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DEVELOPMENT OF A PROCESS CONTROL SENSOR FOR THE GLASS
INDUSTRY

Phase II: Prototype Design, Development and Demonstration

By
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June 1994

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Work Performed Under Contract No. FC07-89ID12781

For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.

By
Energy and Environmental Research Corporation
Irvine, California

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June 1994

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EXECUTIVE SUMMARY

Energy and Environmental Research has developed an advanced multichannel, on-line optical system for the non-contact measurement of forehearth glass melt temperatures at depth. The analyzer employs multiple narrow infrared (IR) band measurements of glass radiation to reconstruct the glass temperature profiles at depth. The TAS replaces expensive Tri-plex thermocouples, which frequently have service lives as short as 6 months to 1 year. By using passive non-contact sensor heads and fiber optic cables, temperature sensitive electronic components can be located at a safe distance from the hostile process environment. This provides significantly better reliability of the vulnerable electro-optic components and ready access for maintenance.

E.1 Forehearth Temperature Analysis System (TAS)

The analyzer consists of three major components as shown in the simplified block diagram, Figure E-1. The robust sensor head contains broadband infrared light collecting optics that focus the optical signal into the fiber optic cable. The optical signal, which is immune to electrical and magnetic interference, is then carried through the optical fiber to the main system signal processing enclosure. This enclosure contains a unique optical multiplexing system. The broadband pyrometric signal is separated by the optical bench into carefully selected narrow bandwidth IR radiation measurements which are converted into electronic signatures. Sophisticated microprocessor driven software is used to deconvolute the electronic signatures into a precise measurement of the glass temperature at melt depth at up to eight sensor locations.

The advantages of the new TAS over the conventional technology are numerous. The new system measures the temperature of the melted glass directly. It can also "look" into the melted glass at various depths of up to 6 inches and can thus be used to develop a three-dimensional temperature profile of the melt. Unlike conventional pyrometric sensors, the TAS should be relatively unaffected by the high background radiation level found in the forehearth. In addition, using fiber optics to link multiple sensors to a single detector means that the equipment will be less costly and probably more reliable than a conventional system, which requires a separate thermocouple for each point.

Glass Temperature Measurement

E-2

Figure E-1. System schematic showing a typical field sensor installation, signal processor and on-board, multichannel spectrometer.

E.2 Phased Program Development

EER conducted the research, development, and field tests on the TAS in two phases. In Phase I, which was completed in early 1991, a breadboarded TAS was designed, assembled, and used to measure glass temperatures in the laboratory. Test results provided valuable input for the design of a larger prototype instrument. In Phase II, EER installed a prototype on an actual glass-forming line. A large bottle manufacturer was the host for the industrial demonstration. Container glass plants are considered to be the best candidates for the first TAS applications because they are generally large, produce about 300 tons per day of glass, consume almost 50% of the energy within the glass manufacturing industry (SIC), and could benefit the most from efficiency improvements.

E.3 Functional and Performance Requirements

The TAS is intended as a partial or full replacement of existing temperature measurement devices, i.e.: submerged Pt thermocouples or visibly sighted optical pyrometers. Both devices have limited functionality. Submerged thermocouples deteriorate fairly rapidly in the hostile environment of the melt, resulting in drift and ultimately open junction failures. Optical pyrometers, depending on wave length(s) selected, measure temperature at depth (1.3 μm) or surface temperature ($>4.0 \mu\text{m}$). Further, the optical signal processing components are located in hostile environments, somewhat mitigated in state-of-the-art devices by optical fiber bundle connections (typically 6 ft) of an optical sensor to its electronics. The still somewhat hostile local ambient environment (temperature, oil mists, etc.) requires electronic component temperature hardening and expensive components. Surprisingly, these pyrometers have fair to good precision ($\pm 5^\circ\text{C}$) and drift ($5^\circ/\text{mo}$) characteristics. A technology which integrates the best characteristics of both methods, the low cost of pyrometers and the multi point and location melt temperature measurements of triplex thermocouples should enjoy wide industrial acceptance. The capability of locating precision optical and electronic signal processing systems remote from the process environment should significantly improve system reliability and maintainability while lowering cost by time sharing expensive signal processing components.

Based upon these general needs and discussions with the industry a performance specification was developed against which to evaluate the TAS. Key performance parameters may be found in Table E-1, and a more detailed specification is discussed in Section 2.

TABLE E-1. CRITICAL TAS PERFORMANCE PARAMETERS

Precision Repeatability, $\pm^{\circ}\text{F}$	1 to 2
Drift, $\pm^{\circ}\text{F}/\text{mo}$	2
Cost, \$/sensor	2200
Mounting, Furnace Penetration	1-1/2" O
Payback on Investment, yrs	1 to 2

E.4 Prototype Development and Integration

A prototype TAS was developed which satisfied the functional specification and based on the earlier Phase 1 development work. The prototype system consisted of the following major subsystems:

- Substantially passive, field mounted optical sensors comprised of a shielded sight tube, collecting and focusing optics, an internal grey body calibrator, and an air purge system.
- Optical fiber communication network comprised of a bundle of high IR transmissivity fibers communicating through air purged conduits connecting eight field sensors to a centralized signal processing system.
- A remote, multiplexed signal processing system acquiring the broad band optical data from all sensors and processing it to four narrow IR band passes having information content relative to melt temperature gradient.
- An operator interface using an industrialized personnel computer, operating in a windows environment, and performing the functions of data acquisition, displays, and disk logging (also modem connected to EER's Irvine Office).

Primary Phase II work consisted of developing the sensor and hardening the previously developed electro-optical components for the field demonstration. An in-situ grey-body calibrator was developed with an electrically energized, precision DC power supply and monitored with an embedded thermocouple. The calibrator could be actuated into the field of the sensor view from a nested position for remote manual calibration. All crucial electronics were placed in a NEMA 4 Enclosure which was temperature controlled with a Peltier, thermoelectric type cooling system with

a remote fan coil fluid cooler. This system was fully staged in the laboratory for functional checkout previous to field installation.

E.5 Installation and Commissioning

The TAS was installed on a forehearth at a local glass container plant. Two locations were selected which did not require coring new crown penetrations. Sensors were installed at the mid-forehearth and bowl positions. The TAS was commissioned within several days and operated continuously for four months, April through July of 1993. No maintenance was performed over this interval, scheduled or otherwise. The TAS continued to perform its primary measurement tasks indicating the overall reliability goals were likely to be met. The grey body calibrator did experience several component failures early on, the air actuator froze and the monitoring thermocouple became detached from the grey body calibrator. Failures are attributable to a significantly more hostile local environment than anticipated (post test sensor temperatures as high as 350°F were observed) Thermal discoloration of the mid forehearth mirror also indicates potentially higher temperatures. The bowl sensor after some initial drift remained extremely stable for the test period, the forehearth sensor experienced systematic drift of between 0.1 and 0.15°C/day, depending on measurement channel. This suggests, with some additional design improvement, that a stable platform might be developed which does not require an in-situ calibrator (a considerable design complication). Thus, some significant objectives of the program were readily demonstrated.

E.6 Prototype Test and Evaluation

All acquired optical band pass and thermocouple (triplex and TAS) data were continuously smoothed with a running average algorithm and logged to disk for future batch retrieval over the modem connection. The narrow band pass (4) measurements are essentially photon counts from the photodetector. The adjacent triplex temperature data was concurrently acquired. Times in which small glass temperature gradients were measured were used to calibrate the sensor channels. This data manipulation was performed off-line with a spread sheet program using daily data files. Daily data files were created so that any 24 hour (diurnal) effects due to production shift or ambient temperature could be more easily isolated and analyzed.

Initial scatter diagrams of reference (triplex) vs sensor (photon count) measurements indicated more than expected data scatter, although functional trends were theoretically correct, e.g.: they followed temperature power laws associated with broad (T^4) and narrow (T^5) band radiation. Considerable effort was applied to statistically bring out process parametric effects. A number of functional transformations, data set editing and pooling, and multiple regressions were performed to assess the information content of the signals. The mid sensor position was the most difficult to resolve because residual errors were of the same order as the gradients being measured ($\pm 8^\circ\text{C}$). Therefore most of the analyses focused on the bowl sensor where gradients were significant. The mid TC on the bowl triplex read consistently the higher (35°C) than the top and bottom locations.

The best correlations were obtained by using the average (bulk melt) of the triplex TC readings with the four transformed $S(\lambda)$ narrow band pass measurements. Regression correlation coefficient (R^2) for the pooled bowl data was a respectable 0.96. For individual triplex TC locations correlation coefficients ranged from 0.86 to 0.95. The resulting standard error of the estimate was $\pm 2.2^\circ\text{C}$.

Thus, the precision objectives ($\pm 1/2^\circ\text{C}$) of TAS functional specification were not met, but considering that typical bowl temperatures were in the range of 1100°C a very respectable accuracy of 0.2% of measurement was achieved significantly better than most single wave length pyrometers.

A post mortem was conducted with the system in EER's optical laboratory to determine if the source of the drift could be deduced through simulation. Fluctuating ambient temperature was strongly suspected as causing a significant portion of the measurement noise and drift. The "as found" sensor was installed on the pilot scale furnace and sighted at a black body target on the furnace floor. The sensor head was wrapped with electrical heating tape and was repetitively temperature cycled over 24 hours for three days. The sensor head was found to systematically generate perturbations on all optical channels causing effective noise or drift (Max to minimum) of 0.6 to 1.1%, consistent with the statistically predicted precision. The sensor head is relatively insensitive to temperature until 80 to 100°C is exceeded, then the effects are quite pronounced. Optical aberrations caused by minute thermal expansions of the optical components are suspected of causing changes in optical signal throughput. The sensor heads were then disassembled and carefully inspected. Outside of the previously mentioned grey body calibrator actuators whose

seals were severely deformed no obvious bowl sensor degradation was visually observed except at the tip of the sight tube. The mid-forehearth sensor mirrored surfaces were discolored, typical of heat stain rather than deposits, and could not be removed with an alcohol wash. This effect probably explains the long term negative drift of this sensor.

E.7 Recommendations

A number of test objectives were demonstrated during the field test, specifically:

- Robust electro-optic system design in a hostile factory floor environment.
- Multi-location, multi-point signal acquisition and transmission with low loss and good signal to noise ratio.
- Reasonable precision and fairly good stability considering the problems with the sensor head.

Clearly, the sensor head needs further hardening, better thermal design and simplification. It also has become painfully clear that in order to develop and correlate a deconvolution algorithm better test control is required than can be achieved in the field.

This project was initiated to fill a need in the glass industry for a non-contact sensor for measuring and taking control action on glass melt temperatures. The glass forming industry (e.g., bottle manufacturing) consumes significant amounts of thermal and electrical energy. Some 25% of the manufacturing cost is directly related to energy use. Careful control of temperature at the point the bottle is molded is necessary to prevent out-of-specification rejections. In general, the entire glass melting and conditioning process is designed to minimize rejection rate, maximize throughput and, thus, control energy and production costs.

This program focused on the design, development and testing of an advanced optically based pyrometer for measuring glass melt temperatures. The pyrometer operates simultaneously at four wavelengths; through analytical treatment of the signals, internal temperature profiles within the glass melt can be resolved. A novel multiplexer allows optical signals from a large number of fiber-optic sensors to be collected and resolved by a single detector at a location remote from the process. This results in a significant cost savings on a per measurement point basis. Reliability and maintainability are also significantly enhanced as critical electro-optics are located off process.

The development program was divided into two phases. Phase I involves the construction of a breadboard version on the instrument and its testing on a pilot-scale furnace. In Phase II, a prototype analyzer was constructed and evaluated on a commercial forehearth. This report covers the activities of both phases.

Glass Manufacturing Needs

The raw materials (silica sand and chemicals) are first melted in the furnace. Several streams of glass are extracted from the refiner section of the melter and delivered to the bottling machines through heated forehearths. The forehearths condition the glass, remove bubbles, and adjust the temperature. At the forming machine a "gob" of glass is punched out of the melt and blown in to a mold. Although the melter consumes the most energy, its temperature control is not as critical as the later processes. Industry has clearly stated that their greatest need is to provide precise, multipoint temperature profile data along the forehearth, the gob, and the mold surfaces. Higher quality measurements and improved process control are the most direct means of reducing rejection rates and improving energy efficiency. At present, the process is controlled by a

combination of operator experience, temperature measurements in various parts of the furnace refractory structure, and through the use of submerged thermocouples and single wave length optical pyrometers. Although submerged thermocouples provide the most direct measurements currently available, they are costly, are prone to drift, and they have short lifetimes. Thus, the critical needs identified by the glass industry are for improved temperature measurement in the forehearth, at the gob, and on the mold surface. Probably the most stringent requirement is sensor to sensor precision and sensor absolute precision ($\pm 1^\circ\text{F}$). Section 2.0 of the report details the industry survey that led to the selection of the targeted applications.

1.2 Summary of the Approach

The stringent accuracy requirements have identified a number of critical optical design issues needing development or design resolution:

- the need for a high signal to noise ratio, multicolor, non-contact pyrometer operating over a broad optical spectrum, 1 to 4-1/2 μm
- elimination of stray internal or external light (reradiated) which could bias optical measurements
- frequent, in situ calibrations against a precision, black body calibrator (speculative depending on inherent instrument stability).

Glass melts are somewhat transparent at certain IR wavelengths. With a typical opaque material, narrow wavelength optical pyrometry will receive radiant emission only from the surface. With glass, the emission represents a sum from various depths within the glass. At short wavelengths, most glasses tend to be more transparent, and the average signal originates from a greater depth. For longer wavelengths, the glass becomes opaque, and the signal represents the surface emission only. The mathematics for calculating the radiant emission from a glass with known properties and a given temperature profile were defined by Viskanta[1]. Thus, in theory, one can take emission measurements at several wavelengths, and through mathematical deconvolution, define the temperature profile within the glass. In the past, the difficulty has been the cost of obtaining the multicolor measurements in the required wavelength range. This we have addressed through the use of the optical multiplexer. The stray light issue was resolved through a

series of experiments which evaluated normal and off normal (Brewster's Angle) sensor configurations and employing narrow acceptance angle optics. A number of black body calibration techniques were also evaluated.

Work was sequentially focused on component development and breadboard testing in the laboratory. Performance was measured against a precision black body calibration source during these tests. A fully integrated breadboard with instrument control firmware was then evaluated in a series of controlled experiments on a pilot furnace with referee, calibration traceable, precision triplex thermocouples (2 sensors, six temperatures). Several design deficiencies were discovered and corrected during the pilot testing. A prototype was then designed and constructed which was fully functional except for deconvolution software for transforming the IR emission signals to melt temperature gradient. The field evaluation was performed at a local glass container plant. Sensors were installed at two positions, mid-forehearth and bowl, adjacent to existing triplex thermocouple locations. The system operated unattended and automatically for four months during which time the data acquisition system logged TAS and forehearth operating data to disk. Disk files were periodically dumped to PC spreadsheet files via modem for off-line data reduction and analyses. Daily files were statistically evaluated to develop functional forms correlating measured triplex data to the four IR measurement band pass centered wave lengths.

1.3 Applications Assessment

Temperature measurements are critical to the control of all pyroprocessing applications and most particularly to steel and glass fabrication. The requirements for accuracy and precision vary widely. Presumably, those process steps requiring real time, multiple location, precision measurement are least satisfied in the market and the obvious application focus for a TAS development and demonstration program.

The rationale for selecting container glass manufacturing as the target process, and the forehearth and forming operations of the glass production line as the most cost effective application are set forth below. This selection is based upon discussions with plate and container glass manufacturers, the manufacturers for forming equipment, and various consultants, associations and agencies connected with the industry. New technology developments such as light weighting of containers for production cost reduction are also considered. It is noteworthy that glass container and press and blown manufacturing, both of which use forehearths, consume about 64%

of the energy used in glass manufacturing [2,3]. Further, post melting temperature control (forehearth and annealing, uses 25 percent of this energy. Preliminary order of magnitude economics using reasonable assumptions suggested energy and production savings should result in a payback on total capital costs for improved forehearth control of less than a year and perhaps as low as half a year.

An aggregate market for steel, glass, and cement applications is estimated at 2865 units and is comprised of systems configured with 8 to 32 sensors. Glass applications dominate this market, comprising about 1800 units.

TABLE 1-1. GLASS INDUSTRY ENERGY USE PROFILES

Process	SIC	% of Industry Use	Annual Tons (10 ⁶)	Value \$(10 ⁹)	Post-Melting %
Container	3221	42	13.5	4.9	11
Press and Blow	3224	22	2.2	2.7	14
Fiber	3211	18	2.0	2.3	10
Flat		18	3.1	1.7	3

Ref: Battelle Rept PNC 5640, June 86.

2.0 PERFORMANCE SPECIFICATION

The development of the functional analyzer specification was initiated by defining furnace operating parameters and glass temperature along the glass path. Conditions are generally characterized by:

- Melt bulk and profile temperatures which are substantially influenced by boundary conditions surrounding the melt.
- The atmosphere over the melt, typically IR radiating and absorbing gases containing H₂O and CO₂ at higher temperatures and cooling air at lower temperatures.
- Progressively lower temperatures and gradients as the glass flows from the melting tank (2800°F) to the annealed product (1100°F).

2.1 Applications Selection

An industrial assessment was performed by integrating user and equipment manufacture input, a literature search, and considerations as to the inherent capability of the proposed instrument. Segments of the glass industry having large energy consumptions on both a unit production as well as average plant basis were first identified by SIC code, e.g.: container glass, pressed and blown glass, fiber glass and plate glass.

The most critical manufacturing step is glass conditioning (temperature and degassing) in the post melting operations. Glass conditioning effects production throughput, packing efficiency (shipped to melted weight ratio), and energy use. Temperatures typically are in the range of 2250 to 2400°F at the rear of the forehearth, and glasses are progressively cooled and homogenized as the melt flows to the bowl, typically at 2100 to 2200 , Figure 2-1. On a modern forehearth temperatures are measured with a triplex Pt-Rd thermocouples, Figure 2-2, at three cross sections (centerline and edges) for a total of nine positions.

Figure 2-1. Forehearth, spout & GOB geometry and process data.

Figure 2-2. Typical container glass forehearth temperature profiles.

In order to effect a control algorithm (usually feedback, sometimes feed forward) the TC measured gradients are normalized to a single weighted temperature commonly referred to as the "temperature gradient efficiency". The control strategy hopefully drives this efficiency toward a target (set point) value, close to 100% (no gradient).

The control logic determines where and how cooling, heating, or some combination are to be applied. Forehearth are typically 3 to 4 ft wide and 24 to 30 ft long. Glass surfaces are smooth because of low linear velocities and viscosity. Temperatures in the bowl around the plunger are the most critical and difficult to measure. Gob delivery (weight repeatability and formability) is highly dependent on viscosity at this point. Optical paths through the head space above the melt are typically 2 to 6 inches.

Forehearth are elevated from the plant floor some 8 to 10 ft and are surrounded by hot ambient, misty (mold oil release) environments. Thus, a TAS capable of relatively passive sensing and having a remote, floor mounted signal processing subsystem should significantly improve reliability and maintainability. Optical systems must be able to look around any optically interfering combustion products (H_2O or CO_2) above the melt to avoid interferences which could confound the radiosity measurement.

Discussions with glass manufacturers and review of the literature have identified three critical points in the forming process where improved temperature measurement is needed. These are:

- **Forehearth.** The temperature of the glass as it is moved from the melting furnace to the forming step is critical if the melt is to have the correct viscosity and surface adhesion properties for forming the product. The thickness of the glass flow at this point suggests that a surface temperature is of minor utility, while a full thermal profile is difficult to obtain. Conventional optical pyrometry measurements are difficult because high background radiation levels that interfere with the measurement. Also, broadband optical pyrometry tends to yield a mixed signal consisting of surface contributions at longer wavelengths and interior contributions at the shorter, more transparent wavelengths.

- Gob. This is the semimolten glass piece that is separated from the forehearth flow for insertion into the mold. Again, control of viscosity and surface properties are critical for optimum molding behavior. This operation takes place in a low background radiation environment. Although conventional optical pyrometry is more easily performed, the gob is cooling at a rapid rate. Thus, the appropriate measurement technique must respond quickly, and would ideally look beyond just the surface.
- Molds. The surface temperature is critical to obtaining appropriate surface finishes, and to obtaining good release of the product. This measurement also takes place in the absence of significant background radiation.

Lehrs are large convective conveyor ovens which anneal or temper glass product usually as part of a continuous production line. Annealing lehrs are not major energy consumers since the containers enter at high temperature from the mold machines and are typically held at about 1000°F over 10 to 20 minutes. Tempering furnaces usually start with a cold product and are therefore about twice as energy intensive.

Annealing lehrs process about the same tonnage as forehearths, but with a heat input of about half, Table 2-1. Temperature distribution (and variances) across the oven (ware and convective gases) and in the machine direction are critical. Control improvements have two benefits.

- Improved productivity, particularly when the melting and forming production are similarly improved.
- Better quality control since the conveyor line heat profile is matched to the cross conveyor product position.

Line production increases would be most significant for tempering operations since their speed is independent of melter pull rates and they are about twice as energy intensive. Annual energy consumption for tempering is not well documented and generally limited to laminated plate glass and kitchen ware, certainly well under 25 percent of the annual glass production and, again, with less overall impact than the forehearth application. Thus, convective ovens are significantly

TABLE 2-1. CURRENT GLASS PRACTICES IN INSTRUMENTATION
AND CONTROL

Primary Steps	Glass Temp. ^{OF}	Efficiency M ² Btu/Ton ²		Current Practice
		Range	Avg	
Melt	2600-2800	3-8	5	Bridgwall Temp/Models
Refine	2200-2400	0.05-0.2		Submerged Probe/ Pyrometers
Condition ³	1900-2100	0.1-0.5	0.3	Submerged Probe/ Pyrometers
Form	1900-2000	0.015-.04	.02 ¹	Pyrometer at Setup
Temper	1000-1200	2.5-6	4 ¹	Recirc. Air Temp
Anneal	900-1200	0.05-.5	.20	Recirc. Air Temp

¹Primarily electrical, converted to fuel equivalent assuming a utility heat rate of 11,800 Btu/kW-hr.

²M² = millions of Btu's

³Condition process performed by the forehearth

less energy intensive and do not have the economic leverage of the conditioning and forming operations.

Measurement methods, Table 2-2, have tentatively been selected from a review of the literature [4 through 13] and incorporate both current practice as well as experimental procedures developed by glass researchers. Current state-of-the-art optical pyrometers primarily use narrow or broad band radiation in two distinct regions of the glass transmissivity curve, Figure 2-3,. These are nominally in the .7 to 1 micrometer (μm) which is visible to very near infrared, and the 4-1/2 to 5-1/2 micrometer which is mid-infrared. Glass optical characteristics at each of these two wavelengths have unique properties which enhance functionality; for example, in the near infrared (almost visible), glass has a very high transmissivity. Instruments sighted at these wavelengths typically measure radiation coming from both the surface and the bulk glass, perhaps representing an average some 2 to 3 inches into the glass. The measurement is susceptible, however, to stray external radiation since glass is also fairly reflective in this wavelength range; i.e., it's apparent emissivity is relatively low. Conversely, when moving to the mid-infrared range the glass emissivity is very high (glass is almost opaque) and therefore its reflective characteristics are relatively low. This, then, provides a fairly accurate surface temperature but give no indication of the temperature gradient below that surface.

The ability to transmit narrow or broad band radiation signals over optical fibers provides significant operational enhancements:

- The signal is immune from electromagnetic radiation and radio frequency interferences caused by electrical machinery.
- Sensitive signal processing (electro-optic and electronic) can be remote from process.

Glass temperature gradients with depth have been experimentally measured using multiple, narrow band multi-wavelength radiometers. Discussions with Professor Viskanta of Purdue University [14] and other literature [15], suggest, that depending upon the physical properties of the glass being measured, between three and five IR wavelengths are optimum. Additional wavelengths to more precisely resolve the temperature vs. wavelength curve, unfortunately also require a higher level of mathematical inversion with its own errors. There is actually an optimum

TABLE 2-2. COMPARISON OF ADVANCED NON-CONTACT TEMPERATURE SENSORS

Item	Mfg.	Product	Optical Fibers ¹			Pyrometry ²			Signal Processing		
			Sen- sor	Tran.	S/P	Color, μm			Target Ref.	MUX ³	μP
						1	2	4			
1	EER	Thermal Analysis System	X	X 20m	X			1/4	Diode Laser	Optical 8-Chan.	X
2	Ircon	Mirage OR Series		X 3m			0.7/ 1.08				
		OZ Series				0.7/ 1.08					
		T Series				2/4					
3	Raytek	Thermalert II				X					X
4	Bloom	Energy Eye					X		X		X
5	William- son	Tru Temp 9100	X	X			0.71/ 0.81			Optical 5-Chan.	X
		Fiber View 6200EP	X	X		2.0/ 2.4					
6	Pyrometer Instruments					X 0.865			IR Laser		X
7	Vanzetti	TM-2 & Vanguard 2		X Couples Sensor to Detector		X 4.5/5.2	X Bifur-cated Fiber			Elec-tronic	X
8	Land	WTA 135/System 3		X 3m		0.7/1.0	0.7/1.1	Second Sensor on Wall			X
9	Accufiber	Model 100	X	X	X					Elec-tronic 8 Chan.	X

Notes:

¹(Trans) signal transmission between sensor and detector, (S/P) spectrometer components.

²1 (one color broad band with no corrections), 2 (two color ratio, gray body assumption), 3 (three color grey body correction), Ref (with special target for reflected radiation or emittance).

³Optical (optical with common detector) or electronic (MUX after detectors).

GLASS SPECTRAL BEHAVIOR--A PROBLEM OF CONSTRAINT OPTIMIZATION

Figure 2-3. Optical approaches using various glass properties.

number in the range of 3 to 5 wavelengths. Therefore, it would appear that the optical design criteria for the proposed instrument should include:

- A minimum of four widely separate measurement wavelengths incorporating the range approximately between .7 and 4.5 micrometers.
- The ability to look deep into the glass without being concerned about boundary conditions at the glass, ceramic back wall interface.
- The ability to transmit this collected light over a fiber optic communication system with low attenuation and high signal to noise ratio.

The literature generally indicates that IR radiation internal to the glass much below 6 inches will not provide sufficient signal to deconvolute temperature. Therefore, the technology is constrained to those parts of the glass manufacturing process where the glass melt or product is relatively thin; i.e., forehearth, gobs, forming mold machine and post-forming tempering and annealing. Based upon this assessment a functional and performance specification has been developed as discussed below.

2.2 Performance and Functional Specification

Based on the previous discussion the advanced sensor should have performance similar to the current state of the art, Pt-Rd triplex, submerged thermocouples:

- less than 50°F drift over life
- ability to look between 4" to 6" into the glass
- installation through a 1" diameter hole in refractory walls
- compatibility with a wide range of glass optical properties (color and absorptivity)
- precision and accuracy close to the ± 1 to 2°F usually claimed for competing triplex TC measurements.

The resulting functional specification, Table 2-3 is the product of discussions with forehearth manufacturers and the Glass Firing Task Group of the Glass Packaging Institute. The result of this activity and the development efforts of a parallel sister program, the development of a moisture analyzer (MAS), were then integrated. MAS component design modifications (optical and software) were identified needed to implement the functional specification and the contemplated measurement methods. The resulting conceptual design was then used to develop a provisional capital cost, and estimate the economics of the selected application.

2.3 Projected Market

The market potential for various configurations of TAS was estimated for those industries and processes where a high penetration can be projected, Table 2-4. There are other specialty, high value added applications not addressed such as continuous manufacturing lines found in high production consumer goods (automobile and appliance paint lines [16] and the electronics industry, ceramic solid state devices) where critical temperature/time control is also required. The estimated provisional market breaks down by TAS configuration as follows:

- Large Scale Systems, 16-32 sensors, 1795 units
- Small Scale Systems, 8 sensors, 1070 units.

TABLE 2-3. GLASS SENSOR APPLICATIONS AND FUNCTIONAL SPECIFICATION

1. Process Description

1.1 Location	Melt Depth Inch	Temp °F		No Temp. Sensors	
		Surface	Melt	Surface	Subsurface
a) Glass Tank		2800-2900	2300-2600	12-24	na
b) Refiner	36-60	2700	2100-2300	3-6	3-6
c) Forehearth	4-8	2200-2400	2100-2300	12-18	12-18
d) GOB/Spout	1-3	-	1900-2100	1-4	1-4
e) Mold, ON/OFF	1/16-1/4	100-500	1900-1200	1-3/section	na

1.2 Interferences

- a) Wall Radiation, differential °F 100-500
- b) Atms 12% H₂O, submicron particulate

1.3 Glass Properties

- a) Index of Refraction 1.30 to 1.48
- b) Transparency, % 0 to 80, 3.3 to 1.5 μm

2. Instrument Performance

- 2.1 Repeatability, °F ±1
- 2.2 Precision, °F ±1
- 2.3 Calibration/Stability, °F/mo. ±2

3. Instrument Interfaces

3.1 Installation Considerations

- a) Component Interconnection
 - Sensor to Shop Floor,m Ground Level, 20-40
 - Cabinet to Control Room,m 100-200
- b) Sensor Environmental
 - Temperature, °F 140°F
 - Vibration 60-200 Hz
 - Contamination Oil Mist

TABLE 2-3. GLASS SENSOR APPLICATIONS AND FUNCTIONAL SPECIFICATION

c) Mounting	
• Permanent Furnace Locations	Thru Refractory
• External Tripod Mount	Portable or Bracket
• Structural Interfaces	1" Penetration thru Ceramics
d) Utility Support - Power	
- Purge Air	110V, 60Hz 10 scfh/Sensor
3.2 Operator Interaction	
a) Control Strategy	Feed Forward, Cascade Back
b) Maintenance Access -	Sensor Head Quick Disconnect
-	Electronics Floor Level
c) Displays	LCD/CRT
4. Design Characteristics	
4.1 Hardware	
a) Sensor Hardening	Passive, SS
b) Electronic Chassis/Enclosure	NEMA 4
c) Computer Architecture	Std Bus
4.2 Communications	
a) LAN Configuration	Star, Multi-Drop Daisey
b) Software/Firmware	DOS/Std Bus
c) Diagnostics	Self
d) I/O Devices/Ports	RS232, 16 I/O Count
4.3 Control	
a) Internal Instrument	Digital, "C" Language
b) External Loop	PID Direct and Cascaded
4.4 Maintenance	
a) System Level	PC Card Replacement
b) Spare Parts	10% of Cost
4.5 Cost	
a) Investment ¹	2200 to 8000 \$/pt
b) O&M ²	200 to 800 \$/pt/yr
c) Payback, yrs	1 to 2

¹Based on current cost of tri-level, submerged thermocouples.

²10% of investment, current submerged TC's need replacement every 9 to 36 months at over \$500/unit.

TABLE 2-4. PROVISIONAL MARKET ASSESSMENT

Application ¹		Equipment		TAS Config.		Note
Industry	Process	Temperature Range, °F	Units	# Sensors	#λ ⁴	
Steel	Reheat-Mill	70-2200	495	16-24	3-4	2
Steel	Reheat-Forge	70-2400	500	8	3	2
Steel	Annealing	70-1400	70	8	3	2
Glass	Forehearth	2000-2400	650	16-24	4	3
Glass	IS Mold	1000-2000	650	16-32	3-4	3
Glass	Anneal/Temper	800-1200	500	8	3-4	3
Cement	Kiln	2200-3500	-	8	2-3	2

Notes:

- 1, Continuous, high production, large equipment volumes or lengths.
- 2, Instrument corrects for reflection and/or departures from grey body.
- 3, Instrument measures glass radiance at different depths.
- 4, Number of band pass filters required to resolve temperature

EER implemented a two-phase project. In Phase I, a breadboard TAS was designed, assembled and used to measure glass temperatures in a laboratory pilot scale furnace. The "proof of concept" test provided key data for the design of a prototype instrument. The focus of Phase I was the evaluation of the two measurement concepts, normal and Brewster's angle, multicolor pyrometry. In Phase II, the prototype instrument was constructed, installed, and tested on a glass forming line. A large glass container (bottle) manufacturer in California participated as a host demonstration site.

The Phase I Development and Laboratory Evaluation objectives were to:

1. Develop the sensors and appropriate signal processing instrumentation which enables remote measurement of surface and subsurface radiosity in the mid infrared and visible wavelengths.
2. Develop radiation models which will determine glass temperature based on sensor radiation measurements.
3. Conduct pilot-scale furnace studies to verify that the EER Thermal Analysis System will accurately measure glass temperatures.
4. Select a glass manufacturing application and assess its cost effectiveness.
5. Develop a plan and design a full-scale system for field evaluation in a suitable glass furnace or process.

These objectives were fulfilled in a six task development program:

- Task 1 — Assessment and Applications Characterization
- Task 2 — Sensor System Development
- Task 3 — Laboratory Scale Furnace System Development
- Task 4 — Laboratory Study and Verification
- Task 5 — Engineering Design and System Economics
- Task 6 — Phase I Report

The results of this work are summarized below and discussed in an interim report [20]; the demonstration program is discussed in Section 4.0.

3.1 System Design

The stringent accuracy requirements have identified a number of critical optical design issues needing development or design resolution:

- The need for a high signal to noise ratio, multicolor, non-contact pyrometer operating over a broad optical spectrum, 1 to 4-1/2 μm
- Elimination of stray internal or external light (reradiated) which could bias optical measurements.
- Frequent, in situ calibrations against a precision, black body calibrator (speculative depending on inherent instrument stability).

The heart of the system is the optical multiplexer shown in Figure 3-1. This system was originally developed as part of an IR moisture analyzer system, but was modified for the current application. The off process multiplexer is capable of accepting eight optical fibers, and exposing each of four narrow bandpass filters. The multiplexer accomplishes this through a rotating commutator. For each rotation of the commutator, light from each fiber is briefly focused through each filter and onto the detector. Thus, 32 distinct optical signals are received by the detector during each rotation. To accommodate the wavelengths needed for this application (1.6 - 4.5 μm), the fiber material was changed from high purity silica to a heavy metal fluoride composition. Several other components were also redesigned to expand the wavelength performance, and an extra lens was added to the optical multiplexer to reduce chromatic aberration over this larger wavelength range. The pulsed signal from the detector is amplified and digitized by an optical bench interface card. The card communicates with an external computer via standard bus computer architecture for data acquisition and eventually for automatic process control. A personal computer operating in a windows environment was used for data acquisition, Figure 3-2.

Figure 3-1. EER optical multiplexer.

Figure 3-2. TAS firmware.

The light collectors are conceptually passive and simple, and are compatible with the harsh environments of the production line. The optical signal is collected by off-axis parabolic mirrors and focused onto the ends of the fibers. The entire assembly is contained within a metal cylinder, including the alignment hardware for the fiber pickup. The fibers are contained within flexible air purged, metal conduit and connected to the remote signal processing system/multiplexer located on the factory floor or in the control room.

An optional in-situ calibration system in several configurations was also developed. Several black body calibration techniques and configurations were conceived and evaluated including hot wires, commercial calibrators and miniaturized targets. An in-furnace, instrumented SiC target was found to be the stable and accurate for pilot scale furnace performance testing. A resistance heated ceramic element which could be translated in and out of the field of view of the sensor for periodic on process in-situ calibrations was also designed, fabricated, and evaluated in the field test.

3.2 Pilot-Scale Furnace

Tests were initially conducted in a box furnace rigged to perform as a pilot-scale test system. The furnace, shown in Figure 3-3, consists of a box cavity of dimensions 12" wide by 20" long by 12" high. Two crucibles placed in the furnace hold the melt (9" high by 6-3/4" diameter). These are instrumented with state-of-the-art triplex submersible thermocouples, Figure 3-4. One crucible sits on a water-cooled plate. This is used to extract bottom heat, to establish a steady-state temperature gradient in the glass. A small catalytic combustor (platinum gauze) is mounted outside the oven, and is used to supply the oven with combustion gas for atmospheric interference tests. The maximum oven temperature capability is 2250°F.

Initially, the furnace and sensor were used to address a number of preliminary design issues. These included:

- Fiber Diameter. The amount of signal transmitted to the detector is proportional to the cross-sectional area of the fiber. Several fiber sizes were tested to select the minimum size that yielded acceptable signal. Both fiber flexibility and cost motivated the need for minimizing the fiber diameter. A diameter of 450 μm was selected for initial development work. Due to availability and poor transmission

Figure 3-3. Pilot scale glass furnace.

Figure 3-4. Reference thermocouple.

characteristics the field demonstration employed a five strand fiber bundle with a 600 μm outside diameter.

- **Signal Recovery.** Proper matching between source output, sensor aperture, optical throughput and detector responsivity are essential to achieving a usable signal. Errors in design and misalignment will also lead to unacceptable losses. A black-body cavity was used to inject a known radiance into the optical system. The signal recovered at the detector was analyzed to determine losses. The actual signal corresponded to 35% of the theoretical signal, with a signal to noise ratio of 30. The "order of magnitude" test showed that the optics were not overly sensitive to alignment and that the optical system was properly matched to the application. Wider band pass filters were selected for subsequent tests to increase signal levels.
- **Calibration.** Several calibration sources were investigated for the pilot and field test. The pilot black body was an instrumented, in-furnace notched silicon carbide block. The emissivity of the block exceeds 0.99, which introduces little error into the calibration relative to a full black body. A ceramic, electrical resistance element, typically an ignition source for gas appliances was used in the field test sensors.

3.3 **Optical Data Acquisition**

Signal integrity can be affected by several types of interferences originating in either the process or along the instrument optical path. Components were therefore evaluated in simulation environments to confirm design insensitivity. Most of the pilot testing focused on four wavelengths (2.4, 3.0, 3.5, and 4.0 μm). These wavelengths were selected to obtain good melt temperature resolution while avoiding water and CO_2 absorption bands which are pervasive in the spectra of interest. Two types of glass were used, a green glass and a flint glass.

Absorbing Gas Interferences

The first test series examined the influence of the background gas on the signal. Testing was usually performed with a furnace air atmosphere. During the course of one isothermal test, the air flow to the furnace was replaced for 70 minutes with flue gas from catalytic combustor. After this, the furnace was again purged with air. No significant change in signal was associated

with the change in furnace atmosphere. This was expected, because each of the measurement wavelengths was selected to avoid water and CO₂ absorption band interference.

Radiation Signal Collection

One of the most important problems faced in furnace optical pyrometry is avoiding contamination of the signal by stray internal light and process background radiation. This is a particular problem in forehearth applications because the use of gas flames above the glass can heat the roof of the furnace to temperatures above that of the glass. Thus, the pyrometry signal can become affected by high energy reflected radiation. Two approaches were investigated to mitigate these effects, shielded: normal angle pyrometry and Brewster's angle pyrometry.

Normal angle pyrometry makes use of the fact that glass reflectivity is relatively low at a normal angle with the surface. In the theoretical limit, a sensor mounted over the glass would see only its own reflection, and reflected radiation originating on the hot walls would not find its way into the light path. In reality, the sensor has a small acceptance angle, which means that some thermal radiation from the walls near the sensor can be reflected off of the glass surface and into the light path. This effect was minimized by placing a small cooled collar around the sensor. The effectiveness of the cooled shadow concept was evaluated by wrapping an electrically heated coil around the cooled collar region. The test showed that the hot coil did not influence the glass signal unless it was inserted into the light path. For these tests the coil was heated to 2300°F, a temperature significantly above that of the glass. Thus, it was concluded the properly executed normal angle pyrometry provides a simple approach to glass melt radiation collection. Note that the collar does not have to be cooled to room temperature. All that is necessary is to cool it to the point where its thermal radiation becomes insignificant relative to that of the glass. Because glass emission is such a strong function of temperature, the collar only needs to be air cooled to 400-500°F below the glass temperature.

Brewster's angle pyrometry is based on the fact that light reflected from dielectric surface (such as glass) is polarized into one plane at the Brewster's angle. By monitoring the glass melt at this angle and using a polarizing filter, all of the reflected radiation can be removed. Initial tests with this approach did not meet expectations. Although the reasons for the poor performance were not fully assessed, it appeared the glass may have lost some of its dielectric properties at high temperatures. Also, Brewster's angle is wavelength specific. Thus, although one of the four

wavelengths used in these tests may have been correctly aligned, the other three would not have been at their critical angles. The Brewster's angle approach was abandoned in favor of the normal angle approach.

The measurement wavelengths were first calibrated against the in-furnace black body to relate detector photon count to temperature. Glass emissivities were derived by comparing color pyrometry measurements from the optical bench with glass thermocouple measurements. The differences between the color measurements and the actual thermocouple readings were attributed to the emissivity, which was generally found to be of the order of 0.9. Emissivities were estimated for each of the two glass types, and each of the four wavelengths over the full temperature range.

Glass absorption coefficients were acquired from the literature. These vary with glass type, wavelength and temperature. Under normal circumstances, these properties should be measured for each glass type under each application.

Temperature Profile Resolution

Two types of temperature gradients were investigated. The first is a time-unsteady gradient induced in the glass by a change in the furnace set point. Due to the high thermal inertia of the glass, over 100 minutes is needed for equilibrium to be reestablished. Figure 3-5 shows the uncorrected color measurements for each of the four wavelengths with time.

These were resolved into temperature profiles using a simplified procedure. An equivalent isothermal temperature was defined from Planck's equation using the radiation measurements of each wavelength which estimates the measured radiance. If a wide range of hypothetical temperature profiles are analyzed with the Viskanta equation [12], one finds that these calculated isothermal temperatures cross the non-isothermal profiles at nearly the same depth. This suggests the temperature profile can be developed by (1) measuring the radiant emission at each wavelength, (2) calculating the isothermal temperature that yields the same emission, and (3) assigning this calculated temperature to a given, fixed depth. Thus, little error is introduced by simply assigning an invariant depth to the calculated isothermal temperature. A stable subset of the pilot test data was evaluated with this technique.

- Plot shows T.C. data and raw color temperature data.

- Optical pyrometer is clearly following the increasing temperature. Is the gradient resolvable?

Figure 3-5. Transient gradient data.

Figure 3-6, each of the four wavelengths generates one data point at a specific depth for specified time. The close relation between the temperatures, and the gradients suggests the power of the approach. It is worth noting that this is a relatively mild gradient, only corresponding to 7°F/inch.

A more powerful technique (not used because of relatively high signal noise) is to hypothesize a temperature profile. The Viskanta equation is then used to calculate the expected radiant emissivities at each wavelength. These are then compared to the measured values. The relative error in measured and the predicted temperature is sequentially minimized by adjusting the trial temperature profile. This procedure is appropriate for any arbitrary temperature profile. For instance, the temperature can be specified at four depths, and a spline routine can be used to derive a physically realistic functionality between the points that can be integrated with the Viskanta equation. Alternatively a specific functionality, e.g.: parabolic or linear, can be assumed for the temperature, and the parameters within the functionality are adjusted to minimize the error.

3.4 Pilot Furnace Interim Results

As a consequence of the early pilot furnace test a significant advancement of the state-of-the-art was made toward satisfying the program objectives. Significant functionality of the instrument system was demonstrated including:

- multiple sensors communicating over an optical fiber network to a common, remote, multiplexing spectrometer
- in situ, sensor specific black body calibration
- temperature profile resolution with two highly diverse container glasses
- operational compatibility with the process environment (temperature, reradiation, and combustion gases)

The most significant design shortfalls were:

- depth measurement of 2" demonstrated, target of 6"

Figure 3-6. Reference TC profile and TAS depth measurements.

- a demonstrated accuracy of $\pm 4^{\circ}\text{F}$ on the edited low noise data, target of $\pm 1^{\circ}\text{F}$

The depth penetration shortfall resulted from what turned out to be a non-optimum choice of visible, near infrared measurement wavelengths. This is easily corrected, requiring only the replacement of band pass filters transmitting closer to the visible in what is the high resolution operating regime of the instrument.

The breadboard tests identified two general areas where design improvements to the system were needed to enhance accuracy and precision. The first is signal noise. In general the signal to noise ratio, between 160 and 650, should not be strongly effecting data quality. However, it was suspected that the noise is generated by slackness in the chaindrive that rotates the multiplexer wheel. Replacing the chain with an notched rubber drive belt should reduce the noise.

The second area of concern is long term drift. For many data sets, the average signal outputs were constant over runs of several hours. There were instances, however, where the signal of all four wavelengths would inexplicably begin drifting in the middle of an otherwise invariant run. This behavior was even noted during long term runs with the calibration source, which eliminated changes in the glass properties as an explanation. The drift was suspected to come from the detector or its supporting electronics. Specifically, the detector is mounted on a solid-state thermoelectric cooler that is designed to maintain a constant temperature. Temperature control is critical because it strongly affects detector response.

3.5 Hardware Redesign

The following design modifications were made to correct the long term drift and short term noise.

- The metal chain multiplexer drive was replaced with a precision timing belt.
- The signal processor NEMA 4 enclosure was actively temperature controlled to within $\pm 1/2^{\circ}\text{C}$.

Noise Reduction

The drive system was redesigned with a belt drive to replace the chain drive. This rendered a much smoother operation of the optical bench with minimal rpm variations. A twin core belt was implemented which was originally designed for precision alignment and positioning applications. The belt offers smoother operation than possible with the chain and does not have the chordal rise and fall (camming effect) of a chain. Additionally the belt does not stretch. Compatible drive sprockets were machined to fit on the optical bench. The motor bracket also was modified to accommodate the change in alignment resulting from the use of slightly thicker sprockets.

A highly stable ($\pm 4^\circ\text{C}$) black body calibration reference was used to characterize the performance of the TAS before modification, Figure 3-6. Note that the scale of this and all subsequent figures have greatly expanded raw count scales to highlight small changes.

The use of the precision timing belt greatly smoothed the operation of the optical bench. Figure 3-7, shows the raw data for a 24 hour period with the new belt showing a three fold reduction in the system short term noise. Through the use of additional digital signal processing, the systems short term resolution stability at 1000°C has been improved to approximately $\pm 1/2^\circ\text{C}$. The results of these tests suggest the system drift must be attributable to something other than the optical bench drive system.

Temperature Stability Characterization Tests

Long term stability testing of the TAS was conducted with the sensor viewing a black body reference at 1000°C for several 24 hour periods. The results of these tests indicated little improvement in long term drift. During a 24 hour period, the signal would drift over a range of approximately $\pm 3^\circ\text{C}$ (Figure 3-8 shows a typical day). After several days of testing a pattern emerged that suggested the measured temperature was related to ambient temperature variations in the lab. Components of the system, (i.e., Sensor Head, Optical Bench, Electronics, etc.) were then subjected to temperature extremes through the use of a small heat gun and a freon mist spray. The effect, if any, on the signal output was observed. The results of this test showed that the optical bench and the optical fiber had a measurable and sometimes significant temperature sensitivity.

Smoothed (25 pnt) Signal Response to Continuous Black Body Radiation (1000°C) - Filter 1

Figure 3-7. Comparison of noise reduction with optical bench belt drive modifications.

Blackbody Stability Test 11/29/91-12/5/91

Figure 3-8. Stability test with temperature controlled signal processor enclosure.

Thermal expansion of the optical bench could result in small changes in the relative positions between the lenses and detector. These changes will vary the spot size of the infrared radiation incident on the detector, thus affecting the detector output proportionally. Although this type of error was previously believed to be negligible, a worst case optical path analysis showed a surprising result. A change in optical bench temperature of 3°C could result in a 0.5% (3°C at 1000°) change in detector signal level.

Further testing was conducted to determine the effect of changes in the ambient (external) temperature on optical fiber transmittance and detector output. It was expected the thermal effects would be minimal, though as a result of the high degree of precision required of the TAS it was known that a 0.5% change in transmittance could result in a measurable system error. Uncontrolled 'shock' tests were performed on the fiber by heating approximately 7 meters of the fiber with a heat gun. Results of these tests, which are quantitatively estimated in Table 3-1, showed there was a measureable thermal effect at all wavelengths and that F4 (4.0 μm) was the most strongly influenced. For all practical purposes, with the exception of F4, the thermal effects of the fiber could be calibrated out in a typical operating environment.

TABLE 3-1. OPTICAL FIBER THERMAL ERROR

<u>Filter Wavelength</u>		<u>Fiber Temperature Error</u>	<u>Detector Temperature Error</u>
		(chg in reading/chg in temp•unit length)	
F1	(2.4 μm)	-0.01°C/°C•m	-7.2°C/°C
F2	(2.6 μm)	-0.01°C/°C•m	-8.0°C/°C
F3	(3.6 μm)	-0.02°C/°C•m	-10.0°C/°C
F4	(4.0 μm)	-0.08°C/°C•m	-11.6°C/°C

The detector sensitivity was even more pronounced. The error effect and thermal stability of the detector thermo-electric cooler (TEC) was characterized by varying and recording thermo-electric cooler (TEC) thermistor voltage and hence the detector temperature. The results are also shown in Table 3-1. Since the detector is held at ±0.05°C under normal operation it was not directly targeted as the root cause of the long term drift. It should be appreciated that the reference black body temperature calibrator is also a potential ambient temperature sensitive error source (at best it has a ±1°C accuracy)

Pilot Scale Design Confirmation

Additional proof of principle testing in the pilot scale furnace was attempted to evaluate the performance of the modified system. Unfortunately, resolution at depth was difficult. An investigation as to cause centered around the fact that all glass melts used in these tests had visually observed bubbles and seeds. The optical effect can be considerable since the bubbles significantly distort the optical path, resulting in signal scattering and losses due to:

- Diffusional scattering due to micro bubbles.
- Mie scattering from bubbles with diameters greater than the measurement optical wavelength, i.e.: Refraction and reflection at the gas bubble-melt interface.

The significantly higher bubble content relative to earlier pilot testing is primarily due to a deteriorated furnace and a conscious decision to run at lower melt temperature, 1800-2000°F (980-1100°C) and shorter residence times (days instead of weeks) which provided significantly less degassing. It should be appreciated that glass refiners in commercial plants are typically operated at 2600°F (1425°C).

In-Situ Black Body Calibration

An approach to correcting long term drift is to provide frequent, automatic in-situ calibrations of the sensor. Since drift may be caused by a component deterioration along the optical path (sensor mirror to photo detector) placement of the calibration source within the sensor sight tube was deemed desirable. A number of broad band infrared illumination source designs were conceptualized including:

- Electrically heated ceramic strips and wires (with and without a reference temperature sensor).
- Process heated targets with temperature sensors.

Several ceramic strip heaters commonly used for gas appliance pilotless ignition were selected for initial evaluation because they are relatively inexpensive (\$10/Unit) in production

quantities, have good black body emission characteristics, and exhibit good reliability through repeated temperature cycles. The strip heater was placed on an axially translating solenoid driven actuator for insertion into the optical path. The frequency of insertion and data acquisition can be under the control of the analyzer CPU. A longer term cycling test was initiated to evaluate stability and repeatability. The best strip heater was initially stable, but after about 48 hours of operation started to show unacceptable variability. This approach clearly will require a significant development effort to perfect. An alternate calibration approach assuming that good short and long term stability can be achieved with the modified prototype would employ the following procedures:

- Core a second hole (1" dia) next to an existing TAS sensor.
- Periodically (field test to determine) insert a triplex thermocouple and initiate a sensor calibration mode (all automatic under analyzer control).

This approach returns the concept to a simple passive sensor design and a calibration relative to an industrial standard. Some additional instrument technician labor is incurred, but it should be modest if system stability is sufficient to require only monthly calibrations.

Interim Results and Conclusions

The detailed analysis and testing of the modified sensing system is summarized below:

- Analyzer long term drift and short term noise improvements have resulted in inherent accuracies of about $\pm 1/2^{\circ}\text{C}$, about equivalent to the black body calibration source.
- Four different concepts of heating elements were evaluated for use in an in-situ secondary calibration source. The use of a SiN igniter element shows some promise, but requires considerable development.
- The black body reference is the source of some of the apparent diurnal analyzer drift due to ambient temperature changes.

- The analyzer has strong ambient temperature sensitivities, specifically the detector and optical bench, which can be substantially mitigated with good internal temperature control (enclosure and detector).
- Pilot furnace tests using poorly degassed glasses resulted in data which make conclusions regarding the effects of glass composition and radiant resolution impossible.

The impact of vapor inclusions in the glass melt can yield a significant degradation in depth measurement capability as a result of Mie scattering from the bubbles. The degree of degradation depends on bubble size and number density.

The above conclusions indicate the significant progress towards correcting previously found deficiencies was achieved and has revealed the limitations of the pilot scale test program. Improvements in glass homogeneity, ambient temperature compensation and calibration techniques should increase the probability of achieving the accuracy goals in the Phase II program.

4.0 PROTOTYPE DESIGN, FABRICATION AND FIELD EVALUATION

The second phase of the project integrated the findings of the development phase into a prototype design for field test and evaluation.

4.1 Objectives and Plan

The objectives of this phase were to:

- Demonstrate that the design is sufficiently robust for the operating environment.
- Confirm that the functional and performance specification developed earlier in the program can be substantially met.
- Use the acquired data to correlate a melt temperature predictor algorithm.
- Perform man in the loop forehearth control with the fully functional hardware and software.

This program phase was performed in five sequential tasks:

Task 7 — Installation Design and Startup

Task 8 — Test and Data Acquisition

Task 9 — Data and Economic Analysis

Task 10 — Phase II Report

Task 11 — Technology Transfer

4.2 Preprototype Sensor Design

The field evaluation program imposed new functional requirements of the sensor that could not be accommodated with the breadboard pilot furnace sensor. A new sensor was designed which was optically identical to the sensor used in the pilot scale program, but adapted to the environmental and process constraints of the demonstration site. This section describes the functional requirements and design of the preprototype sensor.

The demonstration sensor head was designed to incorporate four basic functions. These were to 1) collect radiation emitted perpendicular to the glass melt surface and focus it into the optical fiber, 2) minimize collection of external background radiation, 3) allow for an in-situ calibration check, and 4) incorporate an air purge for cooling. Given that the forehearth is considerably larger than the pilot scale box furnace, the sensor needs to be positioned a greater distance from the melt surface. The sensor was designed to collect light being emitted nearly perpendicular to the melt surface to minimize background reflections. Designed in this way, the sensor could only "see" its own shadow and therefore should not pick up stray radiation reflected from the glass surface. Light collection was achieved by using an off-axis parabolic mirror targeted on a very small spot on the melt surface imaged onto an optical fiber having a collection area of about 650 μm in diameter. This small spot results in a very small acceptance angle of $\pm 0.34^\circ$, however this small angle coupled with a maximum forehearth crown penetration diameter of 1.5 inches limited the sensor length to 36" as measured between the parabolic mirror and the melt surface while maintaining a 0.75" aperture.

The sensor designed for the pilot scale laboratory testing incorporated a cold ring that provides a shadow to fill the reflected radiation field of view of the sensor. This cold surface does not emit enough radiation to cause background interferences because of its low temperature. The same principle was used in the field designed unit, however, because the glass industry reacted negatively to a water cooled sensor concept an air cooled sight tube was developed. This design incorporated a primary sight tube with low purge and concentric outer tube with high air purge flow. The cooled sight tube walls should not self radiate and have a sufficiently large diameter so that the background radiation could not be collected by the sensor.

The last function incorporated into the sensor was an internal black body calibration check. Its primary function was as a reference to determine optical path or electronic degradation. A composite ceramic/metallic heating element was designed into the sensor to serve as an in-situ calibration source. A wedge mirror was positioned on a sliding platform which could be moved in and out of the view of the parabolic mirror. The platform was actuated by an air cylinder mounted on the side of the sensor. The moving platform allows for periodic system checks. This element must be extremely optically stable and repeatable over time. To achieve this objective a thin coat of aluminum oxide adhesive was applied over an electrically heated, ceramic element which operates stably at 1200°C. Second, a thermocouple was attached to the element so that its stability could be

monitored and used to compensate for any drift in the black body calibrator. Figure 4-1 shows the component general arrangement within the sensor.

4.3 Installation Design

The TAS is made up of four major subsystems, the sensors (including fiber), the signal processor, the environmental control system for the signal processor and the data acquisition system. The installation of each of these systems is discussed below.

Sensor Installation

Two sensors were installed on a forehearth at a local container plant. This forehearth was selected because the signal processor could be located in a non-hostile environment and connected with minimal fiber runs to the sensors. Additionally, this forehearth had several openings that allowed sensor viewing of the glass melt without the need for cutting holes in the forehearth refractory crown. Figure 4-2 shows a sectional elevation view of the forehearth and the locations of the sensors. The first sensor was located at the "middle" tri-plex thermocouple location and the second sensor was located at the bowl. These locations were the only openings in the forehearth which were large enough to allow penetration of the 1.25 inch diameter sensor sight tube and coincident with existing triplex thermocouples.

The sensors were supported on an adjustable uni-strut mounting. Figure 4-3 and 4-4 show the middle and bowl installations and the respective arrangements of the support hardware. The middle sensor was supported by a single steel cross member traversing the width of the forehearth. Each end is supported by two short struts clamped to the superstructure of the forehearth. The bowl sensor was supported to a single cross member which traverses the width of the bowl area and is clamped on each end of the superstructure. This system of sensor support and installation provided a sturdy means of securing the sensors in place and required no modification to the existing forehearth superstructure. Clearly, additional sensors could be supported off the same structure in a commercial application.

Conduit was run between the signal processor enclosure and the sensors via a junction box located at an intermediate position. One conduit was used for each sensor and each carried the fiber optic cable, thermocouple wire for the calibration element and power wires for heating the

Figure 4-1. Sensor cross-section view.

Figure 4-2. Forehearth and sensor installation.

Figure 4-3. Sensor support detail, bowl area.

Figure 4-4. Sensor support detail, middle TC area.

element. A sealed conduit between the junction box and the sensors was used to carry purge air for cooling of the fiber and the sensor head. A separate air line was used to distribute air to the sensor air cylinder. Air purge was used over this part of the run because of the high ambient temperatures in close vicinity to the forehearth. The conduit run between the enclosure and the junction box containing fiber optic cable and the thermocouple wires was not air purged. The calibration element power wires were terminated at the junction box. Calibration was to be performed manually using a portable power supply as shown in Figure 4-5. A flow panel was also located at the junction box to regulate air for the purge air systems and the air cylinders during a manual calibration cycle.

Signal Processor

The signal processor receives signals from the two sensors and transmits signals to the data acquisition computer located at the control room on the factory floor. In the pilot test phase of the program, it was found that the optical multiplexer was sensitive to ambient air temperature. Therefore, the enclosure was environmentally controlled with a thermo-electric cooler to $\pm 0.5^{\circ}\text{C}$.

Heat rejection was accomplished with a self contained, closed cycle water cooling system. The water cooling circuit consisted of a water-cooled plate on which the hot side of the thermo-electric cooler was attached and a remote air cooled heat exchanger and a 2 GPM pump. The heat exchanger thermoelectric cooling system were connected via 1/2 inch flexible hose.

The system enclosure was installed on a steel structure attached to a cat-walk connecting the forehearth to a furnace that was no longer in use. The local temperature was at about outside ambient at this location and the fiber optic runs were 30 feet (10 meters). Distance from the enclosure to the forehearth was about 15 feet. The heat exchanger was located about 15 feet from the enclosure in a place where it would not obstruct any walkways. Figure 4-6 locates all the components used in the field evaluation. All components were located on the catwalk around the forehearth above the shop floor.

Figure 4-5. System P&I diagram.

4-9

Figure 4-6. T.A.S.

installation.

Modem

The data acquisition system used an IBM AT personal computer located in the air conditioned control room. The data acquisition software was specifically designed for data retrieval operation of the TAS and was installed in the computer. A 2400 baud modem was also installed on the computer and connected to a local phone line made available for exclusive EER use.

4.4 Data Acquisition and Quality

Dial-up Disk Logger

The main components of the data acquisition system were a PC with custom software, the TAS, and multiplexing thermocouple electronics. The PC was used to control the operation of the TAS and to log data to disk for off-line analysis. The PC was also installed with a modem and communications software to allow remote access of the operating system and data transfer from the test site to EER's Irvine office. The custom software in the TAS allowed the operator to choose any combination of tri-plex thermocouple or TAS data. In addition to logging data and controlling the TAS, real time table and graphic displays were available to assist the operator with the pretest set-up.

Data logging capabilities were expanded from the pilot scale system to 16 data channels. The data logging channels were set up as follows:

1. TAS enclosure temperature
2. Sensor 1 conduit temp (above junction box)
3. Sensor 1 (middle), Filter 1
4. Sensor 1 (middle), Filter 2
5. Sensor 1 (middle), Filter 3
6. Sensor 1 (middle), Filter 4
7. Sensor 2 (bowl), Filter 1
8. Sensor 2 (bowl), Filter 2
9. Sensor 2 (bowl), Filter 3
10. Sensor 2 (bowl), Filter 4
11. Middle Tri-plex thermocouple top

12. Middle Tri-plex thermocouple middle
13. Middle Tri-plex thermocouple bottom
14. Bowl (center) Tri-plex thermocouple top
15. Bowl (center) Tri-plex thermocouple middle
16. Bowl (center) Tri-plex thermocouple bottom.

Data channels were scanned and recorded at 60 second intervals for all test periods. Sensors 1 and 2 were connected to optical multiplexer channels 4 and 6, respectively.

The sensor data was conditioned using a dynamic data smoothing algorithm designed to remove all the low level noise while maintaining rapid response to real data transients. Sensor signal outputs from the band pass filters were calculated with a moving average of 60 sample points and a dynamic weight factor average using moving average and the last acquired data point. The weighting and sample averaging are fully user configurable to optimize the response time and data smoothing required for the application.

The TAS data acquisition parameters are contained in proprietary firmware burned into an EPROM on the TAS central processing unit. The TAS uses a Standard BUS architecture and the CPU uses a 16 bit 80188 microprocessor.

Spreadsheet Analysis

Initial analysis of the data was performed using a spreadsheet software package to manipulate and trend the data. The spread sheet analysis consisted of applying the Plank radiation equation to the data to develop a crude calibration to transform the data from raw signal "counts," as recorded by the data logger, to temperature, referenced to one or more of the triplex thermocouple readings. The TAS data could then be trended with the thermocouples or correlated against the ambient temperature measurements. The spread sheet calibration takes into account the signal intensity, the filter center wavelength and bandwidth to calculate temperature from the raw data.

The spreadsheet analysis was helpful for quickly generating trend plots and making simple statistical analyses of the data. However, the size of the data sets made statistical manipulation of the data difficult.

4.5 Data Analysis

The field test data analysis proceeded in several interactive steps:

- Daily data (temperatures and radiant IR intensities) were partitioned from the monthly data base under the assumption that diurnal effects (if any) due to ambient fluctuations would be easier to identify.
- Daily temperature statistics (ranges and deviations) were developed to identify those test days with the greatest information content with respect to melt temperatures.
- Scatter diagrams relating the four IR measurement frequencies to each of three adjacent triplex thermocouple readings were selectively developed from the daily data base (data smoothed with one minute running average).
- Functional trends were visually observed and radiation intensity transformations (temperature power laws) hypothesized between the IR intensities and the adjacent triplex thermocouples.
- Statistical analyses (multiple regressions) were performed of transformed data to evaluate the sensitivity of the dependent variables.
- Environmental data, signal processing enclosure and purge air temperature, were selectively introduced into the regression analysis to determine if the data correlations could be improved.
- Final correlations were attempted with the best (highest correlation coefficient) transformations and data sets.

4.5.1 Data Base Screening

The data base was first organized into daily files so as to include any diurnal effects, e.g.: those that might be repetitive over 24 hours due to ambient or production shift related effects. This approach was suggested by the earlier pilot and bench scale development data which uncovered

daily cyclic drift correlated inversely to ambient temperature excursions. Although the causes of most of these effects were identified and corrected during the prototype design phase, not all of the optical path (sensor to signal processor) was simulated.

Statistics were then developed around the daily smoothed data files (sampled every minute, 100 point moving average). Table 4-1 summarizes triplex thermocouple ranges and standard deviations. Each case corresponds to one day, cases are consecutive days starting on March 31, 1993. Triplex temperature depth locations are denoted by T(X), T(1) located near the melt surface, T(2) at about the mid point, and T(3) about 2-1/2 inches from the channel bottom.

4.5.2 Data Scatter Diagrams and Trend Analyses

For the days with high melt temperature excursions scatter diagrams were first developed to determine the sensitivity of each wave length (4) to each triplex thermocouple (3). Selective time trending of the measured temperature and IR radiation variables were then tracked to support data interpretation.

Scatter Diagrams

The initial criteria used to screen the data were select days where triplex temperature excursions are greater than the projected analyzer accuracy. Data with daily standard deviations greater than $\pm 10^{\circ}\text{C}$ (bowl and forehearth concurrently) were selected for scatter diagram development. Scatter diagrams are essentially instantaneous comparisons of signal, S(Y) with T(X). Cases 101, 103 and 107 have large temperature excursions, and therefore, potentially high resolving power (signal to noise ratio). In particular, Case 101 has extremely large daily melt temperature deviations. Cases 92 and 104 contain obvious, very large temperature excursions, T3 and T2, respectively, which result in significant data variability. Therefore, these test days were not evaluated. Also imposed on the scatter diagrams is the range of the data from a test day (Case 102) having small temperature excursions. Case 101 bowl temperature scatter diagrams are reproduced in Figure 4-7 for sensor IR band passes (S1 and S2) looking about mid way into the glass melt (e.g.: at the same average position as the thermocouple locations). The plots are raw signal counts from the photo detector for band passes centered at S2 @ $2.4\text{ }\mu\text{m}$ and S3 @ $3.0\text{ }\mu\text{m}$. S2 is acquiring radiation data from almost all thermocouple levels and should have the most

TABLE 4-1. MID FOREHEARTH TRIPLEX THERMOCOUPLE DATA DAILY VARIANCES

Temperature Means, Standard Deviations and Ranges

Case	Mean Values, °C			Standard Deviation			Range, °C			T[Avg, Mean], °C	Standard Deviation	Range °C
	T1	T2	T3	T1	T2	T3	T1	T2	T3			
088	1078.	1083.	1085.	0.405	0.424	0.541	2.60	2.60	2.70	1082.36	0.423	2.50
089	1078.	1084.	1085.	0.373	0.390	0.396	1.90	2.00	2.30	1082.61	0.365	1.80
090	1078.	1084.	1085.	0.360	0.396	0.542	2.10	2.30	14.10	1082.79	0.396	5.90
091	1078.	1084.	1086.	0.541	0.506	0.494	2.30	2.20	2.10	1083.05	0.479	2.10
092	1079.	1084.	1089.	0.555	0.486	<u>50.11</u>	2.70	2.20	<u>677.4</u>	1084.57	19.138	259.20
093	1078.	1085.	1086.	0.321	0.430	<u>0.530</u>	2.30	2.30	<u>2.50</u>	1083.28	0.395	2.10
094	1078.	1084.	1086.	0.260	0.267	0.258	1.50	1.50	1.40	1083.30	0.239	1.30
095	1078.	1085.	1086.	0.364	0.353	0.434	1.80	1.80	2.00	1083.54	0.367	1.80
096	1077.	1084.	1085.	0.846	0.592	0.630	4.10	3.70	3.30	1082.33	0.664	3.50
097	1077.	1084.	1086.	0.416	0.404	0.458	2.50	2.20	2.50	1082.63	0.403	2.20
098	1077.	1084.	1085.	0.253	0.433	0.605	1.90	2.20	2.90	1082.33	0.398	2.00
099	1077.	1084.	1085.	0.236	0.439	0.534	1.80	2.00	2.10	1082.20	0.380	1.70
100	1077.	1084.	1085.	0.335	0.391	0.602	8.20	2.80	12.10	1082.12	0.379	2.90
101	1079.	1086.	1087.	7.666	5.702	4.959	39.40	34.00	32.00	1084.30	5.943	34.00
102	1102.	1103.	1103.	1.651	1.590	1.605	5.20	5.10	4.90	1102.50	1.607	5.00
103	1105.	1107.	1106.	2.293	2.157	2.124	19.50	18.40	17.10	1105.97	2.175	18.10
104	1106.	1111.	1107.	0.613	<u>24.35</u>	0.479	2.80	<u>499.0</u>	2.40	1108.25	8.113	166.90
105	1108.	1109.	1108.	0.842	<u>0.731</u>	0.632	8.90	<u>8.00</u>	7.20	1108.35	0.714	7.90
106	1108.	1109.	1109.	0.302	0.329	0.306	2.50	2.50	2.60	1108.49	0.292	2.40
107	1105.	1107.	1107.	4.292	3.582	3.278	16.80	13.70	12.20	1106.62	3.672	13.90
108	1098.	1101.	1101.	0.144	0.160	0.186	0.90	1.00	1.00	1100.15	0.141	0.90
109	1098.	1101.	1101.	0.173	0.195	0.165	1.10	1.10	1.00	1099.87	0.162	1.00

Notes: T(1), located 1.5 inches below surface
T(2), located 3.25 inches below surface
T(3), located 5.25 inches below surface
 $T(\text{avg}) = (1.5 T(1) + 1.75 T(2) + 2.0 T(3)) / 5.25$

confounded signal, whereas S3 should be more correlated to temperatures T1 (near surface) and T2. The following trends are of note relative to Figure 4-7:

- Sensor channel "S3" appears to be better correlated to all temperature than sensor "S2" (not what was expected per above discussion).
- Sensor "S2" should be most highly correlated to temperature T2 (and sensor S1 even more so).
- There are loops in the scatter diagrams which correlate strongly with thermocouple position, e.g.: are most pronounced at the deepest thermocouple, T(3), by all sensor wave lengths.
- The forementioned loops cause significant data variance.
- IR radiance is varying approximately with a power law which varies between T^5 and T^7 . (Note that the radiation power laws are anchored in the dense, low temperature data range of normal operation and predict the photon count at the sensor.)

Note that black body broad radiation is emitted at the T^4 power and wave length specific radiation at T^5 . Narrow band pass (100 to 300 μm) radiation according to the Plank equation should emit between these two powers. For the analyzer band filters a T^5 law would be expected. Daily data suggests a T^5 to a T^7 law, composite data over several days suggest a power law of between 4 and 5. The daily and day to day variability is high and the data skewed toward the higher power suggesting one of several effects:

- stray radiation is entering the optical path at the sensor head or photo detector
- radiation contributions from depths other than the sighted wave length, due to either higher emissivity or temperature at depth or some combination thereof

101 (BOWL): S3 vs T3

101 (BOWL): S2 vs T3

101 (BOWL): S3 vs T2

101 (BOWL): S2 vs T2

4-16

Figure 4-7. Typical bowl scatter diagram for highly variable day.

- aberrations in the optical path are occurring because of micro-scale thermal expansions causing lens or mirror distortions, or alignments at critical points of connection.

These observations are not easily codified and will require a higher order of analysis to determine cause and effect. Intuitively, they suggest the following:

- There is still a diurnal effect or other uncontrolled variable, primarily as reflected by the high variance and looping data trends.
- There is substantial stray radiation from other sources (hot refractory or combustion products) as reflected by the sometimes greater than T^5 dependence (or from glass depth).

To better understand these results Case 100 having very little time dependent temperature deviation $\pm 0.6^\circ\text{C}$ (within the accuracy of the experiment) was similarly evaluated.

The resulting scatter diagrams, Figure 4-8, show, as would be expected, a shotgun pattern, but some functional dependency. The daily (diurnal) experimental TAS error can be approximately estimated from these data and appears to be between $\pm 2^\circ\text{C}$ to 4°C . Note that the T^7 curve again tends to fit the two data clusters somewhat better than the T^5 curve. Note also that for small changes the power function is essentially linear and given by the first two terms of the power expansion.

$$\left(\frac{T}{T^0}\right)^n \approx 1 + n \left[\left(\frac{T}{T^0} - 1\right) - \frac{1}{2} \left(\frac{T}{T^0} - 1\right)^2 \right] = \frac{I}{I^0} \quad [4-1]$$

where: n , power law, typically 4 to 5
 T^0 , reference temperature, absolute basis, $^\circ\text{K}$ or $^\circ\text{R}$
 I^0 , photon count at reference temperature

The Case 100 data closely duplicate the low temperature data cluster of Case 101 (compare TC/sensor pairs). The relatively high variability and odd functional dependency suggest that some relatively powerful statistics will be required to extract correlations from the data.

100 (BOWL): S2 vs T3

100 (BOWL): S3 vs T3

100 (BOWL): S2 vs T2

100 (BOWL): S3 vs T2

100 (BOWL): S2 vs T1

100 (BOWL): S3 vs T1

Figure 4-8. Typical bowl scatter diagram for stable operating day.

Diurnal Trend Charts

In order to evaluate potential diurnal effects triplex TC time trend charts were developed for a number of consecutive days, Appendix B, and sensor signals superimposed for three random days over the test interval. Two radiation wave lengths were selected:

- highest band pass wave length, S4 @ 3.5 μ m, primarily influenced by melt surface radiation and calibrated against T1
- lowest stable band pass wave length, S2 @ 2.4, measuring radiation components originating throughout the melt depth and calibrated against $(T2 + T3)/2$.

Trends of the measured sensor data for three typical days during the four month test interval, Figures 4-9, 10, and 11, represent 100 point moving averages over 60 seconds. The three triplex TC measurements are similarly trended and show significant, but relatively constant melt temperature gradients for each day. Figure 4-9 typifies a relatively stable day, Figure 4-10, a relatively significant step change, and Figure 4-11 small step changes in the three temperatures. The spectral radiance measurement has been normalized to a reference temperature at time zero on 3/31/93 using a T⁵ model for calibration. Thus, the offset on each of the other days represents long term drift. The following observations are developed from plotting deviations in sensor referenced temperature (cross plots of Figure 4-9, -10, and -11 with time) from the triplex reference, Figure 4-12.

- there appears to be surface radiation or ambient effects that are more process related than diurnal as reflected by the trends in both S2 and S4 which are in one instant contra to the thermocouple movement, Figure 4-11..
- amplitudes of low frequency cycling are greater for S4 than the triplex, but tend to coincide in time with the triplex fluctuations (note, if a T⁷ model were used these amplitudes would be significantly reduced)
- when the triplex temperatures are lined out ($\pm 0.5^{\circ}\text{C}$), Figure 4-9, surface radiance (temperature, S4) is also nearly lined out

F2 Sensor 2(bowl) 3/31/93, File 0890000.XLS

Figure 4-9a. Daily triplex and sensor trend data, sensor signal S2 affected primarily by T2.

F4 Sensor 2(bowl) 3/31/93, File 0890000.XLS

Figure 4-9b. Daily triplex and sensor trend data, sensor signal S4 primarily affected by T1.

F2 Sensor 2 (bowl) 4/13/93, File 1020000.XLS

Figure 4-10a. Daily triplex and sensor trend data, sensor signal S2 affected primarily by T2.

F4 Sensor 2 (bowl) 4/13/93, File 1020000.XLS

Figure 4-10b. Daily triplex and sensor trend data, sensor signal S4 primarily affected by T1.

F2 Sensor 2(bowl) 6/06/93, File 1560000.XLS

Figure 4-11a. Daily triplex and sensor trend data, sensor signal S2 affected primarily by T2.

4-25

Deg-C

1145
1140
1135
1130
1125
1120
1115
1110
1105
1100
1095

Figure 4-11b. Daily triplex and sensor trend data, sensor signal S4 primarily affected by T1.

F4 Sensor 2(bowl) 6/06/93, File 1560000.XLS

- the forehearth and bowl are drifting at different rates (slopes), both magnitude and direction (Figure 4-12); the rates tend to stabilize after 100 days, are different for different signal channels and under worst case conditions average about 6°C/mo.
- the bowl signal, S2, is very stable over the test period and almost meets the performance goal of 1°C/mo.

Time snapshots of the trend data (at an instant in time) have been used to develop melt temperature profiles for both sensor locations. Bowl melt profiles are almost always parabolic, with the largest mid point temperature typically 20 to 30°F greater than top or bottom, Figure 4-13. Mid forehearth profiles are typically flat to within several °C, even when significant time transients are present, Figure 4-14. Top surface temperatures are always the lowest. Largest gradients, and therefore, the most significant information content relative to model correlation, lies within the bowl data. The larger forehearth sensor drift would also tend to confound the data when evaluating population sets including multiple days. Therefore, most of the remaining discussion focuses in the bowl sensor data.

4.5.3 Data Correlation

With the previous section discussion as background, statistical (regression) analyses were performed in several steps to identify functional forms, data edits, and data base apportionments which potentially correlate the data. The following protocol was used:

- the forehearth mid section data, because of small melt temperature gradients and excursions, were evaluated with linear and logarithmic models (good power series approximation with first order terms)
- the bowl data were evaluated with $S^{1/4}$ and $S^{1/5}$ power laws to reflect the non-linearities of larger gradients.

Based on these tentative conclusions a limited subset of the field data was selected for further evaluation. The long term drift data suggest more stable operation after about 100 days of operation. A large number of test days between 88 and 109 have significant daily temperature ranges relative to TAS precision, thus providing large signal changes relative to measurement

Figure 4-12. Sensor drift for two wave lengths at two sensor positions.

Bowl Triplex gradients: file 1020000.XLS

Figure 4-13. Bowl gradient excursions.

Triplex gradients: file 102000.XLS

Figure 4-14. Daily foreearth gradient excursions.

noise. This should improve the chances of developing a statistically correlated model. Further, the major effort was focused on the bowl data because of its larger temperature gradients, better long term drift stability, and greater criticality relative to glass quality. As we shall see this turned out to also be a good choice because the forehearth sensor appears to have substantially degraded optically.

Forehearth Correlations

Initial forehearth correlations were attempted with linear and logarithmic models relating each triplex thermocouple temperature to band pass radiation in each of the four measurement wave lengths.

The best correlations were obtained for a log transformation and only for limited data sets. The data were not well correlated with this model which was abandoned because of its inherent deficiencies.

In reality, the color temperature should vary as the inverse radiation power law and the model should account for radiation originating from depths other than the reference depth.

Bowl Correlations

A moderately successful attempt was made with the bowl data to introduce gradient terms (temperature differences) to correct for this effect using the functional form).

$$T(X) = a_1(X) + a_2(X)S(n)^{1/4} + a_3 TA + a_4(X)(T_2 - T_1) + a_5(X)(T_2 - T_3) \quad [4-2]$$

where:

$T(X)$, correlated temperature at melt depth, X

$T_2 - T_1$, $T_2 - T_3$, measured melt gradients

$S(n)$, photon count for wave length, n

Regression correlation coefficients, R^2 are a measure of residual error after least squares curve fitting to a functional form. Values of $R^2 > 0.9$ to 0.95 are generally required to place a high confidence in the correlation.

A number of fair to excellent ($R^2 = 0.9$) correlations were developed, Table 4-2, suggesting some utility of the concept. However, over 75% of the data base was not adequately correlated, primarily the result of small changes in the measured parameters relative to instrument and process variability (low signal to noise).

Bulk Temperature Predictions

Control strategies are typically implemented by using the weighted average triplex data or near IR radiation pyrometers measuring bulk melt temperature. Therefore correlations were developed using the weighted average temperature, T , in the previous equation:

$$T = 0.28T(1) + 0.33 T(2) + 0.38T(3) \quad [4-3]$$

The weighing factors are based on thermocouple depth; and therefore the composite value should reflect a bulk temperature at the sensor measurement cross section. The correlations with $R^2 > 0.8$ and similar regression coefficients are summarized in Table 4-3 for each of the four test days and each band pass signal, $S(n)$. Composite averages coefficients for the four days were also developed to more easily discuss the data. The band pass signal has been transformed with a T4 model and melt temperature differences, $T(1) - T(2)$ and, $T(2) - T(3)$, introduced to determine if the data base has significant information content relative to gradient. The standard error of the estimate is typically $\pm 2.5^\circ\text{C}$, providing some clue as to daily repeatability.

The regression coefficients, a_i , always produce high correlation coefficients suggesting that the band pass radiation, $S(n)$, for all wavelengths is strongly effected by the average temperature and the gradient. The gradient effect appears nearly identical for each radiation signal (compare composite coefficients a_4 and a_5) with the near surface gradient having the greatest influence.

It should be noted that the fiber conduit air purge temperature (T_A) has also been introduced into the correlation to adjust for potential environmental effects (fluctuations) along the optical cable path. The following general observations are made relative to the correlations:

TABLE 4-2. BOWL GRADIENT CORRELATION OF LOCAL TEMPERATURE

Case	S(n) ¹	T(X) ²	R ₂	T(X) = a ₀ (X) + a ₁ IS(λ) ^{1/4} + a ₂ (T ₁ —T ₂) + a ₃ (T ₂ —T ₃) + a ₄ T _A				
				a ₁	a ₂	a ₃	a ₄	
91	1.6	1	0.78	1.6	0.34	2.2		
	1.6	2	0.75	1.6	-0.65	2.2		
	1.6	3	0.74	1.6	-0.65	1.2		
	1.6	Avg	0.77	2.4	2.00	2.22	0.97	
	2.5	1	0.79	18.4	0.34	2.41		
92	2.5	2	0.76	18.4	-0.65	2.4		
	2.5	3	0.75	18.4	-0.65	1.4		
	2.5	Avg	0.83	25.6	2.66	2.13	.072	
	1.6	3	1.00	4.97	0.51	-1.0		
	2.5	3	1.00	9.00	0.38	-1.0		
101	3.0	3	1.00	17.7	0.16	-1.0		
	3.5	3	1.00	14.8	0.37	-1.0		
	3.5	Avg	0.78	25.1	1.72	1.32	.070	
	1.6	1	0.89	31.8	2.06	0.73		
	2.0	2	0.80	31.8	1.06	0.73		
	3.0	3	0.74	31.8	1.06	-0.27	0.32	
	1.6	Avg	0.93	40.5	0.69	1.04		
	2.5	1	0.89	29.2	2.00	0.53		
	2.5	2	0.80	29.2	1.00	0.53		
	2.5	3	0.74	29.2	1.00	-0.47	0.21	
	2.5	Avg	0.91	31.5	1.07	1.49		
	3.0	1	0.87	54.9	2.38	0.33		
	3.0	2	0.77	54.9	1.38	0.33		
	3.5	1	0.87	41.6	2.21	0.75		
	3.5	2	0.77	41.6	1.20	0.75		
	3.5	3	0.70	41.6	1.20	0.25		
	3.5	Avg	0.96	55.8	0.38	0.68	0.21	
	2.0	Avg	0.91	31.5	1.07	1.49	0.21	

Notes: 1, Sensor wave length signal, S(n)
 2, Triplex thermocouple location, T1(top), T2(mid), T3(bottom)
 3, Correlation coefficient for purge air temperature, T_A

TABLE 4-2. BOWL GRADIENT CORRELATION OF LOCAL TEMPERATURE (Continued)

Case	S(n)	T(X)	R ₂	a ₁	a ₂	a ₃	a ₄
107	1.6	1	0.97	-8.91	4.96	2.37	
		2	0.95	-8.91	3.96	2.37	
		3	0.94	-8.91	3.96	1.37	
	2.5	1	0.96	-2.84	4.31	3.5	
		2	0.95	-2.84	3.31	3.5	
		3	0.94	-2.84	3.31	2.50	
	3.0	1	0.96	-7.57	4.20	3.38	
		2	0.95	-7.57	3.20	3.38	
		3	0.94	-7.57	3.20	2.38	
	3.5	1	0.96	8.15	4.19	3.63	
		2	0.95	8.15	3.19	3.63	
		3	0.94	8.15	3.19	2.63	
		Avg	0.85	95.6	2.87	1.60	0.26
96	1.6	1	0.76	5.70	1.31	0.65	
	2.5	2	0.82	11.7	0.99	1.03	
	3.0	1	0.82	19.7	0.91	0.77	
	3.5	1	0.83	18.3	0.69	1.05	
	3.5	Avg	0.79	12.5	2.24	1.74	.001
91	3.0	Avg	0.83	28.1	2.53	2.02	.048
	3.5	Avg	0.84	31.5	2.54	2.03	.043

TABLE 4-3. BOWL SENSOR BULK TEMPERATURE CORRELATION

Model: $\bar{T} = a_1 + a_2 \cdot S(n) \cdot 0.25 + a_3 TA + a_4 \cdot (T1 - T2) + a_5 \cdot (T2 - T3)$

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Case	S(λ)	R**2	a ₁	a ₂	a ₃	a ₄	a ₅
094	1	0.849	1191.464600	-11.114923	-0.145366	2.462984	1.988885
099	1	0.893	1082.908936	-0.174718	-0.096379	1.613290	1.308744
100	1	0.995	1192.790771	-10.211271	-0.341014	-0.795714	-0.669675
102	1	0.828	1247.005493	-13.965138	-0.317369	4.760950	3.475651
Composite			1179	-8.57	-0.22	2.01	1.52
094	2	0.816	1180.360229	-8.841093	-0.128710	2.379717	1.884008
099	2	0.893	1071.230957	0.894180	-0.94601	1.594071	1.299868
100	2	0.886	1098.412249	-1.813088	-0.82674	2.108621	1.786836
102	2	0.813	1167.802612	-5.289141	-0.291172	4.384490	3.148180
Composite			1129	-3.76	-.149	2.61	2.02
094	3	0.829	1198.969116	-11.090703	-0.114790	2.413068	1.928829
099	3	0.899	1015.816528	6.162806	-0.088115	1.632126	1.350059
100	3	0.886	1056.534416	2.031460	-0.065739	2.064224	1.759915
102	3	0.810	1134.942383	-2.388931	-0.290312	4.283541	3.056540
Composite			1101	-2.08	0.139	2.60	2.02
094	4	0.828	1220.467773	-14.508687	-0.119792	2.418022	1.952517
099	4	0.898	1019.002808	6.493502	-0.094757	1.623717	1.344015
100	4	0.889	1153.824968	-7.882758	-0.095981	2.134506	1.800739
101	4	0.958	540.177551	55.765705	-0.095981	2.134506	1.800739
102	4	0.810	1110.908447	-0.138992	-0.291564	4.233274	3.013746

- over 50% of the data is reasonably correlated, $R^2 > 0.8$
- there is no direct correspondence between the range of the triplex temperature data (Table 1) and the degree of correlation, R^2
- for a given day good correlation is usually obtained for all signals, for a poorly correlated day none of the signals are well correlated

These observations suggest that there is significant information content in the band pass radiation data relative to temperature (bulk and gradient). However, the equations have no practical utility with respect temperature gradient predictions. The fact that the regression coefficients (a) for the highly correlated days and sensor locations have a wide range of values is also disconcerting. A final correlation was performed by profiling all of the early data for both sensor locations. A step wise (manual) linear regression of band pass radiation (1/5 power) to bulk, ambient, and gradient temperatures was performed on unedited and edited data. The best fits incorporated all of the data and all of the regression parameters, Table 4-4. The following are significant conclusions:

- the highest correlation coefficients are obtained at the bowl position and for the highest wave length band pass filters, $R^2 > 0.94$
- all radiant band pass signal are similarly effected by ambient and gradient temperatures, 10°C changes (typical) producing between 5 and 20°C changes in radiant color temperature (signal intensity)
- the greater the wave length, the least the effect of bowl temperature gradient, e.g.: the S(4) @ 3.5 μm signal is most specific to surface radiation as all sub-surface emitted long wave length radiation is reflected back into the melt (note that the bowl has strong gradients with mid depth temperatures 20 to 35°C greater than surface temperature)
- the best bulk temperature accuracy (standard error of the estimate) is about $\pm 11^\circ\text{C}$ (pooled daily data)

TABLE 4-4. POOLED DATA BASE CORRELATIONS

Model: $I[S(n)]^{**0.25} = a_1 + a_2 * T + a_3 * TA + a_4 * (T1 - T2) + a_5 * T2 - T3$

Sensor Location	Case	R ²	SE	a ₁	a ₂	a ₃	a ₄	a ₅	I	T,
Forehearth	I[1M]	0.855	.042	3.485178	0.006472	-0.007846	0.015961	0.008473	10.25	1090
	I[2M]	0.882	.043	1.387903	0.008925	-0.001869	0.022372	0.011860	11.03	1090
	I[3M]	0.788	0.38	4.061132	0.005797	0.000587	0.015165	0.007970	10.38	1090
	I[4M]	0.870	.048	-0.737268	0.009970	0.001791	0.025142	0.013312	10.15	1090
Bowl	I[B]	0.859	0.36	3.141790	0.006234	-0.005343	0.005319	0.005978	9.88	1088
	I[2B]	0.650	.048	5.776657	0.004867	-0.003364	-0.001708	0.001452	11.00	1088
	I[3B]	0.936	.025	2.087736	0.007844	-0.002319	0.003668	0.003554	10.56	1088
	I[4B]	0.956	0.25	0.880155	0.009672	-0.001562	0.001320	0.000714	9.59	1088

All of the above analyses support data interpretation, but don't have practical utility. The data base would typically be used to correlate a deconvolution algorithm to predict the temperature gradient. This approach can only be implemented if the analyzer accuracy is an order of magnitude lower than the temperature differences to be resolved and the top surface temperature estimate is accurately estimated, e.g.: with the long wave length signal. Neither of these conditions are satisfied in the present data. To obtain some idea as to the resolving power of the currently configured analyzer a final global regression analysis was performed using the four bandpass signals as independent variables to estimate bulk glass temperature, Table 4-5. This is essentially a signature approach which estimates bulk (average) temperatures with a high degree of correlation, $R^2 > 0.95$. The standard error of the temperature estimates is between ± 2.2 and $\pm 2.6^\circ\text{C}$. This is short of the $\pm 1^\circ\text{C}$ expected and $\pm 1/2^\circ\text{C}$ targeted, but still a significant advancement in the state-of-the-art. The value of the regression coefficients, $a_i T_i$, give some indication of the significance of a specific thermocouple location. The surface temperature, T_1 , was most influenced by S_3 , and to a lesser extent by S_4 as would be expected from theory (long wave lengths measure surface radiation). The mid temperature measurement, T_2 , was most strongly effected by S_3 , again reasonably consistent with theory. T_3 the deepest thermocouples however, was most strongly effected by the longest wave length, S_4 , a somewhat surprising result. This may be an artifacts in part attributable to the fact that $(T_1 \approx T_3) < T_2$.

The bulk (average) temperature measurements were predicted with the most accuracy ($SE = 2.2^\circ\text{C}$, and best regression correlation coefficient, $R^2 = 0.96$). The dominate wave lengths, e.g.: those with largest regression coefficients, are the signals measured at the higher wave lengths, $S(3)$ @ 2.8 and $S(4)$ @ $3.5 \mu\text{m}$. This is consistent with theory and the bowl temperature profile. S_3 is probably strongly effected by T_2 , which on average is 20 to 30°C higher than either T_1 or T_3 . Thus 15% more radiation is being emitted from the middle level of the melt. The surface temperature T_1 , substantially impacts S_4 . It should not be assumed that this correlation would apply at a different forehearth location having a different profile or for a different glass composition.

TABLE 4-5. SUMMARY OF POOLED BOWL REGRESSION RESULTS (CASES 088 THROUGH 109)

$$T^{\circ}\text{C} = a_0 + a_1 * S[1]**0.2 + a_2 * S[2]**0.2 + a_3 * S[3]**0.2 + a_4 * S[4]**0.2$$

	°C	a ₀	a ₁	a ₂	a ₃	a ₄	R ²	SE, °C
	1	-189,437546	-79.465729	-63.531460	264.410431	74.321510	0.903	4.0
	2	-394.612701	9.985060	-19.767757	296.840240	-63.985352	0.86	4.5
	3	268.836060	-178.294708	37.487980	-110.910004	392.674866	0.95	2.8
	avg	-83.247360	-87.297203	-10.459715	132.239304	149.495651	0.96	2.2

Interim Conclusions

The above results are highly encouraging, full prototype functionality of key TAS components has been demonstrated with a relatively stable analyzer platform. Precision objectives, however, were compromised. Measurement variability is hypothesized to originate from several uncontrolled or unmeasured sources:

- contaminated optics
- inadequate control of sensor and fiber temperatures affecting alignment or transmissivity
- process effects or design defects causing stray light interferences, e.g.: radiation from walls or combustion species.

One obvious concern is the effects of ambient temperature excursion resulting in micro-scale thermal expansions. These, in turn, could result in aberrations along the optical path, particularly at the sensor heads which were exposed to locally high temperatures. This prompted a sensor post mortem as described below.

4.7 Post Demonstration Sensor Tests

The demonstration testing revealed long periods of stable analyzer operation, sometimes followed by transient temperatures which were not well trended by the TAS. Further, some daily temperature signal scatter diagrams showed a looping sensitivity signal error. A test plan was devised to investigate and possibly characterize short term drift from the sensor to help interpret the data. Two factors were viewed as possible sources of signal error. Degradation of the sensor optics could have contributed to long term drift. Second, the sensor head may be sensitive to ambient changes in temperature causing short term (daily) signal drift.

4.7.1 Sensor Head Thermal Sensitivity Test

Sensor head thermal sensitivity was evaluated by subjecting the sensor head to controlled changes in temperature and recording the analyzer output. The recorded output should show

changes in signal output if the sensor head is sensitive to the ambient temperature. The prototype TAS was set up in EER's optical laboratory and the sensor was sighted through the top ceiling opening in the laboratory box pilot furnace. A heated black body target in the box furnace served as a stable source of sensor radiant energy. The sensor head was wrapped with flexible heat tape and attached to a power supply controller to cycle the heat tape on and off at approximately three hour intervals. The sensor output was continuously recorded by the TAS signal processor for a period of three days. For two days the test sensor was subjected to temperature cycles from about 30°C to about 60°C.

Since sensor temperatures in the field were measured in excess of 150°C the test configuration was modified to obtain higher temperatures by wrapping the sensor with insulation. The sensor was cycled through a temperature range from about 30°C to about 125°C. A cross plot of the TAS filter signals versus the recorded sensor head temperature clearly show a temperature dependency. Figure 4-15 through 4-18 show signals varying slowly with temperature to a maximum and then dropping rapidly as temperature continues to rise. Hysteresis is apparent in the plots and may indicate that the thermocouple was not placed optimally to detect critical component(s) influencing the observed behavior, there is some thermal lag between the TC located on the tip of the black body calibration element and the metal components (mirrors and supports) of the sensor head. On the upper (steep) side of these plots the effective sensitivity for the sensors is about 0.6°C change in sensor signal/°C change in sensor temperature for filters 3 and 4, and is about 0.4 °C/°C for filter 2. The cause of the sensitivity is most likely attributable to changes in optical alignment between the sensor reflective optics and the fiber but could also be attributed to changes in the transmission characteristics of the fiber near its termination at the sensor head. The peaking response surface may also be an explanation for the looping seen in the scatter diagrams.

4.7.2 Sensor Inspection

Upon completion of the thermal sensitivity tests both sensors were disassembled and inspected. The purpose of the inspection was to check for possible contamination of the sensor optics and to evaluate the general durability of the sensor component after four months.

Sensor Sensitivity: Filter 1 Cross Plot, file 3240630.XLS

Figure 4-15. Signal sensitivity to sensor head temperature excursions.

Figure 4-16. Signal sensitivity to sensor head temperature excursions.

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Figure 4-17. Signal sensitivity to sensor head temperature excursions.

Figure 4-18. Signal sensitivity to sensor head temperature excursions.

Forehearth Sensor

The most notable observation was a discoloration of the forehearth sensor off-axis parabolic mirror. The mirror underwent two distinct changes while in field service. First, the mirror surface was discolored and lost its surface reflectance (at least in the visible). Its color was purplish or mauve and uniform over the entire parabolic reflecting surface. Second was the fact that all other surfaces of the mirror which were originally black anodized were no longer black. The anodized surfaces had a mottled, oxidized aluminum appearance.

The mirror surface discoloration could result from a number of factors. Since the surface was clean and the other internal components of the sensor insides were clean and free of deposits, the discoloration was probably a result of high sensor temperature. One possibility is that the surface discoloration is the result of oxidation of the aluminum underneath the gold mirror plating or oxidation of one of the other undercoatings used in the gold deposition process. The process for plating a reflective gold surface requires deposition of thin coats of other metals for proper adhesion of the gold. Another possibility is that the anodized surface volatilized and re-deposited on the mirror. As the mirror discolors its reflectivity decreases and, thus, the higher absorption of radiant energy, further increasing the temperature of the mirrored surface. This may be the source of the observed temperature change in the sensor between installation when the bowl sensor was observed to be at about 145°C, as measured by the calibration source TC, and the observed temperature when the sensor was removed which was in the excess of 300°F. The mirror degradation probably explains the loss in signal (drift) with time.

The inside of the sensor body appeared to be as clean as it was when manufactured. The machined aluminum surfaces of the calibration slide mechanism appeared to be un-oxidized and clean. The gold coated 90° prism mirror on the calibrator was clean and looked the same as it did when the sensor was installed. The air cylinder that actuates the calibrator slide mechanism had failed. The air cylinder seals were non-functional and the return spring was weak, probably because the annealed spring steel lost stiffness. Seals on the sapphire windows on the calibration source held up well and all Teflon seals appeared to be in acceptable condition.

5.0

CONCLUSIONS AND RECOMMENDATIONS

A number of program performance and cost objectives were met during this prototype development and demonstration phase. Specifically, the analyzer demonstrated relatively good long term drift stability, good signal to noise ratio, and frequently good to excellent trending with the reference triplex thermocouples. Several major deficiencies were uncovered, primarily traceable to aberrations of the optical path, and therefore, failure to meet the accuracy and precision objectives. The sensor head has specifically been identified as a source of a significant amount of temperature sensitivity leading to measurement variability. These results and conclusions are further discussed below.

5.1

Conclusions

Two sensors were installed in a glass forehearth at its mid-section and in the bowl. The sensors communicated over a fiber optic network to a remote, timeshared signal processing system. The mid section of the forehearth operated vary stably over the three months of test data evaluated, maximum thermocouple temperature differences rarely exceeding 8°C , and for weeks on end maximum differences were frequently less than $2\frac{1}{2}^{\circ}\text{C}$. This condition plus the fact that the sensor at this location tended to have moderate long term drift makes it difficult to extract mild temperature gradient effects out of the data base. Conversely, the bowl position has large gradient effects, maximum temperature differences being 20 to 35°C . Bulk temperatures were also stable over long periods, the largest difference was about 56°C and daily fluctuations were typically greater than $4\frac{1}{2}^{\circ}\text{C}$. Hence, the bowl data was the primary focus of the analysis effort.

General Observations

The analyzer must have a classical power law response to temperature if it is to be correlated to a radiation model. Theoretical power laws for the black body and narrow band spectral (band pass) have fourth or fifth order exponents, respectively and were evaluated against the data.

Exponent fits for any given day typically vary from black body (T^4) to narrow band (T^5). However, frequently even larger exponents correlate the data better. Multiple days are better correlated to a T^5 law. Both T^4 and T^5 data transformations were used in the various functional

forms and data set population partitions evaluated statistically, i.e.: with multiple regression analyses.

Large data scatter suggested that signal to noise ratios were potentially inadequate to resolve small gradient effects, particularly in the forehearth. Best correlations were obtained with pooled experimental data over fewer days (22) than to the 160 day test period. This approach should minimize drift affects, the mid period was selected since it had a number of days with large temperature excursions and was potentially less affected by the observed component deterioration found during the test hardware post mortem. Based on these observations most of the data analysis focused on the bowl sensor data.

Bowl Sensor Performance

Several types of correlations were attempted to 1) identify the critical parameters affecting the TAS profile measurement, 2) correlate functional forms and transformation, or 3) develop a bulk temperature measurement from an IR emission signature.

Best correlations were found using a fifth power law and for pooled, unedited data sets correlated to bulk temperature. Regression correlation coefficient (R^2) and analysis of variances generally supports the assumption of better bowl correlation, although both locations typically produced $R^2 > 0.85$, and for the bowl sometimes as high as 0.96. Standard error of the estimates varied from about $\pm 10^\circ\text{C}$ for individual temperature measurement to $\pm 2.2^\circ\text{C}$ for bulk temperature correlations.

Long term drift stability was relatively good. Sensor signal drift varied from about 2 to $5^\circ\text{C}/\text{mo}$, and is potentially attributed to some combination of degraded optics and the local ambient affecting sensor temperature. Similarly some of the contra-trending and hysteresis observed between sensors and thermocouples is believed to be traceable to local sensor head temperature excursions. Several of the regression and AOV evaluations strongly suggest ambient (conduit purge air) temperatures are affecting the measurement.

Performance Shortfall

Performance shortfalls were primarily in the metrology objectives of the program. Specifically, the $1^{\circ}\text{C}/\text{mo}$ drift and the $\pm 1/2^{\circ}\text{C}$ precision requirements. Best measured values for drift and precision were $2^{\circ}\text{C}/\text{mo}$ and $\pm 2.2^{\circ}\text{C}$, respectively. These errors were sufficiently high to preclude developing a theoretically based deconvolution algorithm for reconstructing a melt temperature profile.

5.2 Recommendations

A number of test objectives were demonstrated during the field test, specifically:

- robust electro-optic system design in a hostile factory floor environment
- multi-location, multi-point signal acquisition and fiberoptic transmission with low loss and good signal to noise ratio
- reasonable precision and fairly good stability considering the problems with the sensor head.

Clearly, the sensor head needs further hardening and simplification. It also has become painfully clear that in order to develop and correlate a deconvolution algorithm better test control is required than can be achieved in the field.

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