major improvement. The magnitude of the improvement may vary. **The following examples are for illustrative purposes only and are not intended to quantify savings.** This can only be accomplished after the system is in service and creditable data has been collected and analyzed.

- 1) Maintaining the correct temperature in the delivery system is very critical to the final product. Any deviation from the temperature set point requires corrective action in the melter and refiner. Some of the corrective actions require large volumes of energy (natural gas and electricity). If furnace operators had a reliable temperature measurement system in the melter and refiner regions of the glass tank, the large swings in temperature could be substantially reduced.

It has been estimated that a ton of molten glass exiting the forehearth has a direct cost of \$6 to \$7 in raw materials and \$27 to \$35 in energy costs. Selecting the averages of these numbers for illustrative purposes, one could assume that a ton of molten glass costs the manufacturer \$37.50 per ton. If the project's temperature measurement system **could reduce energy consumed by 20%**, or \$6.50 per ton, the industry could realize an **annual energy saving of \$135,000,000.**

- 2) It is not uncommon to find a 10% rejection rate in many of the glass plants. Most of the causes of rejections can be traced back to problems in the melting and/or refining process, some of which, are temperature related. Assuming that better control of temperature resulted in a **2% reduction in rejection rate**, the industry could enjoy a **2% increase in sales revenue, or \$222,380,000 per year.**
- 3) Fluctuation of temperature in the melter and refiner, especially with the use of electrical shock, accelerates degradation of refractories in the furnace walls, throats, checkers, and crowns. A reduction in this fluctuation could extend furnace life. Assuming an average furnace life of eight years, and a replacement cost of \$8,000,000, a U.S. glass furnace population of 500 furnaces, and that a

reduction in temperature fluctuation would **increase furnace life by six months**, the industry could realize a **savings of \$29,440,000**.

2.4 Inter-Industry Applications and Benefits

The advanced temperature measurement system and its components have applications in many other industries. High energy consuming industries that require very high temperatures and hostile environments in their manufacturing processes are candidates for this advanced temperature measurement system. Additional industries that require accurate high temperature measurements in their processes are also candidates for the system, especially the "Self-Verifying" features.

There are several major industrial groups that use very high temperatures in their manufacturing processes and have similar challenges as the glass industry

They are:

- Steel
- Aluminum
- Metal Casting
- Cement
- Heat Treating

Industries that do not experience extremely high temperatures, but do require a very high degree of accuracy are also candidates for the "Self-Verifying" feature of the system.

Some examples are:

- Chemical
- Refining
- Energy (Nuclear and Ground Turbines)
- Chemical Waste Incineration

2.5 Market Potential and Commercialization

The U.S. industrial temperature measurement market is estimated to be in excess of \$1.1 billion dollars and is growing at a rate of 6.7% to 7.7% per year. It is also estimated that 46.7% of the contact sensors (60% of the total sensor market) is used in high or very high temperature applications. As the demands for higher quality, and pressures of global competition drive operating limits in high temperature operations to higher and higher levels, the demand for more accurate temperature measurement

will grow at a rapid rate. The glass industry is an excellent example of this market dynamic.

According to a major refractory manufacturer, there are 500 +/- ten glass furnaces in the United States. Each furnace and its delivery systems (1 to 3 per furnace) may have from 50 to 250 temperature sensors, with life expectancies of from 3 months to 3 years.

Commercialization of the system will be addressed by AccuTru's Manufacturing and Marketing Department.

2.6 Project Objectives

This is a two phase project with the majority of the research and development in Phase I and the Beta testing in Phase II. The objectives as stated in the award agreement were broken into 11 specific tasks.

The objectives as stated in the award agreement are as follows:

"The scope of this research project is to develop and test a temperature sensor for application in the glass industry. The sensor is intended to be applicable to as many as possible of the four glass sectors (container, flat, fiberglass, and specialty). A multi-phase effort is being pursued with a decision point to determine advisability of continuance. During Phase I the needs of the temperature measurement sensors will be established, and laboratory tests will be performed on a prototype sensor. Laboratory test results will be compared to project goals and any deviations defined. During Phase II, modifications will be made to the prototype to correct any deficiencies identified during Phase I. A commercial sensor will then be fabricated and a field test will be conducted at host site(s) to verify that sensor performance satisfies all specifications and requirements. Market and economic estimates will be used to define the potential for commercial viability.

2.7 Industry Involvement

AccuTru has been very fortunate to have the cooperation of four outstanding glass companies in this project. The companies are: Anchor Glass Container, Corning Incorporated, Libbey-Owens-Ford, and Owens-Corning Fiberglass. These companies entered into confidentiality agreements and have participated in surveys, technical assistance, providing technical information, use of research facilities, provided samples for research, and use of plant facilities and personnel. AccuTru requested two companies to provide furnaces for new sheath material testing. Both companies accommodated AccuTru's request. All of the companies have volunteered to conduct beta testing of the sensor system at their sites.

2.8 Other Contributors and Consultants

The following are others who have provided very valuable contributions to the project:

Dr. Brent Adams, Material Sciences, Carnegie-Mellon University, Pittsburgh, PA.

Mr. C. Tom Brannon, Microsignal Processing, Brannon Electronics, Inc., Houston, TX

Dr. Daniel L. Callahan, Materials Science, Rice University, Houston, TX

Mr. Roger Holman, Temperature Instrumentation (Glass), Holman & Associates, Painted Post, NY

Mr. Joe Keller, Technical Monitor, LITCO/DOE, Idaho Falls, ID

Mr. William J. Koch, Ceramist, Liberty, MO

Mr. Kelley Meares, Ceramist, President, Ozark Technical Ceramics, Webb City, MO

Scientific Microsystems, Inc., Digital Signal Processing/Software, Tomball, TX

Dr. Jeff D. Smith, Ceramics, University of Missouri-Rolla, Rolla, MO

Mr. Curtis Wilkins, Temperature Instrumentation, LITCO, Idaho Falls, ID

3.0 NEEDS ANALYSIS RESEARCH

A Marketing Perspective

3.1 Objectives

The first step of any of AccuTru's projects of this nature is to develop a comprehensive understanding of the real needs, wants, and desires of the potential customer (end user) at the present, and in the foreseeable future. It is important that this information come from all levels in the organization, starting with the operators of the melt furnaces. AccuTru is interested in information regarding the advantages and disadvantages, both real and perceived, of the existing systems. Ideas for improvement and even speculation as to why the existing systems are inadequate provide important data points. Another objective of this exercise was to open lines of communications at all levels within the organization. AccuTru determined that the first step in this project was to conduct in-depth, confidential, personal and written surveys.

3.2 On-site Interviews

AccuTru staff visited all four glass companies and interviewed furnace operators, plant managers, furnace and instrument research scientists and technicians, and management personnel. Not only did this effort provide valuable information for design purposes, but resulted in subsequent data exchanges and provided opportunities for AccuTru to test out additional concepts with this information base.

3.3 Written Surveys

AccuTru, with the assistance of all four industry participants, and with the assistance of Roger Holman of Holman & Associates, constructed two written questionnaires. One questionnaire was comprehensive, highly technical, and was directed to research and technical personnel. The second was shorter, not as technical, and was directed at plant personnel. There was a very favorable 36% response rate with most of the responses falling into narrow distributions. Some of the plant personnel also responded with phone calls, providing additional data. These calls however, were not counted in the responses, although they did contribute to the validation of the data collected on the surveys. AccuTru staff analyzed the data by company and prepared a summary report for the research and development staff. At the completion of the survey process, a thank you letter and a summary of the contributor's company data was sent to each respondent. The letter thanked them for the information provided, asked them to review the conclusions reached in the survey, and asked the respondents to notify AccuTru if they disagreed with the summary or wished to provide additional information.

3.4 Conclusions

The data from the interviews and questionnaires provided significant information. First, the major problem defined is undetectable drift of the sensor signals, described as repeatability, absolute accuracy, and lack of drift, and the second most prevalent problem was sensor life. But most importantly, the research indicated that the sensor, the subject of the DOE award, was only part of a much larger problem. It also revealed that if the larger problem was not addressed, it would be difficult to develop a solution that would be viewed by the industry as a "major step forward" in temperature measurement.

The major problem, as defined by the customers has five sub-parts.

1. Degeneration, failure, and loss of insulation resistance of the insulators that house the thermal elements.
2. The inner protective sheath is seen as a major problem, providing little protection of the thermal elements once the integrity of the outer sheath protection was breached.
3. In some parts of the glass melt tanks, currently available outer protection sheaths (or thimbles) will last three months or less. This is perceived as a major problem and requires additional research beyond the scope of this project.
4. Some problems are caused by harsh environments (heat, oil vapors, moisture, and electrical noise) around the furnace that penetrates data transmission systems and destroys the quality of signals.
5. Current temperature measurement electronics are unable to evaluate sensor performance while it is in operation.

All these sub-problems need to be addressed in order to meet the specifications reflected in the survey. Plant operators requested the following specifications:

- Repeatability $\pm 0.1\%$
- Accuracy $\pm 0.25\%$
- Operating Range Room temperature to 1845°C
- Drift/Time $<0.15\%$ a year
- Life 8-10 years

4.0 FOCUS

This is an interim report describing the status of development and implementation into the U.S. glass industry of an advanced temperature monitoring system for the primary melt tank. Successful implementation of the new system offers high payback to all four segments of the U.S. glass industry in the areas of improved fuel efficiencies, reduced operation and maintenance costs, reduction in rate of product defects, or scrap rate, improved product quality, extension of plant life, and advancements in new product development.

The advanced temperature monitoring system offers significantly improved accuracy's, reduced drift, increased reproducibility, increased reliability, and increased upper temperature range over sensors now in use. Accurate and reliable measurement of temperature in the primary melt tank has been identified by all four segments of the glass industry as the single most important measurement parameter in the overall glass manufacturing process. All other "down stream" processing is strongly affected by the processing that takes place in the primary melt tank. The accurate and reproducible monitoring of melt tank temperatures, both in the crown and melt regions, offers significant benefits to other important downstream processes in a modern glass plant.

The advanced temperature monitoring system also offers important smart system capabilities, and is termed a self-verifying temperature system (SVS). The system will confirm to the plant operator when the temperature signal output remains within calibration, or specified limits of error, and may be considered a valid temperature. This is designated by the system as a "green light" condition.

In the event of sensor decalibration, the SVS system notifies the operator that decalibration has taken place, and estimates the magnitude and identifies the polarity of the decalibration. This information allows the plant operator to correct for the drift. This is designated by the system as a yellow light condition. A "red light" condition is designated by the system when it is determined that the signal readout is invalid, or not usable. This allows the plant operator to reference other temperature monitoring systems in the melt tank that remain in a "green light" condition so that the tank can continue to operate efficiently.

The SVS capability is particularly important to segments of the glass industry that run the melt tank "hot", sometimes within 10 C of the wall material melting temperature.

The SVS sensor condition and the validity of the temperature readout is determined by processing diagnostic data that is generated within the sensor. This data is transmitted in the form of a "data matrix" to the remote signal conditioning electronics, and then to the signal processing electronics. The data matrix that is generated is continuously "on-line" processed to provide an assessment of the validity of the temperature readout and the condition of the sensor.

The primary focus of this report is on the design of the SVS temperature monitoring system, the status of fabrication, and the status of testing. Where information relating to technical basis or development approach is helpful to understanding of the design, a brief discussion of these topics is also included in the report.

Careful laboratory and field evaluation tests are necessary to verify that the system is sufficiently hardened to provide reliable service under glass plant operating conditions. This is particularly important for the remote signal conditioning component of the system, which cannot always be placed in a control room environment, and must be placed in the vicinity of the melt tank itself. Field testing is also particularly important for the melt tank sensor.

5.0 INDUSTRY COOPERATION

A Technical Perspective

An important objective for the advanced temperature measurement system is that it provide the maximum possible benefit to the U.S. glass industry.

5.1 On-site Visits

To accomplish this, solid cooperation from all four segments of the glass industry was considered critical. As a first step toward obtaining this cooperation, visits were made to major U.S. glass companies, one from each of the primary segments of the industry. The specific objectives of these visits included:

- 1) To define the maximum benefits possible to the four major segments of the industry.
  - A. Container Glass
  - B. Flat Glass
  - C. Specialty Glass
  - D. Fiber Glass
- 2) To determine the specific sensor application benefit the most significant problem, or difficulty that the glass manufacturing plant faces today in temperature measurement. There exist many applications for critical measurement of temperature in the glass manufacturing process, including the primary tank, forehearth, and gob processes.
- 3) Determination of the specific requirements and specifications for the new sensor system that is selected.
- 4) Determine the optimum means of interfacing to existing plant measurement and control systems that are presently in place.
- 5) Establishment of specific requirements for hardening the new sensor system so that reliable operation under actual glass plant manufacturing conditions can be assured.
- 6) Identification of the primary deficiencies in existing glass plant temperature monitoring systems.

One of the most important objectives for the advanced temperature measurement system was the adequate hardening for field service conditions that exist in glass manufacturing facilities. It was important to establish up-front, the actual field conditions and requirements that would be imposed on the system. These requirements pertained to the 1) Sensor, 2) Field Measurement Electronics, 3) Signal Processing, 4) Display; and 5) Field Connections and Lead Cables.

An important aspect of development was to anticipate field requirements in the design of equipment used for laboratory tests to ensure a smooth transition between laboratory environments and operational field conditions. Otherwise, a prototype system might function well under laboratory conditions, but fail to meet important requirements under actual glass plant field service stresses and conditions.

In the visits to each of the four glass companies participating in the development effort, there was a comprehensive inspection of the manufacturing facilities. During the visits, engineering and plant operations contacts were established within each company so that follow-on design efforts could be coordinated with plant personnel knowledgeable about operational requirements and conditions.

Another important objective of the on-site visits was to obtain the cooperation and support of plant management, since time and effort of plant personnel would be required for the project, especially in the design and field evaluation phases of the project.

The visits to the plants were considered very successful. Contacts with management, engineering, and operations were made to support follow-on development efforts.

A visit was also made to a fifth major supplier of glass both in the U.S. and international markets. This company also indicated strong support and interest in participating in the temperature measurement development project. To this point in the project, they have not been included for logistical reasons. Also, their segment of the glass industry is well represented by one of the four original partners. This company currently represents a back-up position.

5.2 GLASS INDUSTRY SURVEYS

After the initial visits, a survey form was prepared, asking for detailed requirements for the advanced temperature system. The form requested specific sensor design data, system interface requirements, and plant service condition information from several levels of glass manufacturing personnel. The form was mailed to all four of the participating companies, to both engineering and operations levels. The completed forms were then returned to AccuTru project personnel for tabulation and analysis. This information formed the starting requirements and specifications for the start of sensor development.

5.3 DIALOG

Numerous follow-on telephone dialogs were then conducted to clarify points of possible ambiguity in the design requirements for the new temperature monitoring system. These conversations were conducted at both engineering levels and operation levels. Additional visits to selected plant facilities were then made to reach compromise and consensus on critical points of design. The objective was to reach consensus with plant personnel on all

important design requirements for the new system. In a recent on-site visit, AccuTru's electrical engineers, responsible for the design and fabrication of the sensor electronics, conducted a comprehensive review of the facility that has been designated as having the most difficult field service conditions.

5.4 ADDITIONAL INFORMATION

In addition to the first-hand information obtained from visits and dialogues with glass plant personnel, information from other sources knowledgeable in glass temperature measurement was obtained. The primary resources included published research literature, discussions with temperature instrument and component suppliers to the glass industry, and dialogues with university and government laboratory personnel considered to be on the leading edge in the areas being studied, or associated areas. Where appropriate, on-going communication, cooperation and support was established.

5.5 SUMMARY

Following the above described efforts, a compilation of requirements for the advanced temperature measurement system were developed. These requirements addressed the following important objectives to the maximum extent possible:

- 1) That the system address as many of the primary needs and desires of all four segments of the U.S. glass industry as possible. Several of the companies expressed a diversity of desires for improved temperature measurement at various points in the manufacturing process. The final objective was a single sensor system that would respond in an effective manner to the majority of the requests and requirements. A second objective was a system that would allow for relatively minor modifications later on, to satisfy other glass plant needs.
- 2) A system that is relatively straightforward to develop and implement in a practical, cost effective manner, into glass industry field operations. To accomplish this objective, a sensor system was selected that is based on established recent advances in temperature measurement in similar hostile service conditions.
- 3) A system that is straightforward for a glass manufacturing plant to implement. This requirement for easy interfacing with existing plant equipment was an important outcome based on information gathered from the visits to all four segments of the glass industry.
- 4) The system should carry a reasonable price.

6.0 TEMPERATURE SYSTEM REQUIREMENTS

6.1 Primary Melt Tank Application

The measurement system that would provide the greatest benefit to each of the four glass companies participating in the project was identified as an advanced sensor system that would better monitor temperatures in the primary melt tank. Improved measurement temperatures in the melt region, and also in the crown region of primary melt tanks was determined to be by both management and operations personnel as the most critical to glass quality, energy efficiency, and new product development.

A contact temperature sensor that enters directly into the service mediums to be monitored was concluded to be the most effective type of measurement sensor. This type of sensor could directly replace, in a staged product evaluation, the existing thermocouple type sensors that are now presently used to measure primary melt tank temperatures.

The container segment of the glass industry, although it relies primarily on simple, hand-held optical pyrometers to measure primary melt tank temperatures, would also derive significant benefit from a contact sensor that could operate directly within actual crown and melt regions in the primary tank. Contact sensors are not generally used in the container segment of the glass industry because reliable performance cannot be obtained from an in situ sensor. Premature failure of contact sensors within primary melt tanks occurs because of the unusually harsh service conditions that exist within these tanks used in container manufacturing.

The identification of the primary melt tank application satisfied two of the most important objectives of the advanced temperature project:

- 1) This temperature sensor application provides the maximum benefit to all four major segments of the U.S. glass industry. An advanced monitoring system will directly improve product quality, energy efficiency, and the capability to rapidly implement processing for new product types.
- 2) Of temperature sensor applications within a glass manufacturing plant, the accurate measurement of temperature within the primary melt tank was determined to be the most critical measurement of temperature taken in the overall glass manufacturing process.

6.2 A Smart Temperature Monitoring System

The capability to determine the magnitude of drift, or decalibration, in a primary tank temperature monitoring system was determined to provide the principal benefit to the glass industry. This was judged as of even greater and direct benefit than improved reliability or accuracy by most companies.

Such a "Smart Temperature Measurement System" would identify to the plant operator when drift, or temperature sensor decalibration, has occurred. It would identify whether the drift is in a positive or negative direction, and the magnitude of the drift. It would also identify to the operator, alternative sensor components within the temperature measurement system that have not decalibrated, and that can be substituted for the primary sensor that has experienced decalibration. This aspect of an advanced temperature monitoring system was determined to provide the maximum benefit to improved process control in today's U.S. glass manufacturing industry.

6.3 Improved Range, Accuracy, and Repeatability

A temperature sensor that eliminates, or significantly reduces the magnitude of drift, or decalibration, was also determined to provide significant benefit to the U.S. glass industry. Temperature sensors in use today can drift as much as 100 degrees F or more within time periods of within 6 months to a year. The decalibrated sensor condition necessitates the plant operations personnel to artificially compensate for these induced errors in temperature measurement. This practice introduces unavoidable uncertainties into the glass manufacturing control process.

Uncertainties in establishing accurate primary melt tank temperatures directly affect product quality, energy efficiencies, and tank life. The condition and life of wall materials used to construct the primary melt tank is directly affected by the tank operating temperature.

In some fiber glass industry applications, the temperature of actual operation in the primary melt tank is within 10° C of the melting temperature of the wall construction materials. Improved measurement of absolute accuracy in the primary melt tank was determined to offer special critical benefits to this segment of the glass industry.

An advanced temperature measurement system for the primary melt tank that would eliminate sensor drift, or decalibration, would provide immense benefit to the glass industry. A consensus of specific performance parameters requested by the U.S. glass industry included:

- 1) Upper operating range: An improved operating range to 1700° C.

- 2) Improved Accuracy: Better accuracy, especially over the upper operating ranges, to within $\pm 0.5\%$ over the life of the sensor.
- 3) Improved Repeatability: Better capability to return to a previously established temperature setting, especially over the upper operating ranges, to within $\pm 0.1\%$ or better.

6.4 Improved Lifetime

Better sensor lifetimes were determined to be important to the U.S. glass industry. Sensor replacement in primary melt tank applications is especially difficult. Often a failed sensor is left in the melt tank because of the difficulty of replacement. This is especially common in the melt region. It is not uncommon for sensors in use today to fail, or seriously decalibrate, within six months to a year.

A consensus of industry participants is a sensor life expectancy of between five to ten years.

6.5 Ease of Replacement

An important aspect of the new sensor design was determined to be the ease of replacement. When sensors are directly inserted into the melt region, a sensor that can be replaced without disturbing the outer protective sheath was determined to offer high value in the reduction of maintenance costs. The outer protective sheath forms the primary barrier between the sensor and the molten glass. Both maintenance costs and safety issues would strongly benefit from a two-component sensor, where the inner sensor component can be removed and replaced by a new component, without disturbing the outer sheath.

6.6 Other Requirements

Other requirements that were determined to be important to wide industry acceptance are:

- 1) Thermal Shock Resistance: The sensor must be able to withstand fracture stresses imposed by sudden insertion into the primary melt tank interior during sensor replacement.
- 2) Vibration: Immunity to the wide variety of frequency and amplitude vibration spectrums that exist in modern glass manufacturing plants. This requirement is important to both the sensor and first stage signal conditioning electronics. A detailed vibration specification is not available. Field test evaluations will be performed to demonstrate sensor and electronics performance.

- 3) Common Noise Rejection: 600 VAC.
- 4) Electrical Leads: System must accommodate up to 150 foot lengths of lead between the in situ primary tank sensor and the first stage signal conditioning electronics. System must accommodate up to 400 foot lead lengths between signal conditioning electronics and control room signal processing electronics.
- 5) Signal Conditioning Electronics: The electronics package must be contained within a minimum size structure of 5 in. x 5 in. x 5 in. The electronics must be hardened for 70° C maximum operations temperatures. (125°C would offer benefit in some selected applications.)
- 6) Primary tank insertion depth. Up to 10 inches is desirable for some applications. Two inches to six inches is common for most applications.

7.0 BASE DESIGN TECHNOLOGY

7.0 Technical Basis

A large part of the foundation for the design of a temperature measurement system that satisfies the above described requirements and desires of the U.S. glass industry is based on recent accomplishments in advanced temperature sensors for hostile service environments developed by the Hanford Engineering Development Laboratory under Dr. Cannon's leadership with private assistance from Mr. Lunghofer. The advancements in high temperature thermometry were made in response to application needs by the U.S. Department of Energy, the U.S. Nuclear Regulatory Commission, foreign governments (Japan, Germany, France, and Great Britain), and private industry. The majority of the advancements involved thermoelement and resistive sensors although some work in optical sensors was also performed.

The temperature range of the new classes of sensors varied from 1600° C to 2400° C. Almost all applications required the insertion of contact sensors into extremely hostile service conditions, which included molten materials, corrosive materials, including 1800° C steam, and other particularly hostile environments. For most of these applications, first-time, reliable operation was a premium requirement.

The work conducted by Hanford was often performed in association with the Oak Ridge National Laboratory (ORNL) and/or the Idaho National Engineering Laboratory (INEL). Advanced temperature sensors created by the team of Dr. Cannon and Mr. Lunghofer were also developed in association with Battelle Northwest Laboratories (PNL), Lawrence Livermore Laboratory (LLL), Sandia National Laboratories (SNL), and Los Alamos National Laboratories (LANL). For many applications development was coordinated with National Institute for Standards and Testing.

Leading edge development work was also performed on "expert system" temperature measurement systems that determine when a sensor is operating reliably, and when the onset of failure modes, and/or decalibration has occurred.

Development included the establishment of commercial manufacturing for all aspects of the advanced temperature measurement systems. A substantial track record of successful system applications in advanced thermometry was established. For the majority of applications, laboratory evaluation testing was performed to eliminate modes of failure prior to actual installation and service in the intended application. Much of this work was materials oriented, and involved the application of recent advances in materials, manufacturing, and processing technology to accomplish design objectives.

AccuTru International Corporation possesses the base technology for advanced high temperature sensors that was developed at Hanford and the associated laboratories. The design basis for an advanced temperature measurement system that meets or exceeds the present requirements of the U.S. glass industry represents an application, or modification, in many aspects of this base technology. Much of the present effort to develop and manufacture the required measurement system is directed toward effective modification of this pre-existing technology to the glass industry application.

7.2 A Self-Verifying Temperature System

A common failing with temperature measurement systems is decalibration or drift. A temperature sensor may continue to provide a signal output, but the signal may no longer correlated with an accurate measurement of temperature. This may result from aging of the sensor under service condition stresses, or other factors. For most applications, there does not exist a convenient method to verify the accuracy of a temperature sensor readout under in situ service conditions.

In some applications, a plant operator may be capable of estimating the general magnitude of temperature sensor decalibration from other operational parameters. It is not uncommon for a plant operator to make a "best guess" at the suspected level of decalibration. For most applications, temperature sensor decalibration introduces undesirable uncertainties into control processes.

The temperature sensor development work that was referenced above, also pioneered work on smart temperature measurement systems. This advanced type of temperature measurement system accomplishes the following:

- 1) Informs the operator if the temperature readout from the sensor is valid, and remains within limits of error.
- 2) Informs the operator if the temperature readout for the sensor has decalibrated, and estimates of the magnitude and direction of the decalibration.
- 3) Informs the operator when the temperature measurement system has failed.
- 4) Informs the operator at the onset of impairments that are developing within the sensor which, if allowed to continue, will degrade the performance of the temperature sensor. This allows the scheduling of preventative maintenance on a regularly scheduled basis prior to the actual occurrence of the failure.

The basic means the smart sensor utilizes to accomplish the above functions is the use of a diagnostic system which scans the temperature sensor on a regular basis. The system utilizes algorithms which analyze signal patterns and detect irregular patterns

that match previously established modes of failure or impairment that can occur in the temperature sensor.

In addition to diagnostics which scan for modes of impairment, more recent versions of "self-verifying temperature sensors" include an advanced temperature sensor made up from multiple temperature sensor elements. The electronics take a "data matrix" that is considerably more complex than a conventional signal read out from a single sensor, such as a stand-alone thermocouple or RTD. Signal conditioning and data processing algorithms process the data matrix from the sensor to compute a "true temperature", or validated temperature readout.

The sensor being developed for glass industry primary melt tank applications combines both of the above methods to establish a verifiable temperature sensor readout: 1) diagnostics that detect the onset of impairment, or otherwise confirms the integrity of the sensor system, and 2) a composite sensor that provides a data matrix that may be computed into a "true temperature" readout.

8.0 TEMPERATURE SYSTEM DESIGN

8.1 System Requirements

After preliminary development work, a temperature monitoring system was designed to satisfy the requirements provided to AccuTru International Corporation by the four companies representing the four major segments of the glass industry. A temperature monitoring system was designed to meet or exceed most requirements requested by the glass industry.

8.2 Expert System Specifications

The system is design to possess "self-verifying" and diagnostic capability. The system design includes the following expert system capabilities:

- 1) Confirms to the operator when the temperature readout is within specified limits of error, i.e., that the output signal is valid. This is designated as the "Green" condition. The "Green" condition also confirms to the operator that there are no physical impairments detected in the sensor that could lead to decalibration in affect the temperature readout in the future.
- 2) Informs the operator in the event that signal decalibration occurs in the reference sensor, causing the temperature reading to outside the specified limits of error. The reference sensor is recalibrated. This is designated to the operator as "Yellow" condition.
- 3) Informs the operator in the event the onset of physical deterioration is detected within the sensor. This allows the operator to anticipate that in the future, the sensor may decalibrate or fail. This condition is also designated as a "Yellow" condition.
- 4) Informs the operator that the temperature sensor has failed, that the signal output can no longer be considered reliable, and that the degree of decalibration cannot be determined. This is designated to the operator as a "Red" condition.

8.3 Target Specifications

Application: Designed as a contact sensor the primary melt tank.

Designed for direct immersion into both crown and melt region environments.

System Compatibility: Designed to directly interface with existing glass plant instrumentation and control systems.

Replacement: Designed to allow for one-for-one replacement with existing primary tank sensors.

Lifetime: Ten years (any life over six months would be considered an improvement).

Immunity from Vibration: Signal Conditioning System designed for immunity from glass plant vibration.

Thermal Shock Resistance: Designed for direct immersion under in situ primary tank temperature conditions.

Signal Readout: The output signal reads out temperature in either degrees C or degrees F depending on operator selection. At the option of the operator, the signal can be made to provide a 4-20 mv output for ease of compatibility with existing plant I & C systems.

8.4 Mechanical Specifications

Sensor Length: 17 to 34 inches, depending on customer requirements.

Sensor Outside Diameter: 3/8 inch to 1/2 inch, depending on customer requirements.

8.5 Temperature Specifications

Temperature Range: Room temperature to 1800°C.

Accuracy: +/- 0.5%°C over the range to 1800° C.

Repeatability: +/- 0.1%

8.6 Electrical Specifications

Common Mode Rejection: Greater than 600VAC.

Signal Conditioning Electronics: First prototypes temperature resistant to 80°C. Final commercial systems temperature resistant to 125°C.

Sensor Connector: Hardened for glass plant conditions. Compatible with primary tank requirements. Compatible with existing plant connections.

Lead Wires: System design allows for up to 150 ft length of lead wire from the sensor to the signal conditioning electronics and up to 1000 ft length cable from the conditioning electronics to the signal processing electronics.

8.7 Temperature System Design

The advanced temperature measurement system is new to the glass industry. An important objective is that the new system be totally compatible with the working environment and operation of glass manufacturing plants in all for segments of the glass industry. To accomplish this, a good understanding of a modern glass manufacturing facility is required.

Part of this understanding was accomplished by visits to manufacturing plants representative of the four primary segments of the glass industry, which is discussed in an earlier section of this report. Continued working relationships with plant engineering and operations personnel is considered essential to the successful design, fabrication, field test, and evaluation phases of advanced temperature sensor development project.

Additional understanding of glass manufacturing technology was obtained by a careful review of the literature that pertains especially to the environment and function of the primary melt tank component of the process. References 1 to 3 provide a particularly good description of glass manufacturing technology that directly pertains to the design of a sensor adequate for the hostile conditions within the melt tank process.

Figure 1 is a drawing showing the overall features of a cross-fired melt tank. The general layout of the melt tank and plant environmental conditions are the determining factors in several design features of the advanced temperature system. These are particularly important in determining: 1) signal lead lengths; 2) melt tank sensor design; 3) sensor connector design, and 4) signal conditioning electronics reliability.

Figure 2 shows a representation of the melt cross-section for a primary melt tank. The interior environment of the melt tank is corrosive to most refractory materials. An important aspect of temperature sensor design is the outer protective sheath material for the sensor. The sheath must be compatible with both the crown and glass melt environments of the tank. An advanced material sheath is an important to the temperature monitoring system being developed. The sheath is particularly important to successful sensor operation in the container segment of the glass industry. Figure 2 also lists the criteria that the new outer protective sheath must satisfy.

Figure 3 provides an overall layout of the temperature sensor system. The sensor is a dual sheath sensor, allowing replacement of the inner sheathed sensor without disturbing the outer sheath. This feature provides several important operational advantages. The primary role of the outer sheath is compatibility with the melt tank corrosive environment. Creep strength at temperature is an especially important requirement for the molten glass region. The primary role of the inner sheath is to provide a protective environment for long term stability of the sensor element components that are creating the temperature readout signal.

Figure 3 also shows that two independent optical isolation links are utilized to provide the common noise rejection that is required for glass plant operations. Up to 600 VAC can be imposed on the sensor from electrical heating of the glass melt. Additional electrical noise is also present in the plant. The optical links allow the signal conditioning electronics to "float" at the common mode voltage of the sensor to which it is connected. Total isolation is provided in the final data transfer mode to the signal processing electronics located in the control room.

Figure 4 illustrates a representative sensor system layout for a typical glass plant manufacturing facility. As noted in the figure, a single signal processing system can control up to 240 separate temperature sensors, located in a variety of locations throughout the glass manufacturing facility. All 240 sensors are capable of possessing expert temperature features such as self-verifying temperature readout and system condition validation.

The present temperature system design can accommodate up to 150 foot lengths of connecting cable between the sensor and signal conditioning electronics. This length is important to allow suitable placement of the electronics in an environment with acceptable vibration and temperature conditions. Phase II electronics design is nearly complete which will allow for 125° C temperature conditions. This feature will allow plant operations additional convenience in placement of the electronics package.

The glass industry requested a maximum size of 5 inches x 5 inches x 5 inches for signal conditioning electronics. The present design accomplishes this within a package that is less than 4 in x 4 in x 2 in.

FIGURE 1. Drawing showing the basic features of a primary melt tank.

PROTECTIVE SHEATH REQUIREMENTS:

- Must be equal or better than platinum clad (.015") aluminium oxide (99.88% pure)
- Corrosion resistance and survival in oxidizing environment
- Thermal shock resistance
- Strength
- Stress creep resistance

FIGURE 2. Sketch showing the cross section of a primary melt tank and temperature sensor placement. Basic protective sheath requirements for the melt tank are listed.

FIGURE 3. High level drawing showing the basic features of the primary melt tank self-verifying temperature system.

FIGURE 4. Sketch showing the general layout of the temperature monitoring system within a glass manufacturing plant.

8.8 Signal Conditioning Design

Reliable operation of the signal conditioning electronics within glass plant operating environments is critical to the self-verifying capability provided by the melt tank temperature system. It is the self-verifying feature that informs the plant operator that the sensor readout remains within calibration, or in the event drift has occurred, the magnitude and direction of the drift.

Although the signal processing electronics are protected by the conditioned environment of the control room, the signal conditioning electronics must be exposed to actual glass plant service environments. The present design accommodates all known plant conditions.

An important part of the remote signal conditioning electronics is a printed circuit board that plugs into the PC in the control room. The card provides isolated power to the remote electronics. Four electrical leads connect the card to the remote electronics: 1) power, 2) ground (isolated), 3) clock, and 4) data.

The master card in the PC contains multiple channels. Each channel can connect up to eight remote signal conditioning units. There can be multiple cards in the PC. It is this feature that allows a single PC to process up to 128 separate remote signal conditioning units and sensors.

8.9 Signal Conditioning

Data from the remote electronics is processed by utilizing expert system algorithms to provide a validated temperature readout. Diagnostic data from the remote electronics is processed to provide an assessment of sensor condition. Figure 6 provides an overview of the basic algorithm components that are used to accomplish these functions.

A Data Acquisition Adapter operates on an ISA bus card. Data is communicated to the Data Acquisition Adapter using an RS485 half duplex data link using a serial communications mode.

The remote electronics waits to receive a message addressed to it from the software. If a remote signal conditioning unit does not respond, it is marked as unavailable and retried on a periodic basis.

The data generated by the sensor is placed in a data matrix. A portion of the data flow is continuous. The signal validation portion of the data matrix is not continuous, but is taken on a periodic basis predetermined at system start-up.

FIGURE 5. High level drawing showing the basic elements of the signal conditioning electronics for the self-verifying temperature system.

FIGURE 6. High level flow chart showing the basic algorithm components of the signal conditioning software for the self-verifying temperature system.

9.0 SYSTEM FABRICATION

9.1 System Components

The following components require custom design and fabrication for the self-verifying temperature measurement system:

- 1) Sensor
- 2) Sensor connector
- 3) Connecting lead cable
- 4) Remote signal conditioning electronics configuration
- 5) Signal processing electronics
- 6) Data processing software
- 7) System control software
- 8) Display software

The following components for the temperature monitoring system are available "off the shelf";

- 1) Connecting lead cable
- 2) Signal processing PC
- 3) Display
- 4) Windows 95 software
- 5) Some signal conditioning units

All of the system components interrelate. The design of the remote signal conditioning electronics is custom to the sensor placed within the melt tank, as an example. Likewise, the design of the signal processing electronics and software are custom to the remote electronics and sensor.

An important aspect of system development and evaluation testing is that each component satisfy specified performance and test requirements. It is also equally

important that the components be carefully test evaluated as an entire system, since the performance of individual components depends in a critical way upon the proper functioning of all other system components.

For proper test and evaluation, all of the system components were required to be developed and fabricated in parallel.

9.2 Melt Tank Sensor

Figure 7 shows the basic outline details for the melt tank sensor. The outer protective sheath is not shown in this drawing. The sensor sheath that is shown inserts into the outer protective sheath, which provides the primary protection from the melt tank corrosive environments. The actual length of the sensor sheath varies depending upon specific customer requirements.

Figure 8 is an overall fabrication drawing showing the general physical proportions of the melt tank sensor. Figure 9 provides additional details of the sensor connector. The construction of the connector is critical to the proper operation and life of the sensor.

Figure 10 provides an enlarged view of the sensor tip region. The sensor tip contains the sensor elements that provide the matrix of data signals for the remote electronics and signal processing electronics to validate the temperature readout.

Figure 11 shows an enlargement of the sensor lead wire feed through region to the connector. Figure 12 shows an enlargement of the sensor lead wire terminations at the connector.

The proper fabrication of all of the above described components are essential for the reliable functioning of the sensor.

To date, a total of six sensor assemblies have been fabricated. Two basic designs have been constructed for evaluation purposes. To date, both basic variations in design have performed well during prototype evaluation tests.

The first set of three sensors did not contain the connection region as shown in the drawings. The second set of three sensors that have been fabricated do possess the connections as shown in these drawings. Evaluation tests on these last sensor systems are now in progress.

As discussed earlier in this report, the overall design of the sensor is based on previously developed technology that provided reliable sensor performance in similar hostile service conditions over a temperature range of between 1600° C and 2400° C. The present design represents an adaptation of this basic design and fabrication

processing technology to satisfy the glass industry primary melt tank service environments.

FIGURE 7. Outline drawing showing basic features of melt tank temperature sensor

SELF VERIFYING TEMPERATURE SENSOR

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960814

FIGURE 8. Outline drawing showing general physical proportions of melt tank temperature sensor.

SELF VERIFYING TEMPERATURE SENSOR

Note 1: "X" length - 18 to 36 inches.

Dimension is specified by each industry to fit the individual furnace application.

Note 2: "Y" length - 3 to 24 inches, and same comment as Note 1.

Note 3: This drawing is not to scale.

AccuTru International Corporation

980814

FIGURE 9. Drawing showing connector detail for melt tank temperature sensor.

NOTE: All dimensions are in millimeters.

NOT TO SCALE

960324
J.G.L.

FIGURE 10. Enlargement showing insulator components in sensor tip region.

FIGURE 11. Enlargement showing details of connection/wire feed through for melt tank sensor.

FIGURE 12. Enlargement showing details of wire element terminations for melt tank sensor.

9.3 Remote Signal Conditioning Electronics

Figure 13 is a functional block diagram showing the remote signal conditioning electronics and related components. Laboratory bench top equipment was first used in operational tests with sensors in laboratory furnaces to establish design operational parameters. Once these were established, the remote signal conditioning electronics was designed. An important aspect of the design was to provide a hardened unit that totally satisfied field operational requirements to be experienced in actual glass industry conditions.

As the block diagram illustrates, the measurement electronics is coupled to a connecting cable and collects and conditions a data signature produced by the SVS sensor. The data signature is comprised of a variety of electrical signals received from the sensor, including lead to lead measurements of impedance and voltage measured across various combinations of leads. Both AC and DC techniques can be utilized. These measurements are then correlated and analyzed to extract the necessary data for measurement and validation of temperature and assessment of sensor conditions.

Within the measurement electronics area multiplexer (MUX), filter and buffer, and two analog to digital (A/D) converters. The MUX operates under the control of the signal processing computer to select particular signals from the sensor elements and then passes those signals to the filter and buffer. The MUX also allows the injection of a known current into the sensor elements for impedance measurements. In addition, the MUX allows the selection of forward or reverse readings of selected sensor elements.

The filter and buffer receive selected signals from the MUX. The filter performs antialiasing to improve the noise performance of the A/D converter. A buffer amplifier provides a higher input impedance to reduce the effect of the resistance of the MUX switches.

The A/D converter is a high resolution Sigma-Delta A/D converter. The A/D converter converts the data signature received from the sensor into one or more digital values representing the data signature. These digital values are then passed to the signal processing electronics and computer for further processing.

Both a primary and secondary A/D converter are used. Some signals from the sensor elements bypass the MUX filter and buffer and, instead, are transmitted directly from the sensor to the primary A/D converter. The primary A/D converter continuously reads these signals. The secondary A/D converter is connected to the sensor via the MUX and can read the primary sensing elements or any other sensing elements in any combination.

A temperature sensor is connected to a secondary A/D converter to allow cold junction calculations to be made. The signal processing electronics receives all of the digital signal outputs from the A/D converters.

FIGURE 13. Block diagram showing the remote signal conditioning electronics for the self-verifying temperature system for the glass industry.

The overall design allows for multiple SVS sensors to provide data back to a central signal processing location.

The micro processor is a RISC architecture type. This unit controls all the functions necessary for operation of the remote SVS electronics. It selects the necessary multiplexer switches and steers the required signals into the proper A/D converter. It then commands the A/C to convert, collects the data, performs mathematical operations, and then passes the information down the communication link. Another function of the micro processor is calibration. All circuitry is of low power type.

The multiplexer section consists of an array of monolithic CMOS devices that are independently selectable switches. It is this feature that allows the micro processor to select any lead pair from the SVS sensor, as well as inject a known current into the sensor for resistance measurements. This methodology also allows the capability to read the resistance of the actual switches as well as the current source and voltage reference for calibration reasons. These features are essential in order for the signal processing algorithms to correctly validate temperature and assess sensor condition.

The antialiasing filters are located between the mutliplexer switch and the A/D converter to improve the noise performance of the A/D converter. Additionally, the buffer amplifiers provide a high impedance to reduce the effect of the "on" resistance of the multiplexer switches. Readings into the A/D converter are differential and may be biased up to allow for reverse readings.

The voltage reference is a low noise type which is designed to give the required stability and accuracy requirements for the A/D conversion.

A non-volatile memory allows for storage of calibration information that is retained during any power outage.

The ID switch provides a means for unique identification of the unit to the communication link.

The isolation barrier is an optical type which is used to provide isolation to the communication link.

The DC to DC converter provides isolated power for driving the circuitry while isolating the circuitry from the power source.

The communication link consists of circuitry that allows bi-directional communication and buffering to allow drive of long lead cabling.

The remote signal conditioning electronics is totally contained within a field hardened package with dimensions less than 2 ½ in. x 2 1/2in. x 2 1/2in. The Phase I electronics is designed for continuous operation at temperatures up to 85 C. This provides a

margin of 15 C over the 70 C required by glass plant conditions. The electronics is also hardened for vibration conditions. 600 A common mode rejection is required by glass plant operations. The optical isolation links utilized in the remote signal conditioning electronics can isolate up to over several thousand volts, providing a margin far in excess of the minimum requirement. The phase I remote electronics is being readied for field test and evaluation in actual glass plant conditions.

Additionally, a Phase II signal conditioning electronics package is being designed that possesses additional field hardening capabilities, including continuous operation at temperatures up to 125 C. This unit will allow glass plant operations additional flexibility in placement of the remote electronics.

10.0 SIGNAL PROCESSING ELECTRONICS

10.1 Signal Processing Electronics

The electronics that measures, conditions, and processing data from the sensor is located in two distinct physical packages: 1) the remote signal conditioning electronics; and 2) a PC containing a custom designed SVS Data Acquisition Adapter. (DAA). The DAA is located in the PC I/O slot, in the control room. The remote signal conditioning electronics is in the glass manufacturing plant at a location convenient to plant operations. From a data processing point of view, both the remote electronics and the DAA function together, in a tandem manner, to process sensor data that is transmitted into the computer for final analysis. The design of the DAA is closely related to that of the remote electronics. The remote electronics contains a micro-controller which is instructed by the PC through the DAA in a Master-Slave architecture.

A half duplex data link using a serial interface buss is utilized in communications between the remote electronics and the DAA/PC. Overall, a single PC/DAA complex controls and processes the data from up to 240 separate remote electronics/sensors located at distinct positions throughout the glass manufacturing plant.

The remote electronics responds to control signals sent to it by the DAA/PC system. Some of the data from the sensor/remote electronics is transmitted continuously. The computer is a standard microcomputer comprising a central processing unity (CPU) of at least a 586 level, random access memory (RAM), and a display panel. The computer executes software stored in the RAM to perform the desired functions.

All messages sent between the DAA and the remote electronics are in a similar format. A preface is contained in the data portion of each message which defines the recipient remote electronics/sensor address. The message frame contains a one byte message type which identifies the message contents to the slave DAA recipient. The message length sent from the DAA to the remote electronics can vary from 2 to 8 bytes, depending on the message type. General message types are categorized into 14 distinct classes, that is, each message is formatted under one of 14 format class types.

Primary data from the sensor is fixed to the main A/D converter and calibrated to provide a high degree of accuracy in the value obtained. Secondary data is collected using a multiplexed 16 bit A/D converter. The contents of the scan are programmed by the host DAA/PC.

The data collected in the remote electronics, or slave electronics, is transmitted to the DAA/PC, or master, in two message blocks: 1) Primary Scan Data; and 2) Secondary Scan Data. Additional data can be taken which is not included in the fixed scans. This is determined by the master DAA/PC as it continues to validate temperature readout

and assess sensor condition. The additional data is requested as the processing software determines the need for additional information to validate temperature and assess sensor condition.

The remote electronics collects data from the sensor and applies smoothing and data filtering according to the data collection parameters sent to it by the DAA/PC. The data returned to the DAA/PC from the remote electronics has been smoothed, filtered, and additionally processed as directed by the DAA/PC. Data that has not been processed by the remote electronics is marked in the message bytes as it is transmitted by the DAA/PC.

The data values that are transmitted by the remote electronics to the DAA/PC are accompanied by two bits describing the validity of the data value. All data measurements transmitted by the host DAA/PC contain a fixed selection of values obtained from the remote electronics/sensor.

Remote electronic Data Scans are collected at varying periods. IN genera. Data Scans are divided into three categories: 1) Scan A; 2) Scan B; and 3) Scan C. Scan A has the highest frequency of collection. Scan periods generally vary between 100 mSec and 255 mSec.

The DAA periodically polls the remote electronics on a frequency determined by the host PC software. This frequency is larger than the remote electronics Poll frequency and smaller than the refresh frequency at which the data is analyzed by the host PC. Typical periods are between 1 to 10 seconds.

Each channel on the DAA is supported by a single micro0processor. The micro-processor relieved by the host PC of the periodic possessing and scan of the remote electronics. Data retrieved by the host PC is via a FIFO memory buffer which an hold up to 64 scan data buffers. A command FIFO contains data that is used to configure the DAA and its attached remote electronics/sensors. This allows the data matrix from each sensor to be reconfigured as determined by the host PC software. The scan rate and other operating parameters are written to the DAA during its initialization by the host PC.

The DAA also provides an interrupt to the host PC which may be enabled by setting a jumper on the adapter. The host PC interrupt is caused when the adapter has Scan Data in the FIFO or when the status has changed.

The DAA electronics is presently being constructed in preparation for glass plant field test and evaluation. Hardening of the entire system is a primary requirement for the overall SVS temperature measurement system. Although the DAA/PC electronics is located in the control room, this electronics is utilized to analyze the remote signal conditioning electronics, which are located in the glass plant with vibration and

temperature conditions. Therefore it is constructed in parallel with the remote signal conditioning electronics.

11.0 SIGNAL PROCESSING SOFTWARE

11.1 Signal Processing Technology

The software used to process the data from the temperature sensor is based on an understanding of the physical mechanisms within the sensor that affect readout validity and also that can impair the condition of the sensor. The remote electronics obtains diagnostic data from the sensor, in addition to sensor readouts, that are then processed to ascertain the condition of the sensor and the temperature readout. The diagnostic data correlates with known sensor conditions.

- 1) Temperature readout valid;
- 2) Sensor free from modes of impairment;
- 3) Temperature readout invalid, and/or decalibration present;
- 4) Impairment detected within the sensor;
- 5) Nature and location of sensor impairment.

Most of the information required to determine the diagnostic data that is required to detect the conditions listed above is obtained from laboratory tests. These tests place the sensor in a variety of accelerated stress conditions that have been established to occur under operational field stresses. Conditions include aging, over-temperature extremes, mis-handling, flawed manufacturing processes, and accident conditions. The diagnostic data patterns are then correlated with each condition, and levels of confidence in detecting each impaired state are established.

Where possible, data is obtained under operational field conditions and added to the data base. All diagnostic data must be correlated with sensor design, construction, and application. For the application in the glass industry primary melt tank, sufficient information can be obtained from the sensor to establish the validity of temperature readout to greater than 99% for the final sensor design.

The general condition of the sensor so that sensor impairment can be predicted prior to actual decalibration or failure is expected to be greater than 60% for the present design.

The base technology has previously been developed for other temperature sensor applications for self-verification and sensor condition assessment. The temperature sensor for the glass industry primary melt tank is an application of this technology.

11.2 Processing Algorithms

Figure 14 is a high level software flowchart used to prepare the necessary algorithms to process incoming data from the sensor. Figure 15 is a high-level software flow chart used to process data that is used to validate the temperature readout. A confidence level is always computed each time the temperature readout is monitored for drift.

Figure 16 is a high-level flowchart used for the algorithms that access the condition of the sensor. A confidence level is also computed each time the sensor condition is evaluated. Not all impairment conditions can be detected to reasonable confidence levels with presently available technology. However, this assessment is only part of the overall data matrix that is utilized in corroborating the validity of the temperature readout. The condition of the temperature readout can be determined to a much higher level of confidence than can overall sensor condition. (This may not appear logical to the reader of this report, but it is nevertheless true. Inquires are welcomed.)

Figure 17 shows a simple high-level identification of the basic algorithms that are used to form the operator display. To form the display, it is necessary to interface with glass plant operators to determine formats, style, information required, and desired options for the display. It is important that the display be simple and readily understandable by the operator. Display options are available, at operator discretion, that call up additional data regarding sensor condition when this is desired.

The software for processing the data is transmitted to the host PC from the DAA that is presently being constructed. It is scheduled for completion at the same time as the remote electronics and DAA electronics since it is necessary to run the system during field evaluation testing.

A simpler form of the above software has been utilized to perform laboratory tests.

FIGURE 14. High level software flowchart identifying major algorithms used to process SVS sensor data

FIGURE 15. High level software flowchart identifying major algorithms used to validate sensor temperature.

FIGURE 16. High level software flowchart identifying major algorithms used to assess sensor condition.

FIGURE 17. High level software flowchart identifying major algorithms for operator display.

12.0 PHASE I EVALUATION TEST

12.0 TEST OVERVIEW

The sensor, signal conditioning electronics, and signal processing electronics are new components that have not previously been test evaluated as stand alone components nor together as a complete system. For this reason, laboratory tests to verify the performance of individual components, laboratory tests on the complete system, and follow-on field performance tests on the complete system are critical to the assessment of the new SSVS temperature monitoring system.

The primary objective of the Phase I laboratory tests was to obtain important functional parameters necessary on the sensor itself which were required for the design of remote signal conditioning electronics. A secondary objective was to evaluate the overall sensor design and construction at furnace temperatures near 1200 C. Tests at the 1200 C temperature were sufficient to establish the design parameters for the electronics. Although the test temperature was not at the rated 1800 C sensor specification level, the 1200 C test data was also valuable as an initial assessment of the design and manufacturing process used for the new sensor.

Figures 18 and 19 show representative data from sensor elements during the time at temperature portion of the tests. The performance of all sensor matrix elements remained extremely stable during all phases of the tests. This data also provided important segments of data required for the electronics design.

High performance bench top electronics were used to monitor sensor parameters during the Phase I evaluation tests. The data from the sensor element matrix was multiplexed into the primary measurement instrument, and then transmitted to a computer for processing and analysis.

Three sensors were fabricated for the tests. Two sensors were fabricated to the primary design, and one sensor fabricated to a secondary design. Comparison of the performance of the two sensor designs was an important secondary objective of the Phase I tests.

FIGURE 18. Representative data taken to monitor the stability of elements from the sensor element matrix. Data was taken to obtain functional parameters necessary to design the remote signal conditioning electronics. The data signifies all stability requirements for the signal processing algorithms.

FIGURE 19. Representative data taken to monitor the stability of elements from the sensor element matrix. Data was taken to obtain functional parameters necessary to design the remote signal conditioning electronics. The data satisfies all stability requirements for the signal processing algorithms.

12.2 TEST OBJECTIVES

Specific objectives for the Phase 1 tests included:

1. Establish operational sensor parameters for the design of the remote signal conditioning;
2. Establish the effectiveness of the output data matrix from the sensor to validate sensor temperature;
3. Establish the effectiveness of diagnostic algorithms in assessing sensor conditioning, and
4. Determine that the sensor element matrix is stable over 200 hour periods at near 1200 C test temperatures.

12.3 TEST PROCEDURES AND DATA

The three new temperature sensors were placed in a laboratory furnace with a calibrated temperature reference. Care was taken that all components within the furnace would remain together in thermal equilibrium.

To satisfy the various objectives of Phase One testing, the temperature tests were conducted in several parts. Each part of testing focused on selected aspects of the objectives. Major aspects of testing included: 1) temperature ramp tests (up and down); 2) temperature stability tests at contact temperature, 3) post-test examination of sensor components.

In order for signal processing to correctly assess sensor condition, and validate temperature readout, certain designated channels from the sensor matrix must remain within specified limits relative to each other. More important than absolute magnitude is the relative drift in signal from the distinct elements. Figure 20 is a representative plot showing data from four sensor elements among with a reference channel. The degree of "overlay" in the data more than satisfied design specifications for the sensor elements.

Figure 21 is a table showing representative data in digital form generated by the sensor element matrix. Experiments were performed during the Phase I laboratory tests as to the best manner to process the data from the sensor.

FIGURE 20. A composite plot of four data channels from the sensor element matrix, plus a reference channel, taken during temperature tests for stability over time at temperature. The data satisfies all performance criteria.

-A-	-B-	-C-	-D-	-E-	-F-	-G-	-H-	XX	-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	YY	TIME
62.919	-0.300	-0.197	-0.197	-0.191	-0.194	-0.189	-0.192	-0.179	-0.322	5.3064	5.3073	4.7723	0.2415	4.7939	5.0297	5.3679	5.5376	0.2443	24:00:00
62.919	1.9474	1.9545	1.9511	1.9677	2.6051	2.6156	-0.314	-0.319	7.3177	5.3379	5.31	5.2751	0.2438	5.4116	5.4465	5.5578	5.5713	0.2524	0:00:11
62.919	2.8137	2.8217	2.8154	2.8285	3.427	3.4428	-0.908	-0.990	7.3246	5.5042	5.4342	5.3987	0.2444	5.593	5.6307	5.6742	5.6529	0.2523	0:00:21
62.919	2.2408	2.245	2.2429	2.2508	3.0938	3.1082	11.346	-0.932	6.5033	5.4515	5.4137	5.3722	0.2441	5.5709	5.62	5.675	5.6638	0.2514	0:00:32
62.919	2.3146	2.3193	2.3144	2.3238	3.0619	3.065	0.5502	0.5536	6.5963	5.414	5.3575	5.3631	0.2441	5.5702	5.5913	5.6443	5.6353	0.2514	0:00:43
62.919	5.5855	6.6779	6.671	6.7048	8.2271	8.2341	1.3396	1.3432	17.159	5.7966	5.7401	5.7424	0.2487	6.3463	6.3313	6.3196	6.3132	0.2625	0:00:54
62.919	6.4799	6.504	6.4987	6.5082	8.0697	8.0133	1.3147	1.3178	15.041	6.0608	5.9428	5.947	0.2486	6.3665	6.3565	6.3715	6.3642	0.2611	0:01:05
62.919	6.4367	6.4514	6.4521	6.4521	7.946	7.9542	1.3682	1.3141	15.957	5.9541	5.8328	5.9372	0.2486	6.3601	6.3523	6.3722	6.364	0.2612	0:01:15
62.919	6.4174	6.4233	6.4197	6.4341	7.9288	7.9351	1.3074	1.3136	15.850	5.9392	5.9303	5.9327	0.2486	6.3554	6.3502	6.372	6.3637	0.2612	0:01:26
62.919	6.394	6.4071	6.3952	6.4071	7.9016	7.9092	1.3136	1.3126	15.916	5.9344	5.9253	5.9277	0.2486	6.3517	6.3448	6.3722	6.3627	0.2612	0:01:37
62.919	6.2462	6.259	6.2464	6.2596	7.9478	7.9569	1.3128	1.3176	15.433	5.9288	5.9186	5.9221	0.2486	6.3467	6.3416	6.3729	6.3638	0.2609	0:01:48
62.919	6.2491	6.262	6.2492	6.2629	7.9293	7.937	1.317	1.3222	15.470	5.9289	5.9176	5.9223	0.2486	6.3467	6.342	6.3729	6.3638	0.2609	0:01:59
62.919	6.2923	6.3057	6.2942	6.305	7.9093	7.9006	1.3234	1.3291	15.574	5.9319	5.9193	5.927	0.2487	6.3468	6.3442	6.3747	6.3644	0.261	0:02:10
62.919	6.299	6.314	6.3014	6.3121	7.9038	7.9134	1.3271	1.3341	15.663	5.933	5.9229	5.9305	0.2487	6.3556	6.3498	6.378	6.3697	0.2611	0:02:20
62.919	6.2824	6.2993	6.2872	6.2974	7.8908	7.8938	1.3276	1.3329	15.687	5.9317	5.9238	5.9328	0.2487	6.3529	6.3468	6.3804	6.3629	0.2611	0:02:31
62.919	9.6148	9.6449	9.6396	9.6654	11.397	11.411	1.5347	1.563	25.154	6.4605	6.343	6.3535	0.2572	6.8297	6.8332	6.8983	6.8975	0.2712	0:02:42
62.919	10.815	10.855	10.837	10.849	12.585	12.585	1.5707	1.5745	25.173	6.4713	6.3554	6.3645	0.2534	7.1045	7.0965	6.4531	6.453	0.2709	0:02:53
62.919	10.624	10.649	10.635	10.643	12.377	12.385	1.5723	1.5755	24.551	6.3974	6.3375	6.3455	0.2532	7.0916	7.0857	6.4576	6.4468	0.2704	0:03:04
62.919	11.751	11.758	11.751	11.768	13.496	13.504	1.5536	1.559	28.329	6.7451	6.6857	6.6929	0.2545	7.25	7.2416	6.4834	6.4736	0.2745	0:03:14
62.919	15.038	15.063	15.041	15.050	16.544	16.540	1.3269	1.3299	33.964	21.119	21.084	21.087	0.2579	23.057	23.043	6.5849	6.5701	0.28	0:03:25
62.919	14.790	14.821	14.755	14.808	16.375	16.319	1.3545	1.3648	33.344	20.873	20.844	20.822	0.2577	22.85	22.832	6.7012	6.6878	0.2794	0:03:35
62.919	14.927	14.963	14.944	14.963	16.468	16.468	1.3358	1.3446	33.961	21.039	21.067	21.054	0.2579	23.071	23.063	6.7153	6.7013	0.2903	0:03:47
62.919	22.043	22.092	22.063	22.077	22.110	22.098	-0.131	-0.119	48.681	28.190	28.665	28.635	0.2655	29.206	29.184	6.9546	6.9528	0.2956	0:03:58
62.919	21.181	21.229	21.160	21.194	21.469	21.465	0.131	0.1449	46.804	27.785	27.773	27.778	0.2646	28.598	28.563	6.965	6.97	0.2933	0:04:09
62.919	21.091	21.139	21.050	21.098	21.414	21.394	0.1583	0.1753	46.604	27.762	27.766	27.768	0.2645	28.554	28.523	7.0153	7.0055	0.2931	0:04:20
62.919	21.021	21.069	21.034	21.078	21.352	0.1704	0.1969	46.452	27.653	27.661	27.611	0.2645	28.535	28.495	7.041	7.0287	0.293	0:04:31	
62.919	20.991	21.060	21.064	21.019	21.358	21.330	0.1772	0.1979	46.437	27.676	27.648	27.594	0.2645	28.531	28.492	7.0551	7.0414	0.293	0:04:42
62.919	20.932	21.014	20.948	20.971	21.317	21.294	0.191	0.2137	46.290	27.579	27.599	27.539	0.2644	28.491	28.458	7.0636	7.0509	0.2929	0:04:52
62.919	20.875	20.969	20.903	20.924	21.292	21.268	0.1928	0.2202	46.167	27.568	27.600	27.536	0.2644	28.504	28.468	7.0677	7.0552	0.2929	0:05:03
62.919	20.817	20.915	20.850	20.872	21.276	21.247	0.2033	0.2277	46.132	27.521	27.546	27.483	0.2644	28.460	28.415	7.0732	7.0614	0.2926	0:05:14
62.919	20.752	20.847	20.880	20.912	21.275	21.248	0.2	0.2228	46.120	27.580	27.580	27.528	0.2644	28.487	28.445	7.0761	7.0631	0.2929	0:05:25
62.919	20.674	20.769	20.808	20.932	21.284	21.255	0.1983	0.2276	46.189	27.531	27.565	27.499	0.2644	28.471	28.431	7.0772	7.0645	0.2927	0:05:36
62.919	20.611	20.727	20.834	20.874	21.259	21.234	0.2058	0.23	46.080	27.529	27.563	27.498	0.2644	28.474	28.431	7.0778	7.0646	0.2927	0:05:47
62.919	20.794	20.884	20.839	20.939	21.22	21.195	0.2235	0.2473	45.946	27.463	27.499	27.433	0.2643	28.476	28.401	7.0808	7.0667	0.2925	0:05:58
62.919	20.815	20.910	20.831	20.937	21.234	21.212	0.2162	0.2429	46.031	27.466	27.502	27.432	0.2643	28.455	28.389	7.0827	7.0688	0.2925	0:06:09
62.919	20.815	20.917	20.836	20.937	21.240	21.217	0.213	0.2411	46.070	27.470	27.513	27.432	0.2643	28.430	28.393	7.0838	7.0693	0.2926	0:06:20
62.919	20.831	20.930	20.854	20.961	21.256	21.236	0.2077	0.2333	46.106	27.495	27.526	27.459	0.2643	28.446	28.408	7.0855	7.0707	0.2927	0:06:30
62.919	20.839	20.936	20.832	20.859	21.233	21.217	0.2174	0.2423	46.066	27.465	27.502	27.436	0.2643	28.422	28.396	7.0865	7.0716	0.2926	0:06:41
62.919	20.768	20.878	20.808	20.875	21.212	21.196	0.2243	0.2467	45.971	27.439	27.469	27.406	0.2643	28.399	28.374	7.0882	7.0735	0.2925	0:06:52
62.919	20.784	20.878	20.805	20.827	21.209	21.192	0.2246	0.2494	45.960	27.432	27.467	27.402	0.2643	28.397	28.365	7.0894	7.0747	0.2925	0:07:03
62.919	20.817	20.908	20.833	20.862	21.232	21.222	0.2193	0.2426	46.077	27.471	27.500	27.438	0.2643	28.421	28.402	7.0902	7.0752	0.2926	0:07:14
62.919	20.750	20.879	20.814	20.841	21.225	21.216	0.2184	0.2394	45.987	27.407	27.519	27.452	0.2643	28.442	28.418	7.0905	7.0756	0.2926	0:07:25
62.919	20.804	20.896	20.827	20.844	21.233	21.215	0.2129	0.2363	46.037	27.478	27.495	27.440	0.2643	28.425	28.387	7.0912	7.0763	0.2926	0:07:36
62.919	20.763	20.854	20.791	20.812	21.205	21.182	0.2304	0.2534	45.912	27.437	27.475	27.414	0.2643	28.418	28.391	7.0919	7.0769	0.2925	0:07:47
62.919	20.827	20.910	20.840	20.855	21.236	21.217	0.2177	0.2405	46.081	27.473	27.496	27.435	0.2643	28.425	28.387	7.0926	7.0776	0.2926	0:07:58
62.919	20.767	20.853	20.788	20.806	21.200	21.176	0.2309	0.252	45.912	27.416	27.445	27.392	0.2643	28.396	28.359	7.093	7.0781	0.2925	0:08:08
62.919	20.795	20.875	20.813	20.821	21.219	21.189	0.2231	0.2457	45.976	27.444	27.463	27.407	0.2643	28.406	28.359	7.0931	7.0782	0.2925	0:08:19
62.919	20.804	20.879	20.839	20.849	21.244	21.260	0.2104	0.2361	46.057	27.465	27.494	27.444	0.2643	28.437	28.384	7.0932	7.0784	0.2927	0:08:30
62.919	20.803	20.867	20.817	20.827	21.229	21.184	0.2246	0.2452	46.032	27.452	27.459	27.414	0.2643	28.419	28.356	7.0902	7.0757	0.2926	0:08:41
62.919	20.763	20.829	20.778	20.798	21.201	21.160	0.2316	0.2534	45.901	27.418	27.447	27.388	0.2643	28.406	28.357	7.0936	7.0786	0.2925	0:08:52

FIGURE 21. Representative data from the sensor element matrix. Data of this type is temporarily stored, smoothed, and first stage processed in the remote signal conditioning electronics.

These experiments were successful in all aspects and allowed several important principles to be validated regarding the optimal design of the remote signal conditioning electronics, including the minimum quantity of data required for the assessment of sensor condition.

Time response measurements conducted as part of the Phase I testing. Time response is not a critical factor in temperature measurement for the primary melt tank. However, variations in time response between selected elements making up the sensor matrix affects how data is processed by the signal conditioning electronics. Figure 22 shows representative data taken to assess time response characteristics of the sensor.

Figure 23 is a representative plot showing a high resolution view of two channels of data from the sensor matrix. The important criteria is the relative relationship of the data from the channels. Figure 24 is a representative plot of the difference in output of two channels of data from the sensor matrix. The data shown in the graph remain stable within $\frac{1}{2}$ C over the time period of this portion of testing.

The data taken during Phase I testing demonstrated that the sensor satisfied all specifications during all phases of the tests. Also, all necessary parameters for design of the conditioning electronics were obtained. The data provided in this section of the report is not intended to be comprehensive but illustrative of the types of data taken during Phase I testing.

An important aspect of fabrication of the sensors for the Phase I tests was the development of the sub-tier supplier for selected ceramic components used in sensor construction. A review of candidate companies was conducted, and an engineering visit was made to the selected company. A review of the processing desired for the components was made with engineering personnel at the firm, and processing procedures for the components were established.

The Phase I tests form the basis for follow-on Phase II tests to be conducted over a temperature range from room temperature to 1800°C. Sensors for these tests have been fabricated, and testing has been initiated.

FIGURE 22. Representative data from temperature tests to determine the time response characteristics of various elements from the sensor matrix. The time response of all elements must fall within specified limits in order for output data to be signal processed. The data shown in this plot satisfies these criteria.

FIGURE 23. Comparison plot of data that has been scaled to observe detail of movement over a 15 degree span.

FIGURE 24. A plot showing the temperature equivalent difference between two separate channels from the sensor element matrix. The important criteria is the magnitude of the difference remaining stable. The data remains within $1/2^{\circ}\text{C}$ over the 140 hour period of stability testing, remaining within the performance specifications for the signal processing.

POST-TEST EXAMINATION

At the conclusion of all Phase I temperature tests, the test articles were removed from the furnace and examined for indications of degradation. All sensors were disassembled, and internal leads, insulators, and sensor elements were visually inspected at 10 X magnification. No indications of pitting, porosity, embrittlement, or other noticeable forms of deterioration could be observed.

The mechanical properties of the metallic elements were also checked. These tests also gave no indication of any significant deterioration. The interior components showed no evidence of intergranular attack or embrittlement, which are not uncommon in high temperature sensors after testing.

Electrical tests were also performed on the components to detect whether electrical properties at room temperature had been altered by the Phase I testing.

Components were carefully compared with as-received components that had not been subjected to temperature testing.

In all of the post-test examinations, no indication of degradation could be observed or detected in either of the candidate sensor designs.

13.0 OUTER PROTECTIVE SHEATH

13.1 BACKGROUND

At present, much of the glass industry utilizes platinum sheaths to protect thermocouple temperature sensors from the primary melt tank environments. These exist several difficulties in this practice.

1. The platinum does not provide reliable protection for many melt tank environments, and limits lifetime and reliability of sensors.
2. The platinum is expensive.
3. The platinum must be carefully inventoried for recovery purposes and to guard against theft, which is a significant additional cost.

In discussions with engineering staff from all four segments of the glass industry, agreement was reached that a better outer protective sheath for primary melt tank temperature sensors would be of significant benefit to the industry. The desired properties for the new sheath material include:

1. Improved corrosion resistance;
2. Overall improved lifetime - 5 to 10 years;
3. Improved high temperature creep resistance;
4. Design to allow simple replacement of the internal temperature sensor if needed.

13.2 DEVELOPMENT RESOURCES

A survey was conducted of centers of expertise that presently exist in the United States, knowledgeable in the area of corrosion of refractory materials in high temperature applications, such as the glass industry primary melt tank. Discussions were also conducted, in some instances, with experts in this area overseas, including Japan. The objective was to apply as much as state-of-the-art technology in new materials for an improved sensor outer protective sheath, as is possible.

A significant existing resource base of expertise exists within the glass industry. This expertise is focused on primary tank wall materials. Although the requirements for the melt tank wall are similar in some aspects to those for an improved sensor sheath, they also differ in several significant ways, including allowable wall thickness. Valuable information pertaining to a new sensor sheath design has been received from these resources.

In addition to participants from the glass industry, relationships with three centers of expertise in materials for use in corrosive environments were developed. All three of these centers are located at U.S. universities.

Also valuable assistance has been received from suppliers of refractory materials, who also possess personnel that are expert in this area.

13.3 MATERIAL SELECTION

Information relating to the resistance of wall materials used in primary melt tank environments was reviewed. Particular attention was given to the nature of corrosive attack on these materials, and design parameters and processing parameters that are known to extend the life of these materials in the melt tank environments. Of particular interest are materials used in melt tanks for the container industry.

A total of eight materials have been selected for evaluation testing. Some of the materials have the same chemical composition, but are fabricated by different processing methods. It is well established that manufacturing processing is a significant factor in the resistance to melt tank corrosion of a material. Processing strongly affects the grain boundary structure, residual trace contaminants, and other properties that determine corrosion resistance, thermal shock resistance, and stress creep strength.

Samples of the eight materials have been obtained from suppliers. One of the samples is a new ternary compound. All of the samples satisfy baseline requirements for a sensor outer protective sheath.

1. The material is known to be or expected to be resistant to corrosion from both the crown and melt regions of glass industry primary melt tank environments;
2. The material is known to possess or expected to possess high stress creep resistance at melt region temperatures,
3. The material can be suitably manufactured to the required geometry's and mechanical tolerances required for the outer protected sheath component,
4. The material is readily available,
5. The material is cost effective,
6. The material is otherwise suitable for fabrication into an outer protective sheath for the advanced temperature sensor.

13.4 EVALUATION TESTING

The initial phase of testing includes placing material samples within the crown regions of melt tank environments. A procedure to accomplish this has been prepared, and the cooperation of selected participant glass companies has been obtained. Great care must be taken not to contaminate the interior of a production melt tank with any of the material samples during the evaluation tests. However, exposure of the materials samples to actual melt tank corrosive environments offers the most direct approach to quick assessment of the resistance of candidate materials to corrosive attack from service environments.

Procedures for laboratory tests are also being prepared to further assess the corrosion resistance of the materials to molten glasses. These glasses are to be doped with contaminants known to accelerate the corrosion process. Laboratory tests to measure stress creep resistance of the materials at temperatures to 1800°C have also been designed.

The following are important objectives of the initial evaluation tests:

1. Determine which candidate materials demonstrate high resistance to corrosive attack by crown region environments of the primary melt tank;
2. Obtain an understanding of the mechanisms of corrosive attack on the samples, especially intergranular attack.

After exposure to environmental corrosive stress conditions, the samples will be evaluated utilizing recently developed analytical techniques useful in assessing the nature of corrosive attack. Additional standard methods of evaluation will also be utilized, including optical and SEM assessment of cross-sectional prepared specimens.

13.5 TEST STATUS

Samples of all eight candidate materials have been prepared for introduction into crown region environments. An essential requirement for the tests to proceed is the design of a holder for the specimens. Tests are planned on the holder to first demonstrate that it will retain the test samples during immersion exposures, and not release any sample material into the melt portion of the tank.

14.0 Beta Test Site Selection

14.1 Criteria for Selection

It was AccuTru's desire to have at least one test furnace from each segment of the glass industry. The test plant site needed to be willing to provide the necessary assistance from installation to data collection during the test, in order to evaluate the test results. We must have the ability to compare the test system against measurement systems currently in use, or in the case where measurement is currently not possible because of hot, hostile environments, accurate data collection and observations were to be made and recorded.

14.2 Industry Commitment

All four industry participants have committed to in situ testing and selected test sites have started preparations for the testing.

14.3 Beta Test Sites

COMPANY	PLANT LOCATIONS
Corning, Incorporated	State College, PA
Anchor Glass Container	Houston, TX
Owens-Corning Fiberglass	Aiken, SC
Libbey-Owens-Ford	Rossford, OH

14.4 Beta Test Protocol and Procedures

Test protocol and procedures are currently being developed for DOE review and approval. Mechanical specifications have been established and the sensors are scheduled for construction in September, 1996. The electronic models have been built. There are some decisions to be made on the exact locations of the sensors in the tanks.

15.0 Conclusions and Recommendations

15.1 Conclusions

Through Phase 1 the project demonstrated in the laboratory tests that it is possible to address four of the five problem areas and that, with the assistance of the University of Missouri-Rolla's materials group, it may be possible to address the fifth problem, the outer thimble. It has been demonstrated in the laboratory that it possible to solve the major identified problem, the inability to identify in situ decalibration (drift).

15.2 Recommendation

To meet the DOE's objectives and the industry requirement for a major step forward in melt tank temperature measurement technology, it is recommended that the following expansion of the "Statement of Objectives" Phase II and a modification to the "Federal Assistance Budget Information" be made.

15.3 "Statement of Objectives" Phase II

It is recommended that the following additions and modifications be made to Phase II of the "Statement of Objectives."

(Add)

Task 2.11 Develop Electronic Hardware and Software

The participant will develop and test hardware and software unique to the glass industry, that will capture the multiple signals generated by the Advanced Sensor developed in Phase I. This new hardware and software will analyze the data and report a temperature and a confidence level indication that the sensor is reporting data that is within special limits of error, stand limits of error, or standard limits of error established by the user.

The electronic package will provide the operator or the process control equipment with a "True Temperature" (The sensor is not experiencing in situ decalibration that is outside the predetermined limits of error.) The system will advise the operator of any decalibration of the sensor, and the direction of movement of the decalibration. The system will also contain an electronic self-verification feature to improve reliability.

(Add)

Task 2.12 Development of an Advanced Outer Protective Sheath

Pursue the research, development and testing of materials for use in the outer protective sheath of sensors used in the melting and delivery operations of the glass industry.

(Modify)

Task 2.4 Host Site(s) Testing

Test plan will be prepared and submitted to DOE for approval. The plan will include the test matrix, the length of test (anticipated to be ~~3-4 weeks~~ *a minimum of 3 months*) and length of any baseline data will be defined in the test plan. The plan will detail the location of sensor(s), depth of sensor(s), and temperature reference systems. *Since this system is novel and unique to the industry, the participants will meet with the management of each industry and Host Site and explain the features and benefits to their operation and the glass industry in general. Additionally, the participants will explain to the industry and plant management the components and operations of the system to be tested, the objectives of the test, and their role in the process.* The sensor will be installed at the industrial host site. The host site(s) will provide locations and structures suitable for mounting the new sensors, plus suitable power. Operational check-out (including data collection system) will be completed. *The participant will supervise the installation, perform the initial calibrations, monitor the initial operations and make required calibrations and adjustments to customize the system to the host furnace operations. The participant will periodically examine the test system, evaluate the data, interview furnace operations personnel, collect data for archiving, and make whatever adjustments and recalibrations may be necessary.*

The sensor system will only be operated in the passive control mode. A postmortem will be performed to examine the sensor and other components of the Advanced Temperature Measurement System. Statistical comparison with existing temperature measurement systems will be made. *The participant will provide feedback to the industry participant's management.*