Energy Assessment Protocol for Glass Furnaces

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1.0 INTRODUCTION

PPG Industries, Eclipse/Combustion Tec and the Diagnostic Instrumentation and analysis Laboratory at Mississippi State University (DIAL) were brought together for this project through their association with GMIC (Glass Manufacturing Industrial Council). The Department of Energy (DOE), Industrial Technology Program, provided funding for the team to develop a set of tools to allow a glass producer to perform an energy assessment. The project goal was to provide DOE a general method outline that can be used to identify opportunities for energy savings on a glass furnace. The objectives of the assessment are to identify where energy losses occur and inefficiencies exist, and to recommend how to address these findings. Therefore actions will be taken based on data gathered during furnace operation, and then the effectiveness of those actions will be determined through data collection after changes are made.

1.1 DIAL at Mississippi State University

DIAL has a demonstrated record of collecting mass and energy data in high temperature environments. DIAL has designed and fabricated several water-cooled probes capable of measuring gas temperature, gas composition, gas velocity and, glass temperature in furnaces with exhaust temperature as high as 1650 ºC. The ability to make these measurements, coupled with wide-ranging pyrometry and thermal imaging capabilities made DIAL ideally suited to perform an energy assessment and develop general procedural guidelines.

1.2 PPG

Seeking to improve energy efficiency, PPG proposed using one of its fiber glass furnaces in the DOE energy assessment. Three factors supported the use of a PPG fiber glass furnace for this assessment. First, the energy balance highlights energy input to the system (melter), system efficiency and opportunities for improvement, which can include improving energy efficiency and reducing emissions. Second, the relationship between energy and emissions can be understood better and perhaps optimized by performing an energy balance. Third, validation data usually consists of temperatures and other easily acquired data, while the data glean in this assessment is not easily collected and therefore enables furnace model validation on a new, higher level. The outcome is either validation of the furnace model, which gives confidence in the model results, or, a better appreciation for the areas of the model that require a review or new inputs. Besides modeling the impact of furnace design changes, a fully validated model allows for quick analysis of simple changes such as the effect of increasing throughput.

1.3 Combustion Tec / Eclipse

Combustion Tec, a brand of Eclipse, Inc., is a supplier of fuel-efficient burners, systems and services to the glass industry. The group's core competency extends from burners and accessories to combustion technology, processes and systems for the glass industry worldwide. More than 850 major glass furnaces worldwide use Eclipse/Combustion Tec equipment.

Eclipse/Combustion Tec has well-qualified, glass industry experienced engineers, project managers, and research scientists. In addition, Eclipse/Combustion Tec has a sales staff that possesses specialized knowledge in ceramics, combustion, fluid dynamics, heat transfer,

manufacturing, electronics, instrumentation and controls, and other energy-related subjects. The company's core products are its fuel-efficient burners supported with complete fuel combustion systems for use with gas, oil, or a combination of gas and oil. Eclipse/Combustion Tec's Primefire® series burners are multi-fuel oxygen burners. It is their expertise in the field and support of their customers that makes Eclipse/Combustion Tec a valuable partner in the development of this energy assessment protocol.

2.0 PROTOCOL DEVELOPMENT

2.1 Initial Furnace Tour

The first step in energy measurements of a glass-melting furnace should be a tour of the furnace and facility to identify (1) access points for combustion space measurements (2) access to water, electricity, and physical space for the sensors and support equipment to be used and (3) space around the furnace for sensor installation. If the boundary established for the energy balance is the furnace itself, then measurement of the exhaust gases should be made as close as possible to the melter/exhaust flue interface. In the case of the worked example, the access was both through the melter stack and through the melter flue. As the sensors tend to be long, for cooling and increased traverse capabilities, access into the furnace at key locations may present some challenges. Therefore, a tour of the melter prior to the measurement effort can identify potential access points as well as identify any changes that may be necessary to either the furnace access areas or the sensors used.

During this initial tour, a thorough examination of the furnace should be conducted and general observations should be noted. The assessment team should identify any obvious gaps in the furnace walls, including any open ports, burner holes or missing bricks. Note whether a means is available to close ports during operation and where there are significant sources of air in-leakage. The stack should be examined for excessive build-up of glass residue, un-reacted batch, and exhaust soot. This review should be repeated just prior to the measurement phase of the assessment.

The assessment team should obtain a list of any energy-related measurements that are routinely taken at the facility, for example, temperatures, fuel gas flow rate, air or oxygen flow rates, and /or combustion stoichiometry. If possible, determine if there is any evidence that the fuel and oxygen flow rates are not within expected range, which may indicate that the flowmeters are out of calibration. Facility representatives should then provide an idea of what controls are exerted based on those measurements. Having knowledge of how the furnace is controlled will allow the assessment team to better identify opportunities for improvements in energy efficiency.

Specific information regarding the use of waste heat should be discussed with the facility personnel. The assessment team and facility personnel should identify the extent to which waste heat is being used to alleviate burdens on the facility. For example, if the feed is hydroscopic, usage of the waste heat to dry the feed should be noted.

Although it is seemingly a minor detail, the definition of standard temperature, as used by the glass facility, should be determined for use in the energy balance.

2.2 Preliminary Mass and Energy Balances

After making an initial trip to the facility and reviewing the information obtained, mass and energy balance skeletons should be developed specifically for the furnace being assessed. This allows the assessment team to identify all the data required to complete a practical energy audit. It will also underscore problems that may be encountered in collecting the necessary data. For instance, there may be physical hindrances that prevent data collection from an ideal location,

and arrangements may need to be made with the facility in order to assure that the required data is collected.

From the preliminary energy balance, a list should be compiled, and include (1) data necessary to complete an energy balance, (2) data necessary to complete a mass balance (3) locations where measurements should be made, (4) measurement tools necessary to collect the data, (5) an estimation of time required for each measurement, and (6) identification of which measurements can or should be taken simultaneously.

The following are items that should be considered in the energy balance: areas of extraordinary heat loss from the furnace to the surroundings, significant non-uniformity and/or asymmetry in temperature distribution within the furnace, considering the walls, ceiling, floor, gas, and glass pool. Where possible, the flame direction, flame size, and flame coverage should be ascertained during the measurement effort.

Additional information that can be obtained from the facility personnel prior to making measurements includes:

1. Wall/Brick thickness
2. Thermal conductivities for bricks and insulation
3. Fuel and oxygen flow rates
4. Number of bubblers (identify if they bubble air or oxygen)
5. Method of measuring fuel and oxygen (or air) flow rates
6. Date of the last calibration on fuel and oxygen flow meters
7. What the facility uses as a density value for the fuel or fuel mixture
8. What the facility uses for standard temperature and pressure for oxygen and fuel flows
9. Other sources of energy input (electrical)

As the information is provided, the combustion stoichiometry can be identified and included in the preliminary mass and energy balance skeletons. The intent is to complete as much of the balances as possible prior to the measurement campaign in order to identify information that will be required for balance closure. The earlier the mass and energy balance skeletons are completed, the less chance there will be of missing key pieces of data.

2.3 Measurements

The measurement trip is obviously fundamental to performing an Energy Assessment, therefore, the importance of preparation and planning cannot be emphasized enough. One important preparatory step is performing pre-trip calibration and testing, which should be completed on equipment and sensors early enough to allow time for repair, either by the assessment team or by a vendor. Allowing enough time to have equipment or sensors shipped to a manufacturer for repair can easily be overlooked.

As discussed previously, it is important to determine the data acquisition points which will best support the mass and energy balances prior to making the measurement trip. In addition to location, timing is also critical. Measurements should be taken during normal furnace operating conditions, and while the pull rate is maintained at a constant level. Where possible for the

actual measurement, it is ideal to obtain data along a traverse at a measurement location. Also for traverse measurements, it is essential that the data be collected at random points, which will preclude the appearance of a trend that potentially does not exist. For instance, five velocity measurements are made linearly across an exhaust flue and the velocity increases at each point along the traverse. This pattern could be an artifact of either a changing velocity profile across the flue, or it could simply be an increase in average flue velocity over time. To prevent the appearance of false profile trends, measurements should be made at random probe insertion lengths (i.e., not sequential one-foot increments) or the measurements should be made during insertion of the probe and repeated during extraction of the probe. Repeating measurements on subsequent days will also help to reflect energy consumption during normal operating conditions.

After taking measurements at the furnace facility, it is important to complete a post-trip calibration of equipment and sensors to rule out the possibility of performance drift that may have occurred during the measurement effort. This calibration provides an additional level of confidence in the data obtained for the energy assessment.

2.4 Results

Inputting the data collected during the measurement effort into the mass and energy balances can provide an overall idea of how efficiently the furnace is operating. However, in addition to the balances, other general aspects of the furnace and facility can influence energy efficiency and provide the opportunity for improvements. Facility and assessment personnel can identify items particular to an operation that should be addressed. For instance, identify to what extent exhaust heat is being re-used; identify whether or not the feed is hydroscopic, and/or whether waste heat is utilized to dry the feed.

2.4.1 Mass and Energy Balance Methodology

The mass input to the furnace consists of:

- Natural gas (fuel) flow into the furnace;
- Air/Oxygen flow into the furnace;
- Batch fed into the furnace; and
- Air infiltration into the furnace.

The mass leaving the furnace consists of:

- The exhaust gases leaving via the flue;
- The molten glass product; and
- Exfiltration gases leaving the furnace via openings other than the flue.

The natural gas is mostly methane, but contains other gases also, so the natural gas composition must be analyzed. A flow meter (usually an orifice meter) gives the flow rate of natural gas into the furnace. Similarly, the composition and flow rate of the oxygen into the furnace are known.

The furnace operators know how much batch is required to make a pound of glass. Thus, an estimate of the rate of batch feed into the furnace from the pull rate is made. In most cases it takes more than one pound of batch to make a pound of glass. The excess represents gases, mostly carbon dioxide and water vapor, which are evolved from the batch as it is heated. There may also be minor amounts of other gases and/or particulate matter. The rate of evolution of these gases can also be estimated from the pull rate and the batch chemistry.

The rate of air infiltration into the furnace is not known. The composition of standard air is known, so the flow rate must be determined from the mass balance.

The composition of the gases leaving the furnace via the flue is known from gas analysis measurements. Some species, such as carbon monoxide, NOx, and sulfur dioxide, are present at ppm levels and may be considered negligible for mass balance calculations. The major species to be considered in the mass balance are water vapor, carbon dioxide, oxygen, nitrogen and argon. Gas analysis readings are traditionally reported on a dry basis, which is the gas composition after the water vapor has been removed. Conventional analyzers do not measure nitrogen and argon, generally, analyzers measure carbon dioxide and oxygen concentrations, and the balance is usually assumed to be nitrogen (or nitrogen and argon). A mass spectrometer can be used to obtain nitrogen levels.

The flow rate of glass from the furnace is the pull rate, which is provided by the furnace operators. If any gas from the furnace is lost via exfiltration, it is assumed that this gas has the same composition as the gases exiting via the flue, and thus is included with the flue gases.

Hence, all mass flows entering and leaving the furnace are known, except the air infiltration rate, and the mass of exhaust gas leaving via the flue and exfiltration is not known.

Knowing the flow rates and composition of the natural gas and oxygen, and knowing the rate and composition of the gases evolved by batch volatilization, a value for the air infiltration rate is assumed and then a mass balance on the gases in the combustion space is performed. The chemical equation for the combustion of fuel is written, assuming that all carbon atoms are oxidized to carbon dioxide, that all hydrogen atoms are oxidized to water (vapor), and that nitrogen and argon do not react (carbon monoxide and NOx are present at ppm levels). The result of this calculation is the composition and flow rate of the exhaust gases. By removing the water vapor, the exhaust gas composition can be calculated on a dry basis, and a comparison of the predicted carbon dioxide and oxygen concentration to the flue gas measurements can be made. If they do not agree, then the assumed air infiltration rate can be adjusted and the calculation repeated. When the calculation finally does agree with the measurements, an estimate for the air infiltration rate is obtained, and all other flow rates and compositions are known.

The predicted mass flow rate of the exhaust gas in the flue, together with its predicted composition and measured temperature, can be used to estimate the mean velocity of these exhaust gases in the flue. This velocity can then be compared to the pitot measurements of exhaust gas velocity as a check.

Once flow rates are known, the energy balance is performed. The mass flow rates, chemical compositions, and temperatures of the natural gas flow, the oxygen flow, the air infiltration flow,

and the exhaust gases leaving the furnace are known. It follows that a calculation of an enthalpy for each of these flow streams can be made.

The glass company personnel provide a value for the theoretical energy required to make a pound of glass. This number is effectively the difference between the enthalpy of the batch and the enthalpy of the glass and evolved gases. There is some question about whether or not this number includes the energy required to heat the evolved gases to the furnace exit temperature. If it does not, then this enthalpy needs to be included separately.

In addition to the enthalpies associated with the mass flows into and out of the furnace, there is the additional heat loss mechanism of conduction through the refractory walls and crown. The heat flux through any refractory wall can be calculated if the temperature on both sides of the refractory is known, and the thickness and thermal conductivity of each refractory that makes up the wall is known. This calculation method is a problem in one-dimensional steady heat conduction.

The glass company provides the thickness and thermal properties of the different types of refractory and insulation. Note that these thermal properties are estimates since the refractory has seen high temperatures and chemical exposure, which impact the original chemical and microstructural properties of the refractory. The temperatures on the outside of each surface were taken from the contact thermocouple measurements on the outside of the furnace. The temperatures on the inside of the furnace were harder to get: these were estimated from a combination of pyrometer wall temperature measurements, glass thermocouple measurements on the bottom of the tank, and crown thermocouple measurements.

For each refractory surface, such as an end wall, an estimation can be made for the average temperature on the inside of that wall, an average temperature on the outside of that wall. Then the conduction heat flux through the wall from one-dimensional steady heat conduction is calculated. The heat flux value (energy/area) is then multiplied by the surface area in order to obtain the heat loss through that section. Summing these contributions from each surface yields the total conduction heat loss.

Energy Balance

The energy balance can be represented as:

Energy input:

- heat of combustion of natural gas (assumes combustion products are cooled to 298 K).
- Preheated gases
- Preheated batch

Energy output:

- Heat of combustion products as they leave the furnace at a temperature greater than 298 K,

- Heat required to make glass, (do you mean to say temperature of glass leaving the furnace?)
- Heat required to raise temperature of gases evolved from batch to furnace exit temperature,
- Heat lost by conduction through refractory.

A mass and energy balance checklist and a mass and energy balance schematic are provided in Attachment 1 and Attachment 2 respectively. The mass and energy balance for the energy assessment performed on the PPG fiber glass furnace is Provided in Attachment 3.

2.4.2 Recommendations/Conclusions

Once the energy audit is completed, the assessment team can recommend changes that may increase facility efficiency. If a determination is made that the changes are cost effective, then the facility can implement the assessment team's recommendations. A follow-up assessment can quantify the effectiveness of the changes. It is recommended to wait for a period of time before making follow-up measurements to ensure furnace stability.

3.0 MEASUREMENT TOOLS

In order to measure furnace properties at various locations in the large furnace, several water-cooled probes are required. Probes used in the worked example are of a common design. These probes may be visualized as consisting of three concentric stainless-steel tubes. The innermost tube, designated tube 3, contains within it the necessary volume and/or aperture required for the instrument. There are two water passages, which are located between the outermost tube 1 and the center tube 2 and between tubes 2 and 3. The two water passages are connected at the end of the probe, so that cooling water can flow from the base (positioned outside the furnace) to the far end inside the furnace and back again. Small tube inserts are placed between the tubes to increase rigidity and maintain flow distribution.

A probe support and traversing mechanism was designed and built. This device allows the probe operators to conveniently adjust the insertion distance and angle of insertion so that the measurement point can be known and positioned as desired. It also provides support for the heavy probes and allows the rapid removal of a probe in the case of an emergency.

Because of the high temperatures typically found in the room near a furnace, special precautions have to be employed. It may be necessary to provide insulated, water-cooled enclosures for all heat-sensitive equipment. A water-air heat exchanger with forced (fan) convection can be used to circulate and cool the gas inside the instrument boxes. For small equipment, a thermal blanket with an ice pack can also be used.

3.1 Surface Temperatures

Exterior Wall

Typically, exterior wall temperature data is obtained using a contact thermocouple. A thermocouple, attached to an extension rod, is placed directly on the exterior surface of the

furnace brick and the temperature is displayed on a thermocouple reader. The temperature tends to decrease as the heat is transferred to the contact thermocouple rod. Therefore, the temperature value recorded should be the maximum temperature reading.

In conjunction with the contact thermocouple data, the ambient temperature is recorded using a bare thermocouple.

Interior Wall

In the application of pyrometry to the measurement of wall temperatures in the furnace, various interferences can occur. Emissions from atomic and molecular species in the visible and near-infrared, and the major molecular species (water and carbon dioxide) in the infrared region may occur. In addition, hot soot, essentially localized near the burners, radiates throughout the infrared region with significant intensity up to 5 μm. Since the burners are located essentially opposite the ports, it is difficult to view the interior walls without interference. Soot radiation, molecular radiation from water, and carbon dioxide are sources of interference. The radiation will be more significant near the burners since very hot molecules are present.

A ratio pyrometer with a spectral response at 0.92 and 0.98 μm with spot size 1:90 can be used for survey measurements at various regions of the wall and crown. This type of pyrometer gives a temperature that is independent of the surface emissivity. Interference from emissions near the burners may be observed with these near-infrared pyrometers, so interpretation of these measurements is not necessarily straightforward. For example, a rather high temperature is obtained when one views the burners or the wall near the burners. Measurements of the wall away from the burners, where molecular radiation and/or soot radiation is minimized, gives lower temperatures more indicative of the true wall temperatures. When burners are nearby a view port being used to view elements of the furnace, emission interference from the flame region can be picked up by the pyrometer.

In addition to the ratio pyrometer, a two-color pyrometer or a 5-μm pyrometer can be used to interior wall measurements.

Glass surface

Glass surface temperature measurements are generally made with a 5-μm pyrometer. When the glass level is relatively close to the port level, to view the glass surface, the pyrometer is tilted down at a small angle. Because these measurements are made at an angle just off normal, significant radiation from the wall may be seen. However, the temperature measurements can be corrected for angle and for wall radiation.

It is clear that the reflection correction is quite significant. If only the correction for the glass emissivity were made, an unreasonably high glass temperature would be obtained. On the other hand, by correcting for reflection effects, a lower more reasonable glass surface temperature is obtained, which interestingly is quite close to that obtained by viewing the glass and omitting all corrections. The reason is that the wall you see reflected in the glass is approximately the same temperature as the glass, so the corrections for the emissivity of the glass and the reflected radiation from the wall essentially cancel out.

Glass surface measurements can also be made with a 5 μm probe-based pyrometer. This system allows one to view the glass surface from the normal direction via a mirror system. To keep the mirror clean, a nitrogen purge gas is used with a nominal flow rate of 80 scfh at 50 psi. Two sources of problems are observed with the use of this system. First, the pyrometer sensor was found to be temperature-sensitive. The radiation from the glass heats the pyrometer and this results in an apparent decrease in the measured temperature. This is somewhat surprising since the pyrometer head is contained in a water-cooled probe and cold purge gas passed around the pyrometer. In any case, post analysis of the change in measured temperature with the internal pyrometer temperature (temperature correction increases with an increase in detector temperature) allows for a correction for this effect with reasonable confidence.

Second, the pyrometer probe was found to be sensitive to interference from the burners. Rotating the probe + 2° or + 5° does not produce a significant change in the recorded temperature. On the other hand, by momentarily turning off the burners near the probe, a significant decrease in the recorded temperature can be observed immediately. The temperature drops in less than 5 seconds, after which the glass starts to cool slowly. These results indicate that the interference is probably a molecular radiation effect from the hot combustion product gas. Unfortunately, it was not possible to make all the measurements with the burners off.

3.2 Gas Temperatures - Suction Pyrometry

In order to measure the gas temperatures in the furnace, a high-velocity thermocouple (or aspirating thermocouple) probe must be used to minimize radiant heat transfer from the thermocouple and its surroundings. Hot gases are aspirated across a thermocouple within a cylindrical radiation shield. The hot exhaust gases heat both the radiation shield and the thermocouple. The shield effectively isolates the thermocouple from the surrounding radiation, preventing the thermocouple from radiating to the cooler furnace walls. A vacuum pump is used to draw the gas, at high velocity, through the shield and over the bare thermocouple. The thermocouple readings are taken at various flow rates, which are measured with a standard flowmeter. Filters are used to prevent exhaust soot from collecting in the flowmeter. Also, considerable water exists in furnaces with oxy-fuel burners. Unless a heated insert is used, the water can condense in the probe. For this measurement effort, water was collected in a filter housing.

A simple arrangement is used to mount the platinum sheath inside the water-cooled probe. A water dam prevents any water condensed in the back end of the probe from reaching the tip of the thermocouple. In addition, the probe is operated with the tip in a slightly elevated position.

3.3 Gas Composition

A gas-sampling probe was used to cool the gas quickly while preserving the chemical composition of the sample. The gas sample from the high-temperature furnace is quenched rapidly by being drawn through a small narrow tube at the end of the water-cooled probe. The walls of this tube are cooled with water and as the gas flows through the tube, convective heat transfer occurs because of the temperature difference between the gas and the tube wall, and as a result the gas cools and the gas chemistry is essentially frozen. Water condensation inside the probe is avoided by use of a heated section in the probe and a heated sample line outside the

probe. The gas sample is subsequently cooled and the water is removed. For calibration of the analyzers, certified calibration gases are used. The system is also periodically checked for possible leaks.

The gas analyzers employed during the worked example were the Siemens and Rosemount units. The Siemens unit is used to measure CO_2 in the range 0-100 %. The Rosemount unit is used to measure the CO in the range 0-10,000 ppm. In addition to the CO detector, the Siemens unit has an electrochemical cell, which is used for determining the oxygen concentration in the range 0-25 %. A Rosemount model 951A gas analyzer is used to detect nitric oxide. This analyzer has seven ranges, which allow measurement of gases with NOx concentrations between 0-10 ppm and 0-10,000 ppm.

The estimated accuracy of the analyzer instruments are: [CO_2] 1%, [CO] 5% of reading, or 1% of full scale (10000 ppm) whichever is less, [0_2], 1% of full scale (25%), or 0.25%, [NO_x], 1% of full scale (10000 ppm), or 100 ppm.

In spite of relatively fast quenching of the gas sample (the gas temperature drops below 1000 K in a few milliseconds), the composition of the gas sample does change some as the gas cools. Generally, the change in the gas composition during the quenching process has a larger effect on the concentrations of species that are present in small quantities than on those that are present in large quantities. The changes in gas composition during the quenching process have been evaluated at two temperatures and they are more significant for the 2200 K gas than for the 1800 K gas. Water vapor (H_2O) and nitrogen (N_2) concentrations tend to remain relatively constant during the quenching process for all temperatures and mixture ratios examined. Carbon dioxide (CO_2) concentrations tend to remain relatively constant at the lower temperature (1800 K) but some changes (2-3%) are observed at the higher temperature (2200 K). Carbon monoxide concentrations tend to remain relatively constant when the stoichiometry is fuel-rich, and CO present in high concentrations. When the mixture is fuel-lean, and the CO concentration is small, the relative change is larger. The concentration of nitric oxide (NO) remains relatively constant during the quenching process, except under fuel-rich conditions where the NO concentration tends to be small.

To check the performance of the gas-sampling probe in the field, calibration gases are used to verify that the gas concentrations are measured with acceptable ranges. A check of the sampling probe is usually made after a series of measurements. To evaluate the performance of the gas analysis probe, measurements are made with various calibration gases. The results indicate the performance is satisfactory, and within the stated accuracy of the instruments.

3.4 Gas Velocity – High Temperature Pitot Probe

The pitot tube is a traditional method of measuring the velocity of a gas. It relies on sensing the difference between the stagnation pressure and the static pressure. The velocity is found from the use of Bernouli's equation together with an empirical Pitot coefficient, which is usually slightly less than one,

$$V = C\sqrt{\frac{2\Delta P}{\rho}}$$

where C is the calibration factor, ΔP the measured pressure differential, and ρ the gas density. Where C is the calibration factor, ΔP, the measured pressure differential and ρ the gas density. Multi-hole probes can sense the direction of the flow in the case that the Pitot is not pointed exactly upstream. The velocity-sensing region covers a cone of 75°. It is difficult to measure small velocities due to the small ΔP. A range of pressure transducers are available which cover the differential pressure range of 0.05 - 5 in of H_2O. This covers the measurable velocity range in the furnace.

Performance checks rely on measurements with the Pitot probe in the airflow before and after its use in a glass furnace. Purge cycles are used to help prevent build-up of particulate in the Pitot tube orifices.

3.5 Thermal Imaging / Flame Monitoring System

As another application of pyrometry, an imaging system was utilized to measure two-dimensional temperature profiles within the glass furnace. The effective wavelength for the imaging pyrometry has been carefully selected to avoid the spectral interferences from various sources noted in Section 2.1 Surface Temperature – Interior Wall. The system was calibrated using a NIST-traceable temperature calibration source. Based on the system response function, temperature-color bins were integrated into the system. Monochrome spectral images were acquired by the system workstation. Applying the system response function to these raw images reveals in near real-time the temperature distribution over the user-selected region-of-interest (ROI). Temperature distributions over the ROI are presented in the second window (false-colored image) which translates the raw B/W image into readily observable bands of temperature distribution. In addition to the two-dimensional thermal information, temperature line profiles across a user-drawn line can also be displayed.

The thermal imaging system acquires interference-free spectral images to yield the thermal information. The same system can be transformed into a flame-monitoring system by utilizing a specific selected bandpass filter, which allows only key combustion spectral radiance to be acquired. With proper observation port location, the geometric flame parameters can be revealed.

Attachment 1

Energy Assessment Checklist

INITIAL FURNACE TOUR

- Determine access points for measurements
- Create area sketches with physical dimensions
    - Floor plan
    - Heights to probe entry ports
    - Identify physical encumbrances
- Identify water supply locations
    - Amount available
    - Distance to supply point/points
- Identify water discharge locations
    - Distance to discharge point
- Identify Electric outlets
    - Amperage and Voltage available
    - Distance to electric source
    - Note which outlets are on different circuits
- Take photographs (with permission from necessary plant personnel)
- Note general furnace observations
    - Gaps in furnace walls
    - Open ports
    - Open burner holes
    - Missing bricks
    - Can ports be closed when not in use
    - Note other sources for air in-leakage
    - Stack
- Obtain a list of energy related measurements taken by the facility
    - Temperatures
    - Fuel gas flow rates
    - Oxygen or Air flow rates
    - Determine normal operating range

PRELIMINARY ENERGY ASSESSMENT

- Develop Mass and Energy Balance Skeletons
    - Identify required data points
    - Identify measurement locations
    - Determine necessary measurement tools
- Collect information from the facility
    - Wall/Brick thickness
    - Thermal conductivities of bricks/insulation
    - Typical fuel and oxygen/air flow rates
    - Bubbler location and flow rates
    - Method of measuring fuel and oxygen/air flow rates
    - Date of calibration on fuel/oxygen flow meters
    - Density value used by facility for fuel or fuel mixture
    - Values used for standard temperature and pressure
    - Other pertinent data
- List potential hindrances to taking measurement
    - Physical
    - Utility limitations
    - Port availability
- Estimate time required to take measurements
- Identify which measurements should be taken simultaneously

MEASUREMENT

- Order calibration gases to be used at the measurement facility
- Perform pre-trip calibration
- Take measurements during normal operating conditions
- Use random positioning– reduce false trending scenarios
- Repeat data collection as necessary – perform multi-day measurements
- Take traverse measurements where possible
- Measure as near to flue/furnace interface as possible
- Perform post trip calibration

- Information to note while taking measurements
    - Glass pull rate
    - Ambient temperatures
    - Fuel/oxy flow rates
    - Glass temperature
    - Date/time

RESULTS

The mass balance can be represented as

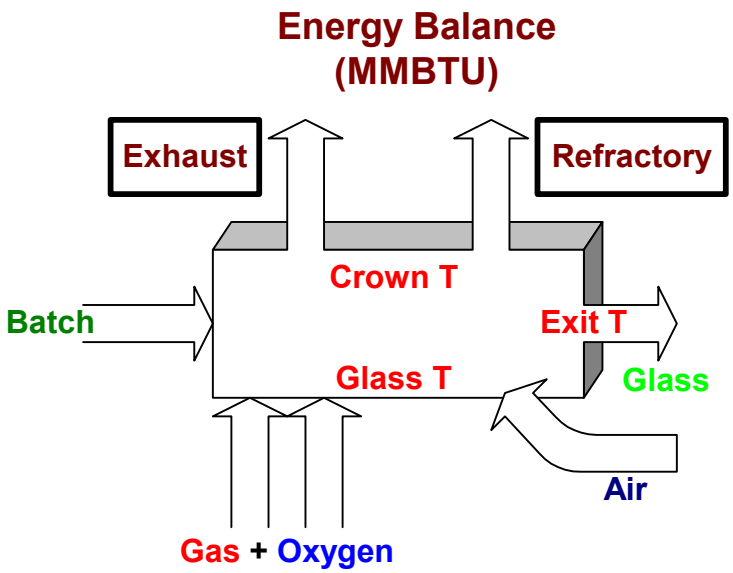
- The mass input to the furnace
    - Natural gas flow into the furnace
    - Oxygen flow into the furnace (for an oxy-fuel furnace)
    - Batch fed into the furnace
    - Air infiltration into the furnace
- The mass leaving the furnace
    - The exhaust gases leaving via the flue
    - The molten glass product
    - Exfiltration gases leaving the furnace via openings other than the flue

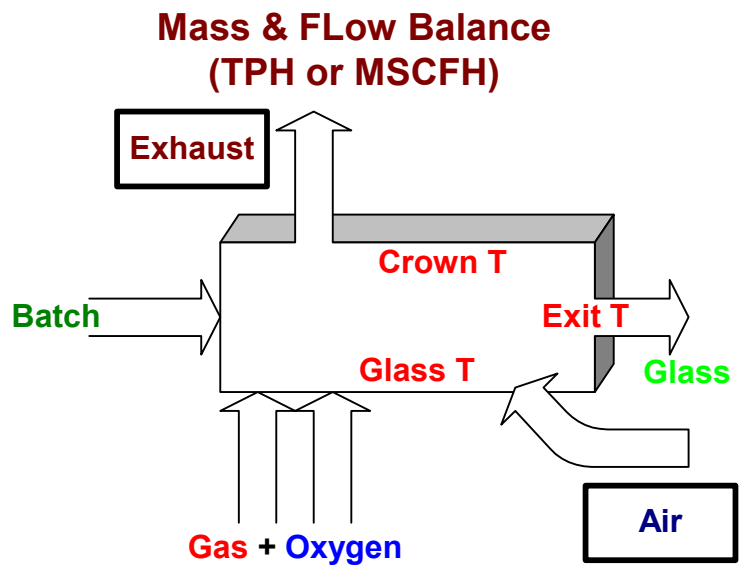
The energy balance can be represented as

- Energy input
    - Heat of combustion of natural gas (assumes combustion products are cooled to 298 K)
    - Preheated gases
    - Preheated batch
    - Electrical energy input
- Energy output
    - Heat of combustion products as they leave the furnace at a temperature greater than 298 K
    - Heat required to make glass (or temp?)
    - Heat required to raise temperature of gases evolved from batch to furnace exit temperature
- Heat lost by conduction through refractory

Attachment 2

Mass and Energy Balance Schematic





Date:	**June 2003**	**Pull:**	**T/day**
Gas:	**MSCFH**	**Oxy:**	**MSCFH**
Eff.:	**%**	**Energy/Glass:**	**MMBTU/Ton**

Figure A-1: Mass and Energy Balance Schematic (provided by John Connors, PPG)

Attachment 3

DIAL/PPG Worked Assessment

Mass and energy balances

A primary objective of our measurement campaign was to construct a mass and energy balance of the furnace. This section of the report shows how these balances were constructed, describes the assumptions that were made, gives the data that were used to compute these balances, and shows sample results.

The basic idea is that, if a furnace is operating steadily, the mass flowing out of the furnace is equal to the mass flowing into the furnace. Similarly, the energy flowing out is equal to the energy flowing in. These balances are dependent on the assumption of steady operation, so that the accumulation of mass and energy inside the furnace can be neglected. It is understood however, that an operating industrial glass furnace does not operate under perfectly steady conditions. The glass pull may change, and the batch feed may start and stop.

The energy assessment team decided that the steady-state idealization is more accurate when applied to a long-term average of furnace operation, rather than to the instantaneous operation. Therefore, daily averages of the glass pull rate, natural gas flow rate, and oxygen flow rate from PPG's plant instrumentation were used to construct the furnace mass and energy balances.

These measurements were combined with the results from DIAL's measurement probes to construct mass and energy balances for the furnace. DIAL's probes were manually inserted, and could not be left in place for long periods of time, and thus represent snapshots of the furnace operation rather than long-term averages. However, repeated measurements made on different days are consistent, so the variation of these measurements over time does not appear to be significant.

Natural gas properties

The natural gas entering the furnace was assumed to have the following properties:

Table 1. Natural gas properties				
Species	Formula	h_f^0(298.15K) [1] J/kg	c_p J/(kg·K)	Mole % [2]
n-Hexane [3]	C_6H_{14}	-1941.78795	1661.890587	0.070083
Propane	C_3H_8	-2357.036398	1670.437963	0.682992
i-Butane	C_4H_{10}	-2316.320403	1667.174312	0.143467
n-Butane	C_4H_{10}	-2172.225821	1677.981406	0.150675
i-Pentane	C_5H_{12}	-2142.852304	1647.767522	0.053833
n-Pentane	C_5H_{12}	-2031.414698	1667.501265	0.035875
Nitrogen	N_2	0.0	1040.57045	0.305775
Methane	CH_4	-4669.832066	2229.198762	95.14509
Carbon dioxide	CO_2	-8949.011836	843.9950557	0.891042
Ethane	C_2H_6	-2818.716666	1746.378804	2.521192

From these properties, this gas mixture has a calculated average molecular weight of 17.09691, a heat of formation of -4578.12 J/kg, and a specific heat of 2150.48 J/(kg·K). The average molecular formula is: $C_{1.051731}H_{4.061704}O_{0.017821}N_{0.006115}$.

Oxygen properties

The oxygen entering the furnace was assumed to have the following properties:

Table 2. Oxygen properties				
Species	Formula	h_f^0(298.15K) [4] J/kg	c_p J/(kg·K)	Mole % [5]
Oxygen	O_2	0.0	918.1668	96.96897
Nitrogen [6]	N_2	0.0	1040.57	3.031034

[1] Enthalpies of formation and specific heats were taken from *Lange's Handbook of Chemistry,* 13th edition and converted from kcal/mole and kcal/(mole·K) into units of J/kg and J/(kg·K), respectively.
[2] Concentrations are the average of analyses of Shelby, NC natural gas on 2 June and 7 July 2003.
[3] Hydrocarbons with 6 or more carbon atoms were taken to be n-hexane.
[4] Enthalpies of formation and specific heats were taken from *Lange's Handbook of Chemistry,* 13th edition and converted from kcal/mole and kcal/(mole·K) into units of J/kg and J/(kg·K), respectively.
[5] Concentrations are the average of oxygen purity measurements on 09 June, 10 June, 16 June, and 17 June 2003.
[6] The plant measures oxygen purity. We assumed that the balance is nitrogen.

From these properties, this gas mixture has a calculated average molecular weight of 31.878, a heat of formation of 0.0 J/kg, and a specific heat of 921.4271 J/(kg·K). The average molecular formula is: $O_{1.939379}N_{0.060621}$.

Air properties

A considerable amount of ambient air infiltrates the furnace and must be included in the mass balance. The ambient air entering the furnace was assumed to have the following properties:

Table 3. Air properties

Species	Formula	h_f^0(298.15K) [7] J/kg	c_p J/(kg·K)	Mole % [8]
Oxygen	O_2	0.0	918.1668	20.25005
Nitrogen	N_2	0.0	1040.57	75.48239
Argon	Ar	0.0	520.7775	0.902881
Carbon dioxide	CO_2	-8949.011836	843.9950557	0.030354
Water vapor	H_2O (g)	-13434.6	1865.399	3.331807

From these properties, this gas mixture has a calculated average molecular weight of 28.59995, a heat of formation of -286.141 J/kg, and a specific heat of 1023.501 J/(kg·K). The average molecular formula is: $C_{0.000304}H_{0.066638}O_{0.438937}N_{1.509686}Ar_{0.009029}$.

Properties of combustion products

The combustion products exiting the furnace via the exhaust port contain many chemical species. Some of these species, such as carbon monoxide (CO), nitric oxide (NO), and sulfur dioxide (SO_2), are present only in very small quantities. Thus, while these species may be important as air pollutants, they may not be present in sufficient amounts to contribute significantly to gross mass and energy balances for the furnace. Accordingly, only the following combustion product species are considered in this calculation: oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), water vapor (H_2O (g)), and argon (Ar).

The gases entering the furnace (natural gas, oxygen, and air) will be roughly at ambient temperature. Hence, their temperatures will be reasonably close to the standard reference state of 298.15 K, and their enthalpies can be calculated by assuming a constant specific heat, i.e.,

[7] Enthalpies of formation and specific heats were taken from *Lange's Handbook of Chemistry,* 13th edition and converted from kcal/mole and kcal/(mole·K) into units of J/kg and J/(kg·K), respectively.
[8] The composition of dry air is from *Mark's Handbook of Mechanical Engineering,* 9th edition, pg. 6-10. Neon, helium, krypton, and methane, which are present in very small concentrations (<0.002%) were omitted. A quantity of water vapor, equivalent to 70% relative humidity at a temperature of 90 F, was added to the dry air to obtain the approximate composition of the infiltration air.

$$h(T) = h_f^0(298.15K) + c_p \cdot (T - 298.15K)$$

The gases exiting the furnace, on the other hand, have a temperature in excess of 1500K, and thus cannot be assumed to have constant specific heats (with the exception of argon). Curvefit formulas were implemented for the variation of enthalpy with temperature.[9]

Mass Balance

The control volume for the furnace mass balance is represented by the solid rectangle in Figure 1:

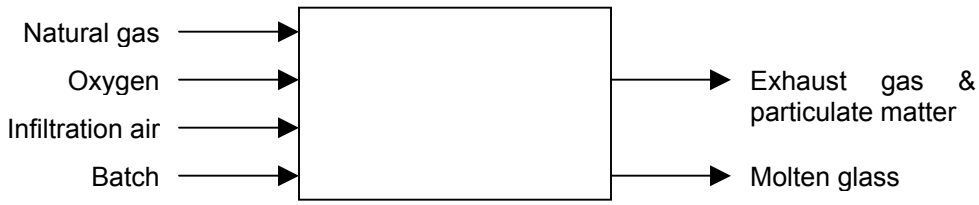


Figure 1. Mass balance control volume.

The volatilization rate for the batch is 20.95%.[10] Hence, a charge of batch weighing 6000 pounds yields 4743 pounds of glass, and 1257 pounds of volatiles. These volatiles comprise 726 pounds of CO_2 and 509 pounds of H_2O,[11] plus small amounts of other species that were considered negligible.

The actual calculation of the mass balance was done using the control volumes illustrated in Figure 2:

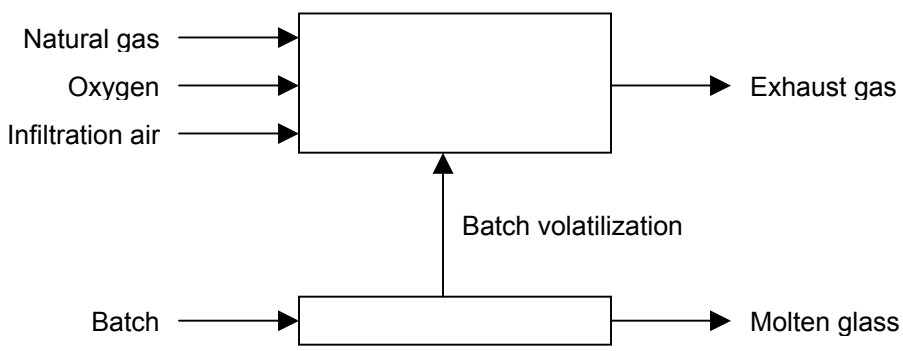


Figure 2. Mass balance control volumes.

[9] Curvefit formula and coefficients for O_2, N_2, CO_2, and H_2O were taken from: Turns, Stephen R., *An Introduction to Combustion; Concepts and Applications,* McGraw-Hill, 1996, Table A.13, pg. 540-541. Separate sixth-order curvefits are used for the 300K-1000K and 1000K-5000K temperature ranges. For argon, a constant specific heat was assumed.
[10] Email from Cheryl Richards, 8 August 2003.
[11] Email from Cheryl Richards, 4 September 2003.

Applying mass conservation to the upper box (combustion space) in Figure 2, there are 4 mass flows into this control volume: natural gas, oxygen, infiltration air, and the gases from the batch volatilization. The natural gas flow and the oxygen flow are measured using installed orifice meters, and the compositions of these gases are given in Tables 1 and 2.

These flow rates are given in standard cubic feet per hour (scfh). One problem encountered was determining the definition of standard. Although atmospheric pressure (101325 Pa) is almost always used as the reference pressure, the definition of standard temperature varies. Discussions with PPG concluded the use of 100 ºF (311 K) as the reference temperature for the flowmeter measurements.

Using 101325 Pa and 311 K as our definition of standard, using the gas composition given in Table 1, and using the ideal gas law, we calculated the density of the natural gas at these standard conditions. Using this density, the gas flow rate in scfh was converted to a mass flow in kg/s. The molar composition in Table 1 was converted to mass fractions, and mass flow rates for each species were computed. These were used to find the number of moles of carbon, oxygen, hydrogen, nitrogen, and argon entering the furnace each second via the natural gas.

A similar calculation, together with the composition data given in Table 2, was used to find the number of moles of carbon, oxygen, hydrogen, nitrogen, and argon entering the furnace each second via the oxygen.

The composition of the infiltration air is given in Table 3, but the amount of infiltration air is not known. Initially, assume a known flow rate for the infiltration air so the mass balance calculation can be explained. The problem of determining the infiltration rate is addressed in the next section.

If an infiltration air flow rate is assumed, then the infiltration air can be treated in the same way as the gas and oxygen, and the number of moles of carbon, oxygen, hydrogen, nitrogen, and argon entering the furnace each second via the infiltration air can be calculated. The air composition data in Table 3 were used for this calculation.

The glass pull rate from the furnace is known. Knowing that, for each pound of glass produced, 726/4743 pound of CO_2 and 509/4743 pound of H_2O are generated, the rates at which these gases are liberated can easily be calculated. These units were also converted into molar flow rates of carbon, oxygen, hydrogen, nitrogen, and argon.

These four flows were then added together to find the total number of moles of carbon, oxygen, hydrogen, nitrogen, and argon entering the furnace each second. It was then assumed that all hydrogen present reacted to form water vapor (H_2O), all carbon present reacted to form carbon dioxide (CO_2), and the remaining oxygen formed diatomic oxygen molecules (O_2). All nitrogen was assumed to form diatomic nitrogen molecules (N_2), and argon was assumed to remain as monatomic argon molecules (Ar).

This calculation gives the composition and flow rate of the combustion product gases. However, since gas analysis measurements are traditionally reported on a dry basis, by

subtracting out the water vapor, the gas composition was also calculated on a dry basis, allowing for direct comparison with the measured values.

Determining the air infiltration rate

It is clear that there was a large amount of infiltration air entering the furnace. On 16 June 2003, the average measured carbon dioxide concentration in the furnace exhaust port was 72.23%, and the average measured oxygen concentration was 4.847%. The water vapor was removed from the gas sample before it entered the analyzers, so there should be no water vapor in the analyzed sample.[12] Other constituents, such as CO, NOx, and SOx, are measured in ppm, and thus are present only in very small quantities. Hence, approximately 23% of the dry combustion product is some other component or components.

Common combustion gas analyzers do not measure nitrogen concentration and, when burning fuel and air, an abundance of nitrogen is present. A common practice is to simply assume that the balance of the dry combustion product is nitrogen. At first glance, it seems unlikely that there should be so much nitrogen in an oxy/fuel furnace. It has been suggested that possibly the analyzers are in error, or that some unknown gas is present. However, a mass spectrometer was used to check the results of the gas analysis instruments. The mass spectrometer results agreed well with DIAL's gas analysis measurements, and showed that the gas, which could not be accounted for, was nitrogen and argon. In addition, mass balance calculations without accounting for infiltration air show that the measured oxygen flow is not sufficient to completely burn the measured natural gas flow; hence, air infiltration is required to supply the additional oxygen needed for complete combustion.

Simply stated, the value for the amount of infiltration air, which was used as an input to the mass balance calculations, was varied. Then, by varying this input, try to make the calculated dry gas composition match the measured dry gas composition (On 16 June 2003: 72.23% CO_2, 4.847% O_2, balance nitrogen and argon) as closely as possible.

This immediately raised an issue: the assumed air infiltration could be varied to make the calculated CO_2 concentration exactly match the measured value, but the oxygen concentration would be slightly off, or the infiltration rate could be set to exactly match the measured oxygen concentration, and let the carbon dioxide concentration be slightly off. In the end, what was done was slightly different: a maximum likelihood technique to find an air infiltration rate that matched both carbon dioxide and oxygen was used. Of course, both cannot be matched exactly, but both can be matched to within the experimental uncertainty of each measurement.

The maximum likelihood method

The maximum likelihood method is an established method, commonly used to fit and analyze experimental data. Descriptions of this method may be found in a number of

[12] The effectiveness of our water removal impingers has been verified experimentally.

places; such as Mathews and Walker[13], Bevington and Robinson[14], Lyons[15], and Press *et al.*[16].

Assume that each measured quantity y_i has a random error associated with it, and that the distribution of the error is described by the normal (Gaussian) distribution with a standard deviation of σ_i. If $\bar{y}$ is the "true" value of the measured quantity, we can compute the probability (or likelihood) P of measuring a particular value y_i from the normal probability distribution function:

$$P \propto \exp\left[-\frac{(y_i - \bar{y})^2}{2\sigma_i^2}\right]$$

Intuitively, this equation says that measurements that are close to the true value are more probable (or likely) than those that are many standard deviations away.

Now suppose that we have taken a series of N measurements, y_i, $i = 1,2,3,\ldots,N$, and that $\bar{y}$ represents a model that we are trying to compare to these measurements. If the measurement errors associated with these measurements are independent, then the probability (or likelihood) associated with the complete set of N measurements is

$$P \propto \exp\left[\frac{-(y_1 - \bar{y})^2}{2\sigma_1^2}\right] \cdot \exp\left[\frac{-(y_2 - \bar{y})^2}{2\sigma_2^2}\right] \cdots \exp\left[\frac{-(y_i - \bar{y})^2}{2\sigma_i^2}\right] \cdots \exp\left[\frac{-(y_N - \bar{y})^2}{2\sigma_N^2}\right]$$

or

$$P \propto \prod_{i=1}^{N} \exp\left[-\frac{(y_i - \bar{y})^2}{2\sigma_i^2}\right]$$

where we have used the rule that the joint probability distribution of two (or more) independent random variables is equal to the product of their individual probability distributions.

By using this equation, we can assess how well the data fit the model -- if the model is true, this formula tells us how likely a given set of measurements actually is. Moreover, if the model contains some unknown parameters (such as the slope and intercept, in the case of fitting a straight line to the data), these parameters can be chosen to maximize the likelihood function; hence the name "maximum likelihood."

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[13] Mathews, Jon and Walker, R. L., *Mathematical Methods of Physics,* 2nd edition, Benjamin/Cummings, 1970, pp. 387-395.
[14] Bevington, Philip R., and Robinson, D. Keith, *Data Reduction and Error Analysis for the Physical Sciences,* 3rd edition, McGraw-Hill, 2003, pp. 180-192.
[15] Lyons, Louis, *Statistics for Nuclear and Particle Physicists,* Cambridge, 1986, pp. 85-102.
[16] Press, William H., Teukolsky, Saul A., Vetterling, William T., and Flannery, Brian P., *Numerical Recipes in FORTRAN, The Art of Scientific Computing,* 2nd edition, Cambridge, 1992, pp. 651-653.

In place of maximizing the likelihood function, in practice the logarithm of the likelihood function, which is equivalent is maximized. The function to be maximized becomes:

$$\ln(P) \propto \ln\left(\prod_{i=1}^{N} \exp\left[-\frac{(y_i - \bar{y})^2}{2\sigma_i^2}\right]\right) = -\sum_{i=1}^{N}\left[\frac{(y_i - \bar{y})^2}{2\sigma_i^2}\right]$$

The maximum likelihood method is thus equivalent to minimizing chi-square. Moreover, in the case where equal uncertainties are attached to each data point, maximum likelihood is equivalent to the standard least-squares method.

Application of Maximum Likelihood to Mass Balance Problem

The maximum likelihood idea is applied to the mass balance problem in the following way: We recognize that the measured O_2 concentration and the measured CO_2 concentration are both subject to measurement uncertainty. Rather than being precise values that our mass balance calculation must match exactly, these measurements and their associated uncertainties instead represent ranges that our calculated values should fall within.

Hence, instead of trying to match one or the other of these measurements exactly, we will try to approximately (but not exactly) match both measurements. We will be happy if our calculated concentrations fall within the error bars around the measured concentrations.

If P_{CO2} represents the CO_2 concentration in the exhaust predicted by the mass balance, M_{CO2} represent the concentration measured in the exhaust, and σ_{CO2} represents the uncertainty in this measurement, then a likelihood:

$$P \propto \exp\left[-\frac{(M_{CO2} - P_{CO2})^2}{2\sigma_{CO2}^2}\right]$$

can be assigned to the CO2 measurement.

Similarly, a likelihood can be assigned to the O_2 concentration measurement:

$$P \propto \exp\left[-\frac{(M_{O2} - P_{O2})^2}{2\sigma_{O2}^2}\right]$$

where P_{O2} is the O_2 concentration in the exhaust predicted by our mass balance, M_{O2} is the measured O_2 concentration, and σ_{O2} is the estimated measurement uncertainty.

The overall likelihood is the product of these two terms, or

$$P \propto \exp\left[-\frac{(M_{O2} - P_{O2})^2}{2\sigma_{O2}^2}\right] \cdot \exp\left[-\frac{(M_{CO2} - P_{CO2})^2}{2\sigma_{CO2}^2}\right]$$

At this point, one could choose the air infiltration rate that maximizes this likelihood function. However, in this case study, some additional factors were included: The gas and oxygen flow rates that are given are themselves measured values, and they also have uncertainties associated with them. Hence, the "true" gas flow rate should be close to, but not exactly equal to, the measured flow rate given, and the same with the oxygen flow rate.

This idea was implemented as follows: In the mass balance calculation, instead of using the measured gas and oxygen flow rates, "tweaked" flow rates were used-- multiplied by numbers that were close to, but not exactly equal to, one. Instead of the measured gas flow rate Q_{GAS}, $F_{GAS} \cdot Q_{GAS}$ was used, and instead of the measured oxygen flow rate Q_{OXY}, I used $F_{OXY} \cdot Q_{OXY}$. The likelihood function was expanded to include the variables F_{OXY} and F_{GAS}:

$$P \propto \exp\left[\frac{-(F_{OXY}-1)^2}{2\sigma_{OXY}^2}\right] \cdot \exp\left[\frac{-(F_{GAS}-1)^2}{2\sigma_{GAS}^2}\right]$$
$$\cdot \exp\left[\frac{-(M_{O2}-P_{O2})^2}{2\sigma_{O2}^2}\right] \cdot \exp\left[\frac{-(M_{CO2}-P_{CO2})^2}{2\sigma_{CO2}^2}\right]$$

Consider, as an example, the mass balance calculation from 16 June 2003. The average measured CO_2 concentration in the exhaust was 72.23%, or a mole fraction of 0.7223. We estimated that the uncertainty in this reading was 0.5%, or a mole fraction of 0.005. Since error bars with 95% coverage encompass approximately 2σ, our estimated σ was thus 0.0025. Similarly, the measured O_2 mole fraction in the exhaust was 0.04847 with a σ of 0.0025.

The uncertainties in the gas and oxygen flow rates were estimated to be 1% of the reading, hence σ for each flow rate was 0.005. The final likelihood function thus became:

$$P \propto \exp\left[\frac{-(F_{OXY}-1)^2}{2(0.005)^2}\right] \cdot \exp\left[\frac{-(F_{GAS}-1)^2}{2(0.005)^2}\right]$$
$$\cdot \exp\left[\frac{-(0.04847-P_{O2})^2}{2(0.0025)^2}\right] \cdot \exp\left[\frac{-(0.7223-P_{CO2})^2}{2(0.0025)^2}\right]$$

F_{OXY}, F_{GAS}, and the air infiltration rate were treated as independent variables. The measured oxygen flow rate was multiplied by F_{OXY} to get the "tweaked" oxygen flow rate. The measured gas flow rate was multiplied by F_{GAS} to get the "tweaked" gas flow rate. Using these "tweaked" oxygen and gas flow rates, and the air infiltration rate, the mass balance calculation was used to calculate the oxygen and carbon dioxide concentrations in the exhaust, P_{O2} and P_{CO2}. From these, the likelihood function (or its

logarithm) could be evaluated. The three independent variables (F_{OXY}, F_{GAS}, and the air infiltration rate) were varied to find the values that produced the largest value likelihood function. The results with the data of 16 June 2003 are as follows:

Table 4. Mass balance results for 16 June 2003		
Oxygen flow factor, F_{OXY}	1.000628	
Gas flow factor, F_{GAS}	0.9993768	
Air infiltration rate	17159.81 scfh[17]	
Predicted exhaust gas composition (molar, wet)		
Species	Predicted mole fraction (wet basis)	
Carbon dioxide	0.3070670	
Oxygen	0.020519344	
Nitrogen	0.096570246	
Water vapor	0.5748489	
Argon	0.00099447882	
Predicted exhaust gas composition (molar, dry)		
Species	Predicted mole fraction (dry basis)	Measured mole fraction (dry basis)
Carbon dioxide	0.7222539	0.7223
Oxygen	0.048263658	0.04847
Nitrogen	0.2271434	Not measured
Argon	0.0023391189	Not measured

The procedure appears to be totally successful. The flow factors, F_{OXY} and F_{GAS}, are very close to one. The gas and oxygen flow rates are "tweaked" by less than a tenth of a per cent, which is well within the 1% uncertainty assigned to these flow rate measurements. The predicted exhaust gas concentrations of carbon dioxide and oxygen (on a dry basis) are within one hundredth of a percent of the measured values.[18] This also is well within the experimental uncertainty for these measurements.

Table 5 shows similar mass balance results for 09 June 2003, and Table 6 for 10 June 2003.

[17] 100 F was used as the reference temperature for defining standard conditions.

[18] Since the gas analysis results are reported in percentages, the possibility of confusion exists. If the measured oxygen concentration were 4% and the predicted value were 5%, this is a difference of 1% in absolute percentages, but a 25% relative difference. In the comparison above, we are comparing absolute percentages.

Table 5. Mass balance results for 09 June 2003		
Oxygen flow fudge factor, F_{OXY}	1.001674	
Gas flow fudge factor, F_{GAS}	0.9983152	
Air infiltration rate	12545.57 scfh[19]	
Predicted exhaust gas composition (molar, wet)		
Species	Predicted mole fraction (wet basis)	
Carbon dioxide	0.3159310	
Oxygen	0.016672641	
Nitrogen	0.076052405	
Water vapor	0.5905955	
Argon	0.00074844307	
Predicted exhaust gas composition (molar, dry)		
Species	Predicted mole fraction (dry basis)	Measured mole fraction (dry basis)
Carbon dioxide	0.7716842	0.7718
Oxygen	0.040724128	0.04125
Nitrogen	0.1857635	Not measured
Argon	0.0018281261	Not measured

Uncertainty of infiltration estimate

The best estimate of the air infiltration rate was determined by the maximum likelihood procedure. One might well question how robust this estimate is -- how sensitive it is to small errors in measuring the exhaust gas composition or errors in metering the inputs to the furnace?

A Monte-Carlo procedure was used to answer this question. Starting with the data from 16 June 2003, a pseudorandom number generator was used to add error to the data. (More precisely, an additional known error was added to the measured values, which already contain some error.) The random error added was Gaussian (normal) and had a zero mean. The standard deviation was chosen based on the uncertainty in each measurement. The errors added to the oxygen and gas flow rates had standard deviations equal to 1% of the reading. The errors added to the measured CO_2 and O_2 concentrations had standard

[19] 100 F was used as the reference temperature for defining standard conditions.

deviations of 0.005 (corresponding to an uncertainty of 1% in absolute concentration units).[20]

Table 6. Mass balance results for 10 June 2003		
Oxygen flow fudge factor, F_{OXY}	0.9911399	
Gas flow fudge factor, F_{GAS}	1.008797	
Air infiltration rate	22229.08 scfh[21]	
Predicted exhaust gas composition (molar, wet)		
Species	Predicted mole fraction (wet basis)	
Carbon dioxide	0.2994877	
Oxygen	0.020157171	
Nitrogen	0.1171734	
Water vapor	0.5619242	
Argon	0.0012576368	
Predicted exhaust gas composition (molar, dry)		
Species	Predicted mole fraction (dry basis)	Measured mole fraction (dry basis)
Carbon dioxide	0.6836434	0.6829
Oxygen	0.046012968	0.04286
Nitrogen	0.2674728	Not measured
Argon	0.0028708198	Not measured

For each set of data generated in this manner, the maximum likelihood method was used to estimate the mass balance. This procedure was repeated 10,000 times, generating 10,000 estimates of the air infiltration rate, etc. Statistics calculated from these estimates provide a means of determining the uncertainty in the output of the maximum likelihood calculation.

The standard deviation of these 10,000 estimates was 715 scfm. The 95% uncertainty interval is $\pm 2\sigma$, hence the uncertainty in the air infiltration estimate is 17160±1530 scfm for 16 June 2003.

[20] Note that the random error added during the Mont Carlo procedure was twice as large as the uncertainty assumed when constructing the likelihood function. This was done intentionally, to see what the effect would be if the errors were larger than one thought.
[21] 100 F was used as the reference temperature for defining standard conditions.

Mass balance closure

An independent check of the mass balance accuracy may be obtained from the pitot velocity measurements in the exhaust port. On 17 June 2003, the exhaust port was traversed with a unique water-cooled pitot probe of our own design.

The cross-section of the exhaust port is a narrow, vertical rectangle. The pitot tube was inserted vertically from the top of this duct. Velocity measurements were made at distances of 1 foot, 2 feet, 3 feet, 4 feet, and 5 feet from the inside surface of the top of the duct. Although the duct was traversed vertically, all measurements were made on the horizontal centerline of the duct.

Given the mass flow rate and composition of the exhaust gases from the mass balance, the measured temperature of the gas in the exhaust port, and assuming the gas is roughly at atmospheric pressure (for purposes of determining the gas density), we calculate that the average exhaust gas velocity should be 8.730 m/s on 16 June 2003.

The average of the pitot velocity measurements on 17 June 2003 was 9.970 m/s. The calculation is about 12% lower than the measurement. This level of agreement is not too bad, because:

1. The pitot measurements and the gas analysis measurements used for the mass balance were not made on the same day.

2. . The pitot measurements were all made along the center of the port. Velocity profile effects should cause the centerline velocity to exceed the average velocity.

Energy balance

The energy balance was performed in basically the same manner as the mass balance. Entering the furnace are the following flows:

1. Oxygen,

2. Natural gas,

3. Batch, and

4. Infiltration air,

And the following energy flows leave the furnace

1. Combustion gases from oxygen / natural gas combustion, via the exhaust port,

2. Gases produced by batch volatilization, via the exhaust port,

3. Molten glass,

4. Thermal (blackbody) radiation through the exhaust port, peepholes, and other openings, and

5. Conduction heat losses through the refractory.

Kinetic and gravitational potential energy are negligible in this situation.

Combustion energy

The combustion reaction has, as inputs, the oxygen, natural gas, and air entering the furnace. The combustion products leaving the furnace are the output of the combustion reaction. The energy released in the furnace by these reactions is:

$$q_{furnace} = \dot{m}_{oxy} h_{oxy}(T_{inlet}) + \dot{m}_{gas} h_{gas}(T_{inlet}) + \dot{m}_{air} h_{air}(T_{inlet}) - \dot{m}_{prod} h_{prod}(T_{exhaust})$$

where the mass flow rate, $\dot{m}$, of each gas is multiplied by the specific enthalpy, h, of that gas. It is assumed that the specific enthalpy is a function of temperature only, and that the oxygen, natural gas, and air enter at the temperature T_{inlet}, and that the combustion products leave the furnace at a temperature $T_{exhaust}$.

The standard enthalpy (or heat) of combustion of a fuel is defined as the heat released if the reactants are initially at some reference temperature (usually 298 K), and the reaction products are cooled to this reference temperature before being released. The higher heat of combustion assumes that the water produced by hydrocarbon combustion is released as liquid, while the lower heat of combustion assumes that water vapor is released. The lower heat will be used exclusively in this calculation.

The energy released in the furnace can be written as

$$\begin{aligned} q_{furnace} &= \dot{m}_{gas} \Delta h_{combustion} \\ &+ \dot{m}_{oxy}(h_{oxy}(T_{inlet}) - h_{oxy}(298K)) + \dot{m}_{gas}(h_{gas}(T_{inlet}) - h_{gas}(298K)) \\ &+ \dot{m}_{air}(h_{air}(T_{inlet}) - h_{air}(298K)) - \dot{m}_{prod}(h_{prod}(T_{exhaust}) - h_{prod}(298K)) \end{aligned}$$

where the standard enthalpy of combustion is customarily given per unit mass of fuel.

Temperature data for the oxygen, natural gas, and especially infiltration air entering the furnace were not available. Therefore, T_{inlet} was assumed to be 298 K, and the equation for energy release becomes:

$$q_{furnace} = \dot{m}_{gas} \Delta h_{combustion} - \dot{m}_{prod}(h_{prod}(T_{exhaust}) - h_{prod}(298K))$$

Therefore, the energy deposited in the furnace by the combustion reactions is simply the enthalpy of combustion of the fuel, minus the energy lost when the combustion product gases leave the furnace at a temperature of $T_{exhaust}$ rather than 298 K.

The mass flow rate of each stream (including the infiltration air) is available from the mass balance results. The exhaust gas temperature is available from the thermocouple measurements -- on 16 June 2003, the average of our exhaust gas temperature measurements was 1267.4ºC.

Evaluation of the energy release, using the data of 16 June 2003, gives 8.625 MW as the enthalpy of combustion of the fuel, 1.840 MW as the thermal energy lost due to the elevated temperature of the exhaust gases, for a net energy release inside the furnace of 6.785 MW.

<u>Energy required to make glass</u>

Consider the reaction: $Batch + Heat \Rightarrow Glass + Gases$

According to PPG, 6000 pounds of batch produces 4743 pounds of glass, 726 pounds of CO_2 and 509 pounds of H_2O. The process requires 2.5×10^6 Btu per ton of glass produced (at 2600ºF).

The glass pull rate was used to find the batch feed rate, and also the rate of liberation of carbon dioxide and water vapor from batch fusion losses. These calculations were done as part of the mass balance.

The temperature of the molten glass leaving the control volume was not measured by the assessment team. So, it is assumed that the molten glass temperature is equal to the 2600 ºF value that was used when determining the energy requirement. The energy required to make the glass was thus found from:

$$q_{glass} = (1250\ Btu/lbm) \cdot \dot{m}_{glass}$$

It was initially assumed that the 2.5×10^6 Btu per ton figure provided for this calculation included the energy required to heat the released carbon dioxide and water vapor to the exhaust gas temperature. However, this assumption is not correct. Therefore, an additional enthalpy sink was added to the energy balance, to account for the energy required to heat these gases to the exhaust gas temperature.

The flow rates of these gases are known from the mass balance. The enthalpies of CO_2 and H_2O at the exhaust gas temperature can be found from the curve fit formulae discussed earlier. However, a question remains regarding the value that should be used for the starting temperature. For these calculations, 298 K was used as the initial temperature of these gases, and the energy requirement was then,

$$\begin{aligned} q_{volatiles} &= (726/4743) \cdot \dot{m}_{glass} \cdot (h_{CO2}(T_{exhaust}) - h_{CO2}(298K)) \\ &\quad + (509/4743) \cdot \dot{m}_{glass} \cdot (h_{H2O}(T_{exhaust}) - h_{H2O}(298K)) \end{aligned}$$

This was an arbitrary assumption, and is probably wrong. The batch volatiles are given off as the batch is heated, so the figure of 2.5×10^6 Btu per ton of glass should include the energy required to heat the batch devolatilization gases to some elevated temperature.

However, this temperature is unknown. So, the energy required to heat the batch fusion loss gases from 298 K to the furnace exhaust temperature has been included.

Using 16 June 2003 as an example, 3.992 MW are required to produce the glass, plus an additional 0.716 MW required to heat the gases from the batch from 298 K to an exit temperature of 1267.4ºC.

Conduction heat loss through refractory

A significant amount of energy is lost through the refractory that encloses the furnace. The inner surface of this refractory is at a much higher temperature than the outer surface, so heat conduction through the thickness of the refractory removes heat energy from the furnace.

During the field campaign, the refractory surface temperatures were measured inside and outside of the furnace. A surface contact thermocouple was used to make a temperature survey of the outside of the furnace, and pyrometers were used to measure surface temperatures inside the furnace.

Not all surfaces inside the furnace could be measured by the pyrometer. In these cases, the inner refractory surface temperature was estimated from available data. The inner surface temperatures of the end walls were estimated from the pryometer measurements of the adjacent side (breast) walls. The inner surface temperatures of the crown were estimated from thermocouples installed in the crown. The inner surface temperatures of the refractory below the glass line were estimated from thermocouples installed in the bottom of the glass pool.

Knowing the inner and outer surface temperatures, the heat fluxes through the refractory could be computed from Fourier's Law of steady-state heat conduction. The calculation was complicated by the fact that the refractory was comprised of two of more layers of different types of refractory, and the fact that the thermal conductivity of each type of refractory varies as a function of temperature.

A computer program was written to solve this problem. Given the inner and outer surface temperatures, the composition of the refractory (number of layers, thickness of each layer, type of refractory comprising each layer), and the refractory properties (a table of thermal conductivity versus temperature for each type of refractory), this program solves the steady-state one-dimension heat conduction problem, and outputs the conduction heat flux through the refractory.

Table 7. Refractory conduction heat loss						
Location	Area (m^2)	Construction	Temperatures[22] (°C)		Heat flux (W/m^2)	Heat loss (W)
			Inner	Outer		
Crown (back 1/3)	*p*	*p*	1487	481	X.xx	5.93e4
Crown (front 2/3)	*p*	*p*	1430	352	X.xx	9.89e4
Back wall	*p*	*p*	1536	202	X.xx	3.41e4
Front Wall	*p*	*p*	1515	205	X.xx	3.33e4
Breastwall	*p*	*p*	1580	211	X.xx	4.36e4
Breastwall	*p*	*p*	1566	189	X.xx	4.34e4
Basin sidewall	*p*	*p*	1358	308	X.xx	1.67e5
Basin sidewall	*p*	*p*	1358	321	X.xx	1.66e5
Basin endwall	*p*	*p*	1314	320	X.xx	5.28e4
Basin endwall	*p*	*p*	1366	320	X.xx	5.58e4
Basin bottom (back)	*p*	*p*	1322	343	X.xx	1.14e5
Basin bottom (front)	*p*	*p*	1373	316	X.xx	4.16e5
TOTAL						1.2846e6

p = Proprietary

[22] Measured on 16 June 2003.

A similar calculation, using the 10 June 2003 surface temperature data, gives the total heat loss through the refractory as 1.2823×10^6 Watts, which is very close to the value given in Table 7 for 16 June 2003.

Some caveats apply to this calculation:

1. Heat transfer calculation was one-dimensional. Surface areas used were those of the inside (hot side) surface. Effects of corners will increase heat loss.

2. The calculation was performed using the geometry and thermal properties of new refractory. Erosion and wear will reduce the refractory thickness. Chemical changes due to glass attack will change thermal conductivity of the refractory.

3. The thermal properties available for the refractory sometimes did not span the entire temperature range of interest, so extrapolation of the thermal conductivity versus temperature data for some of the types of refractory in use was performed.

4. The thermal properties of the refractory are representative of the unused state and may not be accurate when referring to refractory that has seen high temperature and corrosive environments for long periods of time.

<u>Radiation energy loss (exhaust port)</u>

The inside of the furnace, an enclosed volume, is nearly a blackbody. (It would be a blackbody if it were isothermal.) If the temperature of this blackbody is estimated to be 1800 K, then the corresponding blackbody radiation energy flux is 5.95×10^5 Watts per square meter.

This energy will be lost through every peephole or opening in the furnace. Unfortunately, we do not know the areas of the furnace openings, and so this loss mechanism cannot be included in the energy balance.

One opening that is known is the exhaust port. The control volume for this energy balance has a boundary that slices across the exhaust port right at the point where it exits the furnace. Hence, the net radiation flux across this surface should be included in the balance, along with convective energy fluxes.

The refractory inside the exhaust port is hot, so some energy will radiate back into the furnace. Unfortunately, these radiation fluxes during were not measured during the field campaign. At the suggestion of John Connors, we assumed that the inside surface of the refractory inside the exhaust port has a temperature 200°F (111°C) less than the exhaust gas temperature (~1250°C). This assumption results in a blackbody temperature of 1412 K in the exhaust port, and a corresponding energy flux of 2.25×10^5 W/m^2 from the inside of the exhaust port back into the furnace.

The net energy flux is then 3.70×10^5 W/m^2. The net energy lost through this the port by thermal radiation is thus 0.257 MW.

Energy balance results

Table 8 summarizes the energy balance results for 16 June 2003. Tables 9 and 10 show similar results for 09 and 10 June 2003, respectively. As referenced in Section 2.4.2, temperatures and energy usage was reviewed a few months following these measurements to verify energy savings as a result of the changes implemented.

Table 8. Energy balance for 16 June 2003		
Energy in		
Heat of combustion of natural gas	8.625 MW	100%
Energy out		
Combustion gases leaving furnace	1.840 MW	21.3%
Batch volatiles leaving furnace	0.716 MW	8.3%
Energy used to make glass	3.992 MW	46.3%
Energy loss through refractory	1.285 MW	14.9%
Radiation loss through exhaust port	0.357 MW	4.1%
TOTAL	8.190 MW	95.0%
Energy unaccounted for	0.435 MW	5.0%

Table 9. Energy balance for 09 June 2003		
Energy in		
Heat of combustion of natural gas	8.636 MW	100%
Energy out		
Combustion gases leaving furnace	1.819 MW	21.1%
Batch volatiles leaving furnace	0.722 MW	8.4%
Energy used to make glass	3.963 MW	45.9%
Energy loss through refractory	1.282 MW[23]	14.8%
Radiation loss through exhaust port	0.357 MW	4.1%
TOTAL	8.143 MW	94.3%
Energy unaccounted for	0.493 MW	5.7%

[23] Refractory temperature measurements were not made on 09 June 2003. Therefore, the value for 10 June was used instead.

Table 10. Energy balance for 10 June 2003		
Energy in		
Heat of combustion of natural gas	8.672 MW	100%
Energy out		
Combustion gases leaving furnace	1.876 MW	21.6%
Batch volatiles leaving furnace	0.700 MW	8.1%
Energy used to make glass	3.946 MW	45.5%
Energy loss through refractory	1.282 MW	14.8%
Radiation loss through exhaust port	0.357 MW	4.1%
TOTAL	8.161 MW	94.1%
Energy unaccounted for	0.511 MW	5.9%

All energy balances fail to close by approximately 5%. This means that we have not accounted for all losses, or else we are underestimating at least one loss mechanism.