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Design of an Experimental Electric Arc Furnace

By Alan D. Hartman and Thomas L. Ochs

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	MHz	megahertz
atm	atmosphere, standard	min	minute
°C	degree Celsius	mm	millimeter
°C/min	degree Celsius per minute	μm Hg	micrometer of mercury
cm	centimeter	μs	microsecond
ft	foot	pct	percent
h	hour	psig	pound (force) per square inch, gauge
Hz	hertz	scfm	standard cubic foot per minute
in	inch	sLm	standard liter per minute
kHz	kilohertz	V	volt
lb	pound		

DESIGN OF AN EXPERIMENTAL ELECTRIC ARC FURNACE

By Alan D. Hartman[1] and Thomas L. Ochs[2]

ABSTRACT

Instabilities in electric steelmaking furnace arcs cause electrical and acoustical noise, reduce operating efficiency, increase refractory erosion, and increase electrode usage. The U.S. Bureau of Mines is investigating methods to stabilize these arcs. To perform experiments to test new hypotheses, Bureau researchers designed and instrumented an advanced, experimental single-phase furnace. This report describes this furnace, which was equipped with high-speed data acquisition capabilities for electrical, temperature, pressure, and flow-rate measurements; automated atmosphere control; ballistic calorimetry; and view ports for high-speed cinematography. Precise environmental control and accurate data acquisition allow the statistical design of experiments and assignment of rigorous confidence limits when potential furnace or procedural modifications are tested.

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INTRODUCTION

As part of its ongoing program to improve productivity in steel production, the U.S. Bureau of Mines is conducting research to improve operating efficiency and reduce electrical and acoustical noise in electric arc furnace steelmaking. Electric arc furnaces account for approximately 40 pct of the total U.S. steel produced (*1*).[3] In the steelmaking process, small changes in efficiency or productivity can have a significant impact on marginal profit. Unfortunately, standard experimental furnaces are not well-suited for quantitative evaluation of modifications that produce subtle performance changes. The Bureau designed and built an experimental single-phase furnace equipped with precise instrumentation that monitors small performance changes. Quantities measured include electrode consumption, furnace atmosphere composition, thermal energy transferred, voltage and current waveforms, and arc motion.

Electrode consumption was directly measured using standard balances. In experimentation, interest was on the effects of the furnace atmosphere on the consumption of electrode material, since 6 to 7 pct of the cost of producing steel in an electric arc furnace is attributed to electrode consumption (*2*). To allow close control of the atmosphere, the furnace shell was redesigned as a gastight unit with electronic flowmeters and controllers under computer control. With this system, the mixture of gases introduced into the furnace atmosphere could be closely controlled.

Energy accounts for approximately 36 pct of the total cost of converting scrap to liquid steel in an arc furnace (*3*). Therefore, even a small increase in energy transfer efficiency could result in cost savings. In the experimental furnace, a copper block was used as a ballistic calorimeter for measuring thermal energy transferred. An array of thermocouples was arranged on and in the copper block to measure the temperature field. This measured-temperature profile was then used to estimate the total energy transferred to the copper target during experimentation. The overall electrical efficiency can be closely estimated by utilizing the calculated thermal energy and the measured electrical energy input to the system.

Voltage and current signals acquired from across the arc are susceptible to transmission noise and distortion because of the high magnetic fields. A fiber-optic transmission system was installed to minimize the magnetic field effects. This fiber-optic system translated analog voltage signals (obtained close to the arc source) to optical (frequency-encoded) signals for transmission to the data acquisition system, which was housed in a walk-in Faraday cage. This combination of short analog electrical signal length with extensive shielding and grounding of the data acquisition system led to high-fidelity electrical waveform capture.

Preliminary experiments indicated that the geometry of the electrode tip or arc target plays an important part in the arc behavior. So that researchers could directly observe and record the arc motion with high-speed cinematography, orthogonal ports were installed on the gastight furnace shell. Heat-resistant glass windows were located at the end of rectangular ducts to prevent soot clouding or thermal stressing. The furnace atmosphere test gases were injected between the windows and the arc to cool the glass and avoid cracking.

These additions to the experimental furnace, combined with precise data acquisition, enabled the design of quantitative, statistically valid experiments to investigate the effects of changes in furnace equipment or procedures.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Experiments were conducted in a 200-lb-capacity, single-phase-ac electric arc furnace. The power supplies for the furnace consisted of two single-phase-ac welders connected in parallel. Each welder was rated at 1,500 A welding current and had a load voltage of 40 V. Primary rating (single phase) was 440 V and 170 A. The secondary voltage signal was measured across the arc while the current signal was received from a 0.0001009-ohm, water-cooled shunt located on the bus bars. For atmosphere control, the traditional shell was replaced with an airtight, water-cooled shell equipped with two orthogonal view ports (fig. 1). The shell dimensions were 38 in long, 28-1/2 in wide, and 33 in high. The view ports allowed two 90° views of the arc to be captured onto 16-mm film via high-speed cinematography (fig. 2). The front and side view ports were 14 in long by 25 in wide by 8 in deep and 8 in long by 25 in wide by 8 in deep, respectively.

Arc target materials can be varied to consist of a graphite block, a steel block, or a copper block. A copper block was used as an arc target for ballistic calorimetric measurements. A threaded, circular copper insert (6-in diam by 3-in height) for the copper block was screwed into place underneath the arcing electrode. This allowed easy removal of the copper insert for machining to ensure a

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[3] Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

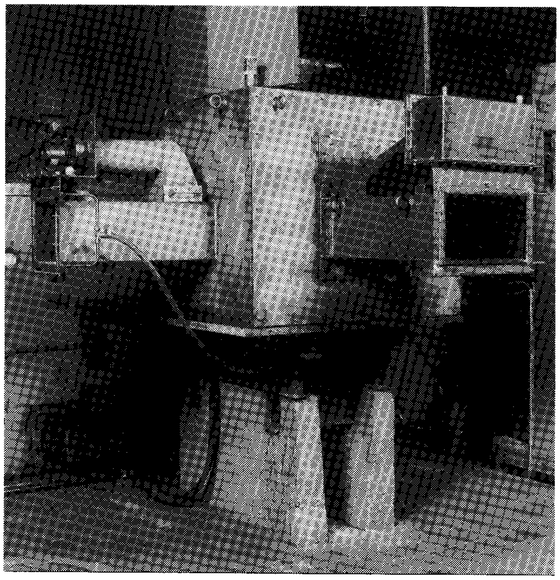

Figure 1.—Exterior of electric arc furnace enclosure showing two view ports at 90° to each other.

consistent flat surface at the beginning of each test. One of the two 3-in-diam graphite electrodes was threaded and inserted into the block. This allowed data to be taken across a single arc to avoid any averaging effect when two opposite polarity arcs were present while maintaining the same electrical and magnetic paths for the system (fig. 3). The arcing electrode used a coupling for easy electrode tip changes. The coupling did not interfere with arcing. The tips used were 6 in long with 3 in of thread, as shown in figure 4, and had varying tip shapes.

The furnace enclosure allowed the arc atmosphere composition to be controlled. Gases could be introduced into the furnace in three locations: through the arcing electrode and through both view ports. Small blowers were used to circulate the furnace atmosphere gases in the view ports through a glass-fiber filter to keep the view ports clear of smoke and/or soot. The view ports were also cooled with the incoming gas. Mixed-composition gases were obtained by in-line mixing of the pure gases, as shown schematically in figure 5. Porter Instrument Co., Inc., mass flow controllers[4] were used to control the flow rate of the incoming pure and exiting mixed gases. Exiting gases were sampled to ensure that proper atmosphere composition was obtained. All controllers were calibrated at the factory for nitrogen gas use, and other gases could be monitored by applying a correction factor (*4*). The controllers had the ranges shown in tables 1 and A-1.[5]

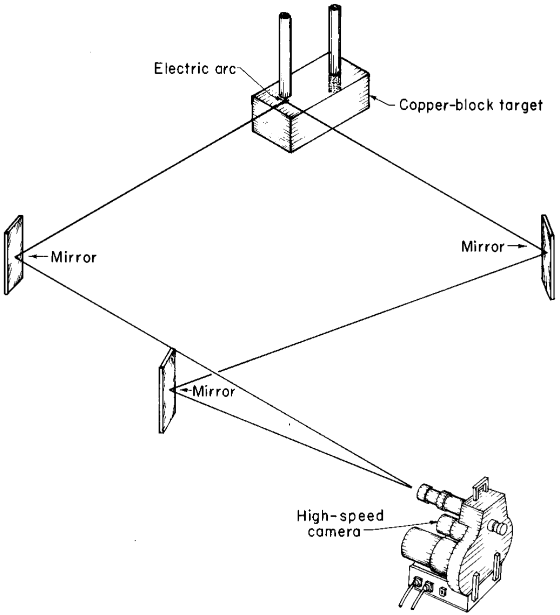

Figure 2.—Mirror setup for orthogonal views of arc into high-speed camera.

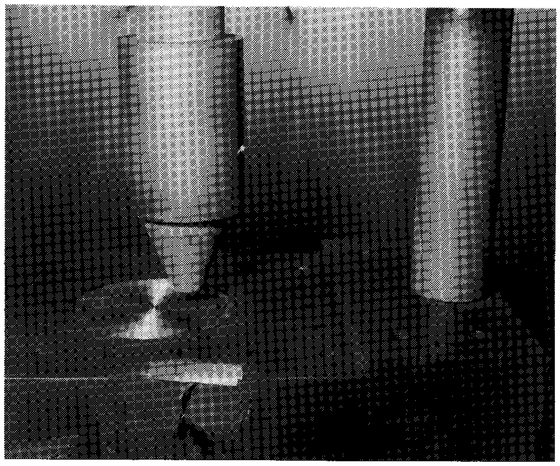

Figure 3.—Interior of electric arc furnace enclosure showing copper-block and electrode configurations.

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[4] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[5] Table numbers preceded by A- refer to tables in the appendix at the end of this report.

Table 1.—Capacity ranges of flow controllers

Flow controller	*Range, sLm N_2*
1	0- 20
2	0- 50
3	0- 30
4	0-100
5	0-500

The flow controllers used a 0- to 5-V input signal from a Data Translation, Inc., DT2815 (12 bit digital-to-analog resolution) analog output board within a personal computer for setting the desired flow rate (*5*). A proportional integral-derivative control scheme was used to maintain the flow-rate set points. The actual controlled flow rates were monitored by the data acquisition system.

Thermocouple, flow controller, and pressure transducer signals were acquired by an Analog Devices, Inc., μmac 4000 analog-to-digital measurement system with a rated accuracy of ±0.1 pct full scale (table A-2). The system has a capacity of 24 channels (*6*). The first eight channels were dedicated for type K thermocouples (±2.2° C standard error limit) in the interior of the furnace. Seven of these were located either on or inside the copper block, and the eighth one was positioned in the furnace atmosphere (fig. 6). The next five channels were designated for reading the voltage output from the flow controllers. Remaining channels were used to record the furnace pressure (Omega Engineering, Inc., model PX831, 25 psig full scale, ±0.25 pct full-scale output) (*7*) and electrical power consumption from various meters described below. The digital output from the μmac 4000 was sent to an Intel Corp. 80386-based computer for storage by an overall acquisition program written in GW-BASIC language (fig. 7).

Secondary transformer electrical signals were monitored with various meters and equipment (fig. 7). Power-monitoring equipment included a Scientific Columbus, Inc., type SC-10 meter on loan from Bonneville Power

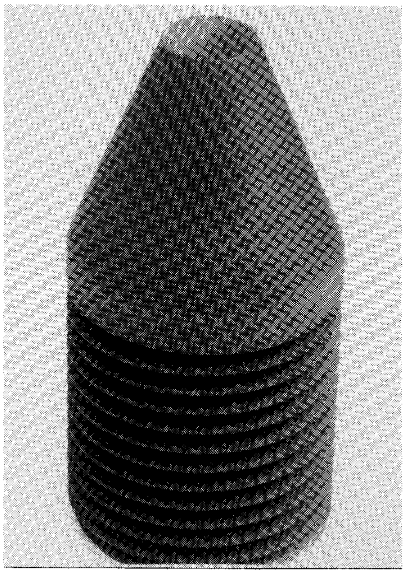

Figure 4.—Typical threaded, conical-shaped electrode tip (6-in length by 3-in diam).

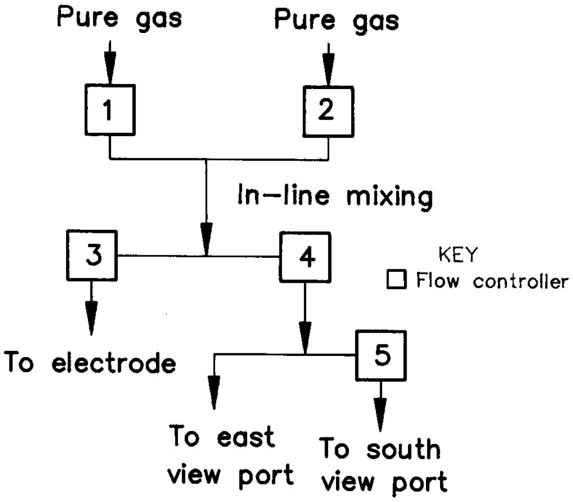

Figure 5.—Schematic of gas-flow-controller system.

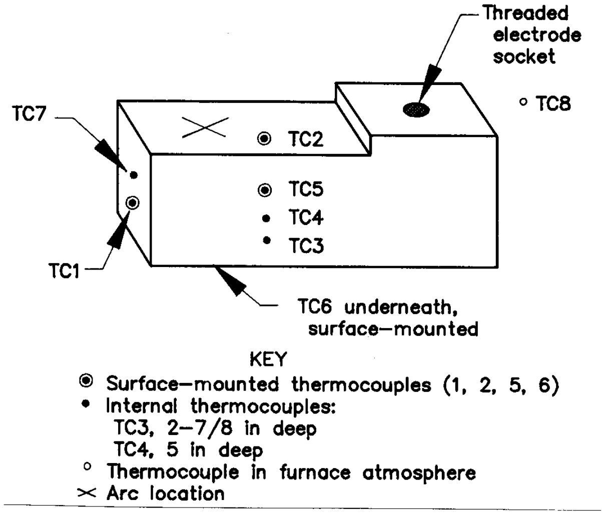

Figure 6.—Thermocouple (TC) placement inside furnace and on copper block.

Administration (*8*). A Valhalla Scientific, Inc., 2101 digital power analyzer was used to obtain true root-mean-square power readings (±1.0 pct full-scale-rated accuracy, see table A-3) (*9-10*). An integrated-circuit system was designed and comprised of isolation amplifiers, true root-mean-square converters, and a multiplier chip to obtain true root-mean-square data without the phase angle parameter. A Keithley Instruments, Inc., 197 multimeter (±4.2 pct total full-scale-rated accuracy, table A-3) was used for monitoring average instantaneous power for comparison purposes (*11*).

Orthogonal views of arc movement were directed into a Redlake Corp. HYCAM-II rotating-prism high-speed camera with a mirror system, shown in figure 2. Film capacity was 400 ft of 16-mm acetate or 450 ft of polyester film. The camera had a maximum rated speed of 11,000 full frames, 22,000 half frames, or 44,000 quarter frames per second. The camera had an internal timing light generator that placed a red indicator mark in the margin of the film at 100, 1,000, or 5,000 Hz. A second light-emitting diode could mark the other film margin to indicate external events (*12*). An event synchronizer on the camera was used to trigger a Data Translation precision data 6000, model 52, waveform analyzer (±0.01 pct full-scale-rated accuracy, table A-2) to begin waveform acquisition when the camera had accelerated to maximum speed and stabilized (approximately 200 ft of film at 44,000 quarter frames per second) (fig. 7). The event synchronizer was a simple contact closure that completed a circuit to the external trigger on the waveform analyzer. The waveform analyzer captured approximately 20 full cycles of the secondary voltage and current signals at 50 kHz (16,384 points per signal). The electrical data were stored on 5-1/4-in floppy disks for later coordination with approximately 13,000 quarter-frame images on the film (*13*).

When the waveform analyzer was triggered by the camera, it in turn triggered a LeCroy Corp. 6810 digitizing system that recorded longer electrical waveforms (up to eight megasamples at ±0.04 pct full-scale-rated accuracy, table A-2) than the waveform analyzer (*14*). The digitizing system was used to record the voltages and currents from the primary and secondary sides of the transformers and also to record the furnace cooling water temperature (fig. 7). All electrical signals into the digitizing system were transmitted by Dymec, Inc., 1-MHz analog fiber-optic links (±0.7 pct subsystem accuracy,

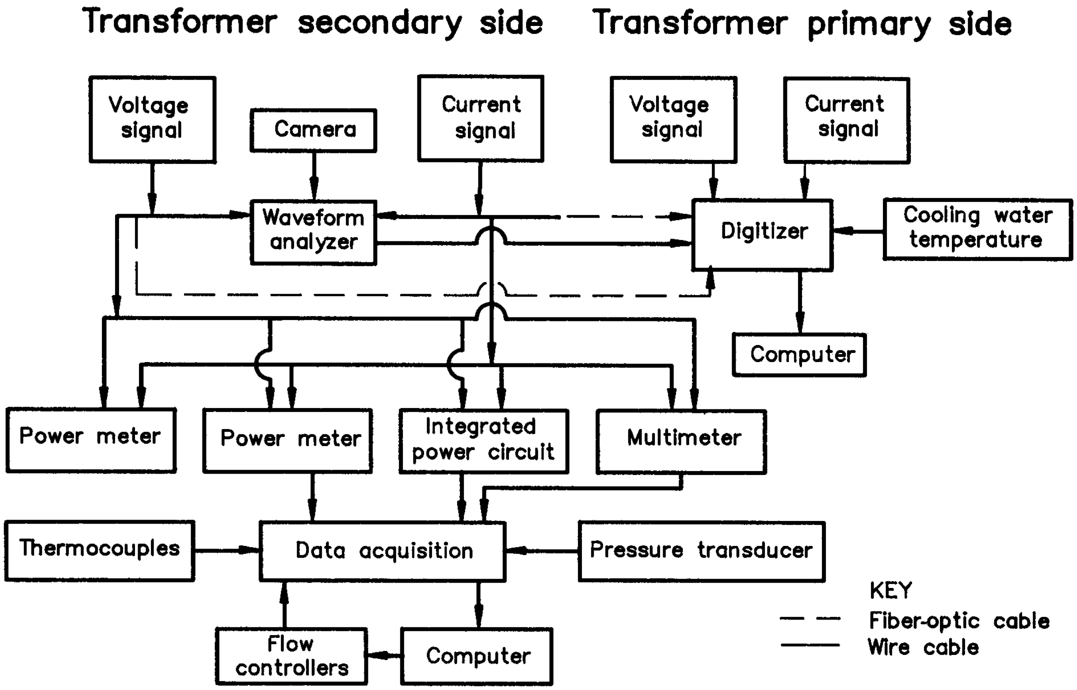

Figure 7.—Overall schematic of data acquisition system.

table A-4) to achieve electrical isolation (*15*). Data acquisition rates were varied at 50, 100, and 500 kHz. Although the fiber-optic links and isolation amplifiers (appendix) are rated at up to 1 MHz operation, 500 kHz deration was used because of rolloff of the input signal at higher frequencies.

Operational aspects of the experiments included heat treatment of electrode tips for removal of volatiles. The tips were placed in a graphite-element-resistance furnace capable of a maximum temperature of 1,600° C. The furnace chamber was evacuated down to 50 μm Hg, and then the temperature was increased from room temperature to 1,500° C at a rate of 10° C/min. The temperature was held at 1,500° C for 15 to 60 min at full vacuum. The furnace was then quenched with helium for approximately 2 h.

The experimental electric arc furnace preparation included replacement of the view port glass-fiber filters before each run. View ports and the furnace interior were vacuumed to remove any soot or carbon residue from previous tests. The 6-in-diam by 3-in-deep threaded copper insert for the copper block was resurfaced after each test so that a flat surface was always present at the start of each test. The test electrode and copper insert were weighed before each test, and pictures were taken before the front of the furnace was installed. The furnace was leak tested and purged for 1 h before the start of the tests, with the test gas at a flow rate of 1.5 scfm (0.10 scfm through the electrode, 0.70 scfm to each view port). Flow measurements were ±1.6 pct full scale (table A-1). For tests using electrodes with gas holes and no gas through the electrode, the electrode was purged initially for approximately 2 min and then the gas to the electrode was shut off. A pressure relief valve on the furnace shell top was set to relieve pressure at 1 psig.

Cooling water for the electrode clamps, shunt, and furnace shell was started 1 h before the test. Data-recording equipment were also turned on prior to testing to provide an adequate warmup period. Test duration was approximately 8 min. During that time, the LeCroy digitizing system was programmed and controlled by Asyst Software Technologies, Inc., 3.1 software (*16*) to acquire data every minute starting with 100-kHz sampling and then switching to 500- and 50-kHz sampling. Real-time videotaping of the arc was taken for the test duration. The high-speed film was taken approximately 4 min into the testing sequence. At the end of 8 min, the power to the furnace was turned off, and if there was gas flowing through the electrode, it was shut off to provide accurate cooling curves for the copper block. After the conclusion of the test, the system was cooled for 1 h with the cooling water and test gases flowing to the furnace shell. After cooling, the front of the furnace was taken off, pictures were taken, and the electrode tip plus copper insert were weighed individually.

Tabulation, graphical representation, and statistical analysis of the data, such as energy transfer efficiency, energy consumption, and electrode consumption, were completed with various software packages on a personal computer. Voltage and current electrical waveforms were plotted and correlated with the high-speed-film arc images. On the film, there was a constant offset of five full frames between the timing marks and the exposed frame. This was due to the light path being physically removed from the light-emitting diode location. During analysis, it was important to compensate for the offset. In most high-speed cinematography, an intense auxiliary light source is necessary, but the arc allowed operation at f8 (ratio of the focal length to aperture setting), resulting in a reasonable depth of field of approximately 6 in, with no supplementary light source. The films were viewed on a photographic motion analyzer at rates that varied from a single frame to 24 frames per second. Combining images from the motion analyzer with electrical signals from the waveform analyzer allowed the identification of individual arc events and the corresponding changes in the voltage and current characteristics. High-speed-film images were also enhanced by video-camera digitizing used by an image-processing system. This system allowed edge, additive, and subtractive image enhancement by utilizing selective gray and false color levels.

RESULTS AND DISCUSSION

This advanced, experimental single-phase furnace, in conjunction with high-speed data acquisition systems, allowed statistically designed experiments to be completed with at least 90 pct confidence in the measurements. Experiments were designed (1) to provide an efficient way of confirming or denying conjectures about the response of the arc to variables such as electrode tip shape, gas composition, and gas-injection location (hypothesis testing), (2) to assess the reliability of estimates and conjectures, (3) to estimate the variability of the experimental materials, (4) to increase precision by eliminating extraneous variation from the comparisons of interest, and

(5) to provide a systematic, efficient pattern for conducting the experiments. Replication and randomization were utilized in completely randomized, statistically designed experiments. Replication provides an estimate of experimental variation, increases precision, and broadens the base for making inferences. Randomization was used to limit bias and to ensure independence among the observations.

Measured results consisted of electrode loss in grams, energy consumption in kilowatt hours, and heat (energy) transfer efficiency in percent. Energy transfer efficiency was defined as the amount of heat transferred to the copper-block-arc target, converted to energy units, divided by the total amount of energy delivered to the furnace, and multiplied by 100 for a final value represented as a percentage. Other results included the synchronization of the high-speed films with voltages and currents from the primary and secondary sides of the transformers. Figure 8 shows an example of a section on a secondary voltage waveform as it corresponded to the arc movement on the high-speed film (*17*). The "ringing," labeled "A" in the figure, represented the attachment and detachment of a third arc root onto the electrode and is depicted in the lower half of the figure. Use of real-time acquisition of electrical signals for monitoring and controlling the furnace performance may be a possibility for future investigations.

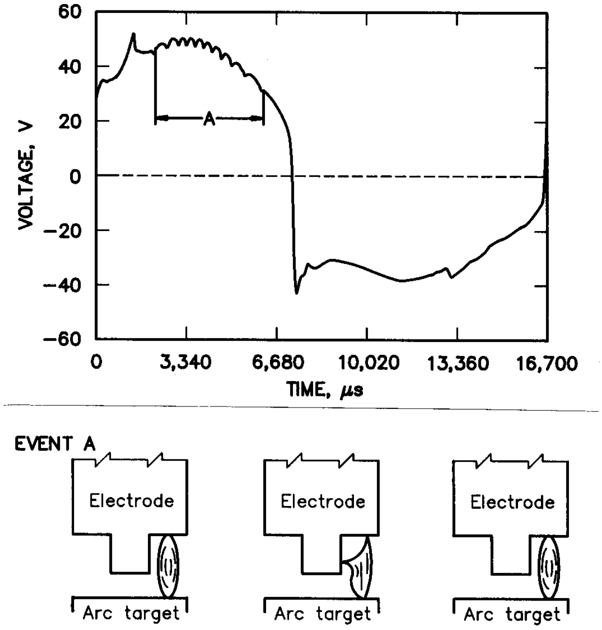

Figure 8.—Voltage waveform (top) with film arc image synchronization (bottom). (Event A are attachment points.)

CONCLUSIONS

A single-phase experimental electric arc furnace was designed and instrumented to evaluate responses to different treatment variables such as, but not limited to, electrode tip shape, atmosphere compositions, and different atmosphere injection schemes. At least a 90-pct confidence level can be achieved for the resulting responses such as electrode loss, energy consumption, and heat (energy) transfer. Real-time synchronization of the electric arc movements with electrical signals was accomplished.

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APPENDIX.—INSTRUMENTATION ERROR BUDGET

Uncertainty in measuring furnace operating parameters falls into two categories. The first category is systematic uncertainty involving calibration, precision, and accuracy of the data acquisition components. The second category of uncertainty involves arbitrary fluctuations in operating conditions (referred to as random error). Random errors are addressed in the statistical design and repetition of experiments. These design considerations are part of the experimental procedure in each process studied and are covered in the reports on individual experiments (*18*).[1]

The systematic errors are based on manufacturing specifications, calibration, and testing of the individual components. The maximum expected combined error for each data acquisition subsystem is covered in tables A-1 to A-4. Temperature errors are based on a variation of ±2.0° C over the period of an experimental run and on the temperature coefficients for the equipment.

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[1] Italic numbers in parentheses refer to items in the list of references preceding this appendix.

Table A-1.—Total error budget of atmosphere-monitoring subsystem, percent full scale (±1.8 pct)

Error mode	Analog-to-digital converter	Digital-to-analog converter	Mass flowmeter
Temperature	±0.006	±0.004	±0.2
Rated accuracy	±.1	±.025	±1.0
Pressure error based on 4 atm differential	NAp	NAp	±.4
Subtotal	±.1	±.026	±1.6

NAp Not applicable.

Table A-2.—Error budget for each instrument of data acquisition subsystem, percent full scale

Error mode	LeCroy 6810	Data Translation precision data 6000	Analog devices µmac 4000
Temperature	NAp	NAp	±0.006
Rated accuracy	±0.04	±0.01	±.1
Total	±.04	±.01	±.1

NAp Not applicable.

Table A-3.—Error budget for each instrument of commercial-power-monitoring subsystem, percent full scale

Error mode	Valhalla 2101	Keithley 197
Temperature	±0.05	±0.2
Rated accuracy	±1.0	±1.0
Philips isolation amplifier	NAp	±3.0
Total	±1.05	±4.2

NAp Not applicable.

Table A-4.—Total error budget of fiber-optic subsystem, percent full scale (±0.7 pct accuracy)

Error mode	Transmitter maximum	Receiver maximum
Temperature	±0.04	±0.20
Frequency and voltage conversion	±.05	±.05
Supply voltage	±.06	±.10
Nonlinearity	±.10	±.10
Subtotal	±.25	±.45