

## **Final Technical Report**

### **Development/Demonstration of an Advanced Oxy-Fuel Front-End System**

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## **Executive Summary**

Owens Corning and other glass manufacturers have used oxy-fuel combustion technology successfully in furnaces to reduce emissions, increase throughput, reduce fuel consumption and, depending on the costs of oxygen and fuel, reduce energy costs.

The front end of a fiberglass furnace is the refractory channel system that delivers glass from the melter to the forming process. After the melter, it is the second largest user of energy in a fiberglass plant. A consortium of glass companies and suppliers, led by Owens Corning, was formed to develop and demonstrate oxy/fuel combustion technology for the front end of a fiberglass melter, to demonstrate the viability of this energy saving technology to the U.S. glass industry, as a D.O.E. sponsored project.

The project goals were to reduce natural gas consumption and CO<sub>2</sub> green house gas emissions by 65 to 70% and create net cost savings after the purchase of oxygen to achieve a project payback of less than 2 years.

Project results in Jackson, TN included achieving a 56% reduction in gas consumption and CO<sub>2</sub> emissions. A subsequent installation in Guelph ON, not impacted by unrelated operational changes in Jackson, achieved a 64% reduction. Using the more accurate 64% reduction in the payback calculation yielded a 2.2 year payback in Jackson.

The installation of the demonstration combustion system saves 77,000 DT/yr of natural gas or 77 trillion Btu/yr and eliminates 4500 tons/yr of CO<sub>2</sub> emissions. This combustion system is one of several energy and green house gas reduction technologies being adopted by Owens Corning to achieve aggressive goals relating to the company's global facility environmental footprint.

## **Introduction**

Oxy-fuel combustion technology has successfully been used by Owens Corning and others in glass furnaces to reduce emissions, increase throughput, reduce fuel consumption and, depending on the costs of oxygen and fuel, reduce energy costs. Conversion of glass melter combustion systems from air/fuel to oxy-fuel have occurred for over 15 years so the technology is now widely recognized as a low risk, proven way to improve the furnace combustion process. It is estimated that one quarter of U.S. glass manufacturers have converted melters to oxy firing<sup>1</sup>

After the furnace, the next largest energy consuming process in a reinforcement fiberglass plant is the front end. Based on the successful conversion of several melters to oxy-fuel firing, Owens Corning initiated a project to develop and demonstrate that oxy/gas combustion could be applied to a front end achieving energy reduction and related benefits.

A consortium of glass manufacturers and glass industry suppliers including Osram Sylvania, BOC and Eclipse was formed to support and steer this project which was accepted for Department of Energy cost sharing sponsorship based on the technology's potential to reduce energy consumption in one and possibly more sectors of the U.S. glass industry. While the primary focus was fiberglass, other glass sectors originally identified for potential use included TV and lighting.

## **Author's acknowledgments**

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OWENS CORNING Granville team:

Harry Adams, Dave Baker, Chris Jian, Peggy Milliken, Bruno Purnode, Chris Spegele & Bill Toth

Consortium members

Neil Simpson – (formerly) BOC, Kevin Cook – Eclipse, Tim Jenkins – Osram Sylvania

Plant Furnace Teams

Owens Corning's Guelph and Jackson furnace department teams

D.O.E. partners

Elliot Levine & Brad Ring

.

## Background

### Why oxy/gas combustion is more efficient than air/gas combustion

#### A) Eliminating the nitrogen

A reinforcement fiberglass melter front end consists of long, narrow, covered refractory channels that deliver glass to the fiber forming process. These front ends have traditionally used air/gas burners located in the sidewall of the refractory superstructure, firing into the combustion. Conventional front end air/gas combustion systems supply an air/gas mixture to the burner as opposed to separate air and gas streams being combined at the burners. This is done as the long lengths of combustion piping required for a front end make preheating the air supply impractical. Given the impracticality of maintaining preheated air temperatures, a mixture of air and gas is delivered in one common line to reduce the amount of piping involved.

Air is comprised of approximately 1 part oxygen and 4 parts nitrogen with other minor constituent inert gases. The 79% nitrogen component is inert and does not contribute to the combustion reaction. Stoichiometric combustion occurs when the optimal mixture of reactants is used and complete combustion is achieved (i.e. there is no unreacted oxygen or fuel left over). The stoichiometric reaction equation for air/fuel combustion is shown in Fig 1.

Lack of preheating air in an air/gas front end combustion system results in a significant portion of energy being consumed to heat the nitrogen in air from an ambient temperature to the temperature of the combustion space.

Fig. 1 Air / Gas Stoichiometric Combustion:



Use of oxy/fuel burners in a front end eliminates the inert nitrogen and the wasted heat load it represents. See Fig. 2

Fig. 2 Oxy / Gas Stoichiometric Combustion:





## Background

### Why oxy/gas combustion is more efficient than air/gas combustion - cont'd

#### B) Hotter oxy flame

The temperature of an air/gas flame is ~3600 F. The temperature of an oxy-gas flame is ~4900 F. A hotter oxy/gas flame positively impacts the radiant heat transfer in two ways.

- i) Higher heat flux from the flame

Fig 3 is the Stephan Boltzman Law expressed with temperatures for the flame to glass radiant heat transfer process in a glass melting situation.

Fig. 3 - Stephan Boltzman Law

$$\dot{Q} = \varepsilon \cdot \sigma \cdot A \left( T_{\text{flame}}^4 - T_{\text{glass}}^4 \right)$$

$\sigma$  = *constant*

$A$  = *surface area*

$\varepsilon$  = *thermal emissivity, fraction of energy emitted by flame*

$T$  = *absolute temperature of emitting and receiving surfaces*

Radiant energy emitted is proportional to the fourth power of the absolute temperature differential between the flame and the glass. Thus, a higher flame temperature dramatically increases the radiant energy heat flux from the flame.

It must be noted that the flame is not the only source of radiant energy. The glass also receives radiant energy re-emitted from the refractory superstructure. Convective heating through the movement of hot combustion gases over the surface of the glass also contributes to the total heat transfer.

## Background

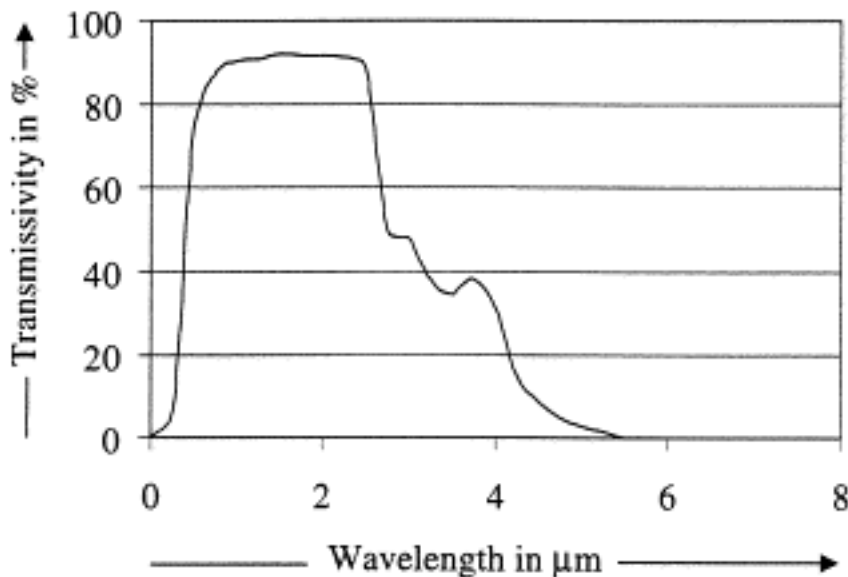
### Why oxy/gas combustion is more efficient than air/gas combustion - cont'd

#### B) Hotter oxy flame

##### ii) Glass Transmissivity

Transmissivity is a physical characteristic of glass describing the ability of radiant energy to penetrate below the surface into the glass. If the radiant energy has a shorter wavelength, glass transmissivity is better. Radiant energy in the 1 to 2.5 micron range is optimal. Above 4 microns glass becomes significantly more “opaque” to radiant energy<sup>2</sup>.

Fig. 4 Glass Transmissivity vs. Wavelength<sup>3</sup>



The spectral distribution of radiant energy from the hotter oxy/gas flame is biased to the shorter wavelength range and thus a greater portion of the radiated energy is accepted by the glass. This should also have a positive impact on reducing the vertical thermal gradient in the glass and improving thermal homogeneity.

Thus, the hotter flame's greater heat flux coupled with better glass transmissivity characteristics associated with shorter wavelength oxy/gas flame radiation both contribute to better heat transfer to the glass.

## **Background**

### **Barriers to implementing oxy/gas combustion on a front end**

The hurdles to implementation of oxy/fuel burners in a front end relate to the fact that front ends are relatively long, narrow troughs of glass that require a large quantity of closely spaced burners (< 1' apart, both sides for an air/gas system) to distribute the energy evenly. The hurdles consisted of:

#### **a) Overheating**

Front end burners with outputs of 0.04 - 0.1 MM Btu/hr do not have the large flows of oxygen and gas (compared to melter oxy burners with outputs of 2-5 MM Btu/hr) for cooling of the burner. As an oxy/fuel burner has a flame temperature of ~5000 F, vs. ~3500 F for an air gas burner, overheating, soot formation and degradation of the burner or the burner block material can result.

#### **b) Capital Cost**

The close spacing of side fire burners in a front end system results in a large capital cost for upgrading to oxy/fuel burners if existing burners and blocks are substituted on a one-for-one basis. Side fire oxy/fuel burner systems are commercially available and have been successfully supplied for trial purposes by others (Eclipse & BOC/BH-F). This project involved the installation of burners in a top fire configuration, parallel to centerline of the channel, as opposed to the traditional side fire configuration in which burner alignment is perpendicular to the centerline of the channel. This allowed one top fire burner, with higher flow, to replace 10 to 20 air/gas burners.

## Objectives

### Project Objectives

The objectives of the project were:

- a) develop an oxy-fuel burner that would be suitable for use in a front end
- b) lab test the burner and integrate supporting combustion control hardware
- c) conduct extended pilot scale tests in a production environment to assess impact on the process and ensure there were no unforeseen issues that would hinder burner use in a full scale installation
- d) demonstrate front end oxy firing on a full scale permanent installation, verify energy savings and assess burner life

The project was structured in three phases

- I) development: modeling & equipment design
- II) pilot/field trials
- III) full scale installation to demonstrate the technology

## Performance Targets

### Technical

The new combustion system should not have any negative impact on the process. This translated into the metric of having a **heat distribution that was as uniform as or more uniform than the existing system for a forehearth.**

In terms of gas consumption, the **front end oxy/gas burner system was projected to use 65% to 70% less gas** than an air/gas burner for the heating requirement of the glass due to elimination of the heating of nitrogen and the improved high temperature radiant heat transfer to the glass.

As CO<sub>2</sub> emissions are directly proportional to the amount of gas combusted, the **reduction in CO<sub>2</sub> emissions was projected to be 65 to 70%.** Based on the assumption that nitrogen could be kept out of the combustion space (no air leakage) **lower NO<sub>x</sub> levels were also anticipated.** In melters, reductions in NO<sub>x</sub> of greater than 70% have been achieved.

### Economic

For the Jackson installation, the **payback target was 1.8 years** with an **annual operating savings of \$464,000 based on \$6/DT gas costs.**

## Results

### Consortium evolution

The original consortium for the project consisted of the following companies:

<u>Company</u>	<u>Glass Industry Sector or Supplier</u>
Owens Corning (award recipient)	fiberglass
Osram Sylvania	lighting
Thomson	TV
BOC	Oxygen supplier
Eclipse	Combustion equipment supplier

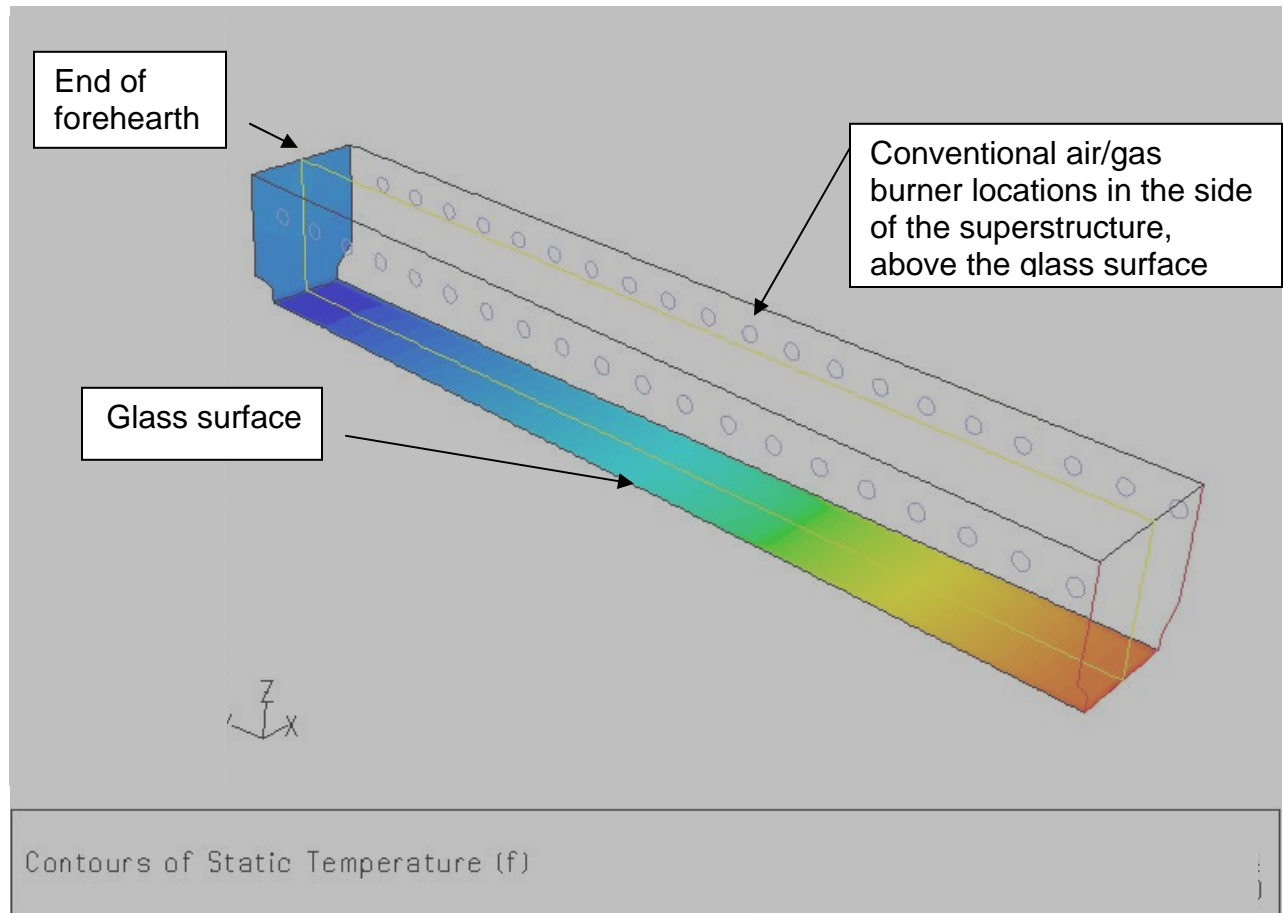
In June 2004, Thomson Electronics withdrew from this D.O.E. sponsored project.

## Results

### Phase I - Development: modeling & equipment design

An early goal of the modeling done for the project was to determine whether a top fired configuration – chosen to reduce the burner quantities and capital cost – could distribute the heat in the forehearth as evenly as the existing air gas system.

Fig. 5 Temperature distribution, forehearth glass surface – conventional air/gas firing



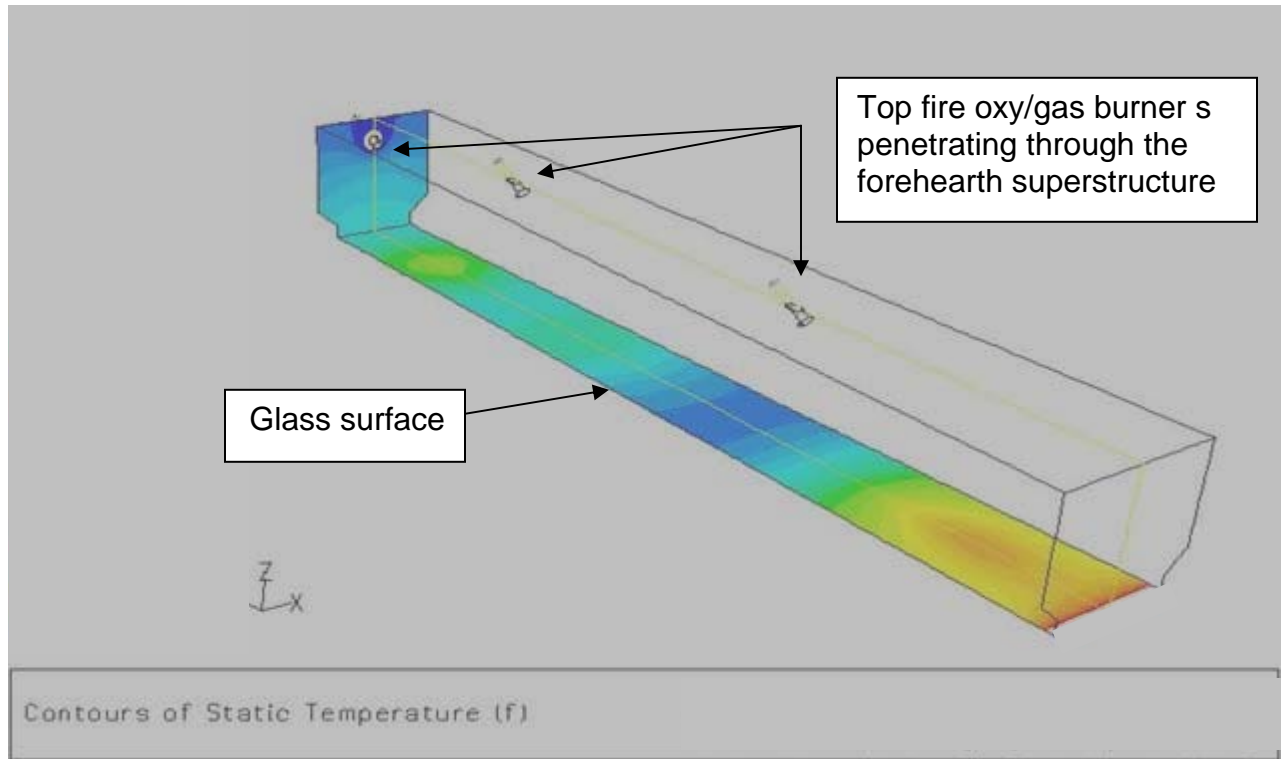
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The modeling indicated a temperature gradient over the surface of a forehearth with the existing air/gas firing system would be 50 F with the coldest surface temperature at the end of the forehearth.

## Results

### Phase I - Development: modeling & equipment design - cont'd

Fig. 6 – Temperature distribution, forehearth glass surface – top fired, oxy/gas firing



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The modeling of the top fired oxy burner system indicated the temperature gradient over the glass surface of a forehearth would be 35 F, a 15 degree improvement in thermal homogeneity. As the goal for the top fired oxy burner program was to ensure the heat distribution was as good as or better than the conventional side fired design, the concept was deemed acceptable for continued development.

While this model was of the combustion space and did not include the glass bath, it could be extrapolated that the vertical gradient from the hot glass surface to the bottom of the glass would likely be improved as well, given the transmissivity characteristics of glass with the shorter wavelength, hotter oxy/gas flame. See Fig. 4 Glass transmissivity vs. wavelength.

For the burner, a tube in tube design was developed in research conducted prior to starting the consortium based demonstration project. Burner block geometry was modeled in conjunction with the burner to achieve acceptable block temperatures. For the early trials, burner blocks were cast in an air set castable refractory. This was later upgraded to a fired refractory for better thermal shock properties and melting temperature resistance.

## Results

### Phase I - Development: modeling & equipment design - cont'd

Efforts to enhance burner performance through alternative burner designs continued on after the pilot installations were in operation. In conjunction with Dr. Peter M. Walsh – Sandia National Laboratories / University of Alabama, through the D.O.E. GPLUS+ program, further trials were conducted to evaluate alternative burner designs for use with existing air/gas burner blocks as well as the top fired burner block. Cross sectional areas of the gas tube bore and oxygen nozzle annular space were varied to evaluate flame shape and combustion density with a variety of velocity ratios. A venturi concept to increase oxygen velocity at the burner exit was also tested. Burners and blocks were equipped with thermocouples to allow for quantitative evaluation based on gas tube temperature as high burner temperatures were known to cause material degradation and/or carbon formation issues. Some of the burners experienced rapid melting failure during testing. No changes to the basic design were adopted based on these trials. The final report by Dr. Walsh, “Improvement of Oxyfuel Burner Design and Operations”, dated Feb 23, 2006, provides a thorough overview of previous work by others on oxygen/natural gas fired forehearths.

Fig. 7 Flame of Venturi style burner



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## Results

### Phase I - Development: modeling & equipment design - cont'd

Fig. 8 Flame of Basic OC design burner



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The standard OC burner creates a flame with high luminosity and a narrow initial cone.

## Results

### Phase II – Pilot/Field Trials

Promising modeling results led to single burner, and multiple burner, short duration lab trials at the OC Granville Technical Center. A shortened forehearth superstructure was constructed to allow burners to be tested at normal operating temperatures. A zone skid for controlling and metering flow was jointly developed with Eclipse.

Single burner trials of 8 hours duration were conducted to assess the burner flame for impingement on the burner block. Minor design improvements to address gas tube to oxygen nozzle concentricity resulted.

Production trials for the top fired design were initiated in Owens Corning's Guelph, ON plant in 2003 as an earlier production curtailment had created an opportunity to drill holes in cover tiles on three forehearth. These longer term trials provided several months of run time to test burner, block and zone skid for reliability.

Fig. 9 Installing burners for the pilot installation in Guelph, ON



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## Results

### Phase II – Pilot/Field Trials – cont'd

During these trials the first melt down failure occurred on a conventional forehearth. While the damage to the cover tile did not allow replacement of the burner block as it was fused to the cover tile, the remaining burners were re-profiled and production was able to continue without a conversion efficiency penalty. This was a significant finding with respect to how robust the system was.

Inspection of the burners after several months service indicated that high temperature oxidation of the tip of the gas tube was a nearly universal issue. This resulted in a material upgrade for the gas tube from stainless steel to a high temperature alloy.

Other issues included turbulence causing flame deflection and refractory overheating. This led to elimination of a few burners in locations of the combustion space where exhaust gases had large changes in direction.

## Results

### Phase III - Full scale installation to demonstrate the technology

The Phase III full scale permanent installation of front end oxy firing equipment was constructed in June & July 2004. The construction work was done in conjunction with the rebuild of an Owens Corning melter in Jackson TN that was being converted to oxy firing and to a new glass formulation. Thus, a supply of on-site generated oxygen was available. An on-site oxygen supply (vs. a liquid oxygen supply) is critical to having favorable economics for the conversion to front end oxy-fuel firing.

Fig. 10 Front End Oxy-Fuel burner in operation in Owens Corning's Jackson TN plant



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## Results

### Energy & Operating Cost Reduction

Energy savings data for the D.O.E. project sponsored installation in Owens Corning's Jackson plant is summarized below. Data for a subsequent full scale installation at Owens Corning's Guelph ON plant is also shown.

Table 1 – Energy & Operating Cost Reductions for Jackson & Guelph

Plant	Front End Nat. Gas Used	Reduction in Nat. Gas Used	Front End Total Energy Used *	Reduction in Total Energy Used	Energy Saved	Operating Cost Redcution**
	[DT/hr]	[%]	[DT/hr]	[%]	[DT/yr]	[\$/yr]
<b>Target Natural Gas Energy Reduction</b>		<b>65-70</b>				
Jackson TN						
Air/gas (Mar 04)	16.5		16.6			
Oxy/gas (Dec04)	7.3	<b>56</b>	7.9	<b>53</b>	<b>77,000</b>	<b>\$333,000</b>
Guelph ON						
Air/gas (Mar 05)	24.9		25.1			
Oxy/gas ( Apr 05 )	9.0	<b>64</b>	9.8	<b>61</b>	<b>135,000</b>	<b>\$513,000</b>

\* including estimated electricity for combustion air blower or O2 plant operation

\*\* assuming an average cost for natural gas of \$ 7.40 US / DT, oxygen cost included

DT = decatherm = 1,000,000 Btu

The “raw data” of before and after conversion natural gas consumption is shown in the “Front End Nat. Gas Used column.

The second column, “Reduction in Nat. Gas Used” compares the targeted energy savings to the actual results achieved. While Jackson's gas consumption reduction of 56% was less than the goal of a 65 – 70% reduction, there were other operational changes that affected the gas consumption reduction result. **A 64% reduction in gas consumption was the measured result for a conversion in Guelph, ON** that was not impacted by other operational changes.

## Results

### Capital cost and payback

Table 2 summarizes the financial results for the conversion of the front end combustion systems on 2 furnaces from air/gas to oxy/gas firing

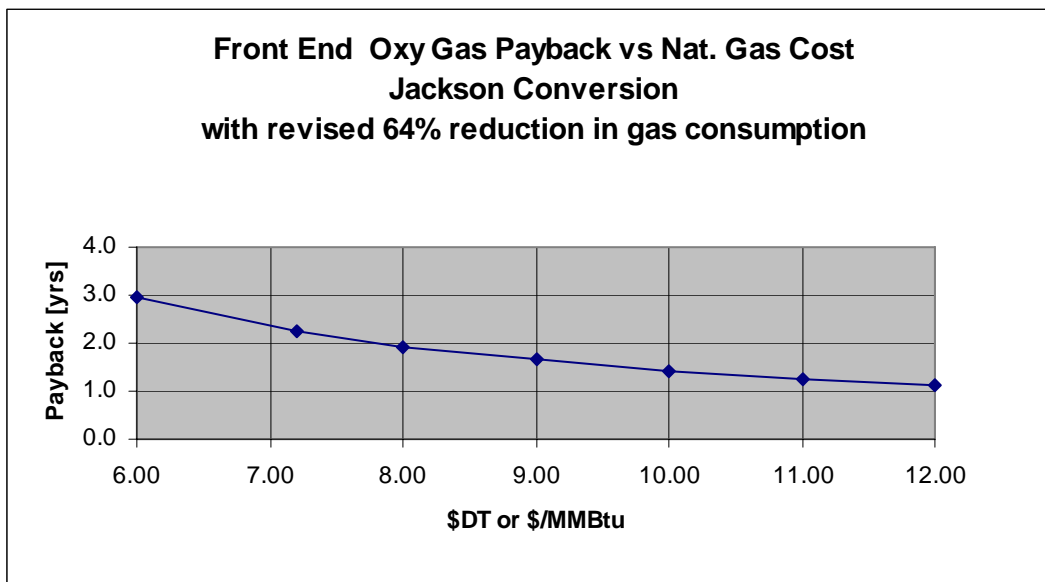
Table 2 Financial Results

	Cost of Gas [\$/Dt]	Reduction In Gas Consumption [%]	Capital Cost <sup>3</sup> [\$]	Net Savings [\$/yr]	Payback [yrs]
Project targets	6.0	65	850,000	464,000	1.8
Jackson – actual results, not adjusted for other operational changes	7.2	53	1,028,000	333,000	3.1
Jackson – gas consumption adjusted per Guelph actual results	7.2	64% <sup>2</sup>	1,028,000	458,000	2.2

Notes:

- 1) Cost of O<sub>2</sub> not reported – proprietary information
- 2) Gas consumption reduction in Guelph – data obtained in conversion of combustion system that was not affected by other operational changes
- 3) Capital cost of project does not include R&D developmental costs or any superstructure refractory costs as the project was done at a rebuild when refractory would be replaced

Fig. 11 Payback vs. Gas Cost



## Results

### Environmental

#### *CO<sub>2</sub> – Greenhouse gas reduction:*

As the amount of CO<sub>2</sub> released in combustion is directly proportional to the amount of fuel burned, a 64% reduction in gas consumption **reduces green house gas emissions by 64%. For Jackson, the actual, unadjusted natural gas savings (56% reduction) was 77,000 DT/yr or 77,000,000,000 Btu/yr.** See Table 1.

Using conversion factors from Table 2.1b “Comparative data (by weight) for some typical fuels”, North American Combustion Handbook <sup>4</sup>, a simple estimate of the amount of **CO<sub>2</sub> emission eliminated by converting one front end is:**

$$\frac{77,000,000,000 \text{ Btu}}{\text{yr}} \times \frac{1 \text{ lb nat. gas}}{21,830 \text{ Btu}} \times \frac{2.55 \text{ lb CO}_2}{\text{lb nat. gas}} \times \frac{1 \text{ ton}}{2000 \text{ lb}}$$

**= 4497 tons CO<sub>2</sub>/yr**

#### *NO<sub>x</sub>*

Exhaust gas samples of the Jackson front end were collected. Significantly higher levels of NO<sub>x</sub> were found compared to the air/gas system. This was attributed to air leakage or ingress into the forehearth combustion space. However, the increase, on a mass basis was significantly less than the reduction in NO<sub>x</sub> achieved by the converting the melter to oxy firing so the net impact of the total combustion system conversion made at the time of the rebuild was a net reduction.

### Manufacturing productivity and product quality

Bulk glass to fiber conversion efficiency is considered proprietary information for the fiberglass industry so before and after conversion efficiency data is not provided. In general terms, there was no negative impact on conversion efficiency or product quality for either the Jackson or Guelph installations.

### Proposal to investigate conducting a trial on a lighting glass front end

At the December 2004 consortium meeting, the potential for conducting a trial of the technology at one of Osram Sylvania’s facilities was discussed based on preliminary positive results. The issue of the use of air injection on lighting glass front ends to provide cooling when necessary, in addition to heating, was raised. As air injection at burners was a requirement, and an increase in NO<sub>x</sub> was highly probable and deemed not acceptable, Osram Sylvania declined an offer by Owens Corning to model front end burners on a lighting glass furnace front end channel. Accordingly, no further development work was pursued.

### Feedback to the U.S. glass industry

The project proposal called for a technology workshop for Glass Manufacturing Industry Council (G.M.I.C.) members to be held at the end of the 2 year project. At the December 2004 consortium meeting attended by all consortium members, including representation from the D.O.E., the topic of how best to how to conduct the workshop to disseminate project results was discussed. Conducting a workshop at either the Owens Corning Jackson plant or Owens Corning's Science and Technology Center were two options proposed. As consortium members Eclipse and BOC both felt that a wider audience from the U.S. glass industry would be reached if a presentation were made at the Glass Problems Conference, this approach was adopted. The author made two presentations at the Glass Problems conference in October 2005 in Champaign Urbana, IL, as part of a G.M.I.C. sponsored series of energy conservation presentations. Energy savings, project costs, implementation challenges, net operating cost savings and payback were included in the presentation along with a technical explanation on why oxy firing is more efficient. Input from consortium members was obtained to ensure content was appropriate and complete.

Additional presentations on the project were made at the D.O.E. sponsored Ohio Technology Showcase in September /05 and the American Ceramic Society spring meeting in May 2006 to ensure project results were widely communicated.

### Commercialization

Several meetings and conference calls were held in January through March 2006 to develop licensing and commercialization terms. A royalty-based licensing structure in which Eclipse and BOC would market the technology was developed. Both of these consortium members are glass industry suppliers and have extensive contacts for supplying equipment in several sectors of the U.S. glass industry. Accordingly, this was deemed a practical approach with the greatest likelihood of success. A net savings vs. energy cost spreadsheet (including capital costs) was supplied by Owens Corning to assist with developing the value proposition for the technology for potential licensees. Operational training services provided for a fee to BOC and Eclipse was proposed to allow these companies to successfully commission the technology at a licensee's site. OC could similarly provide consulting support to the licensee. To ensure success of any future installation, it was agreed that the end user must be willing to model their front end system and conduct their own pilot trials.



## Accomplishments

### A) Technical & financial

For the Jackson, TN demonstration installation the following results were achieved:

- ☐ Reduced natural gas consumption by 77,000 DT/yr
- ☐ Reduced operating costs by \$458,000/yr
- ☐ Reduced CO<sub>2</sub> green house gas emissions by 4,497 tons/yr
- ☐ Implemented the technology without negatively impacting the manufacturing process

### B) Communicating results to the U.S. glass industry

- ☐ Presentations of project results were made at three glass industry gatherings as well as two D.O.E. Industrial Technologies Program project reviews
- ☐ A marketing pamphlet outlining the technology and the project was created by the D.O.E.

### B) Patent status

Two patents relating to the technology were applied for based on research done prior to starting the demonstration project.

- ☐ **OXYGEN-FIRED FRONT END FOR GLASS FORMING OPERATION**  
US application published October 9, 2003 as 2003/0188554  
PCT application published October 16, 2003 as PCT/2003/084885  
PCT Status - Applications now being prosecuted in individual offices  
Status pending for the following countries: Czech Republic, Poland, Norway, Mexico, Korea, India, Canada, Brazil, Great Britain, France, Spain, Germany and Belgium
- ☐ **LOW HEAT CAPACITY GAS OXY FIRED BURNER**  
US application filed June 9<sup>th</sup> 2004  
PCT Status - Applications now being prosecuted in individual offices  
Status pending for the following countries: Brazil, Canada, China, India, Korea, Mexico, Norway, Great Britain, France, Spain, Germany, Belgium, Japan, Italy, Czech Republic, Finland, Netherlands and Turkey

## Conclusions

Front end oxy firing has been demonstrated at Owens Corning plants to be a viable energy and cost saving technology for the fiberglass sector of the U.S. glass industry.

The project substantially met the majority of technical objectives including: energy reduction, operating cost savings, green house gas emissions reduction, and no adverse impact on production efficiency or product quality.

The goals not met include: NOx emissions reduction and commercialization.

Converting a front end to oxy/gas firing delivers a significantly higher reduction in gas consumption than converting a glass furnace. This is due to the lack of preheating of combustion air for a front end air/gas combustion system. A 64% reduction in gas consumption was achieved.

Top firing, as opposed to traditional side firing, reduces the number of burners required to achieve satisfactory heat distribution which lowers capital cost.

The economic attractiveness (payback) of front end oxy firing is dependent on:

- a) the cost of natural gas and oxygen – primary factors
- b) the equipment capital cost – secondary factor

With natural gas costing \$6/DT, a 3 year payback should be achievable. With gas costing \$8/DT a 2 year payback should be achievable. (Based on 2004 capital costs.)

Project participation by multiple parties increases the level of co-ordination and communication required but provides alternative perspectives and more experience. This increases the probability of a successful outcome for a developmental project.

## **Recommendations**

Extensive modeling and pilot trials are key to ensuring the success of any future installation oxy-fuel front end combustion system.

Front end oxy firing should be considered as an “add on” application to oxygen firing a glass melter. This approach is essential to achieving acceptable financial results as a sufficient base load of oxygen is required to justify on site oxygen supply which provides oxygen at a much lower cost than delivered liquid oxygen. (The exception might be the case where a pipeline supply of lower cost oxygen was available to a glass plant).

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