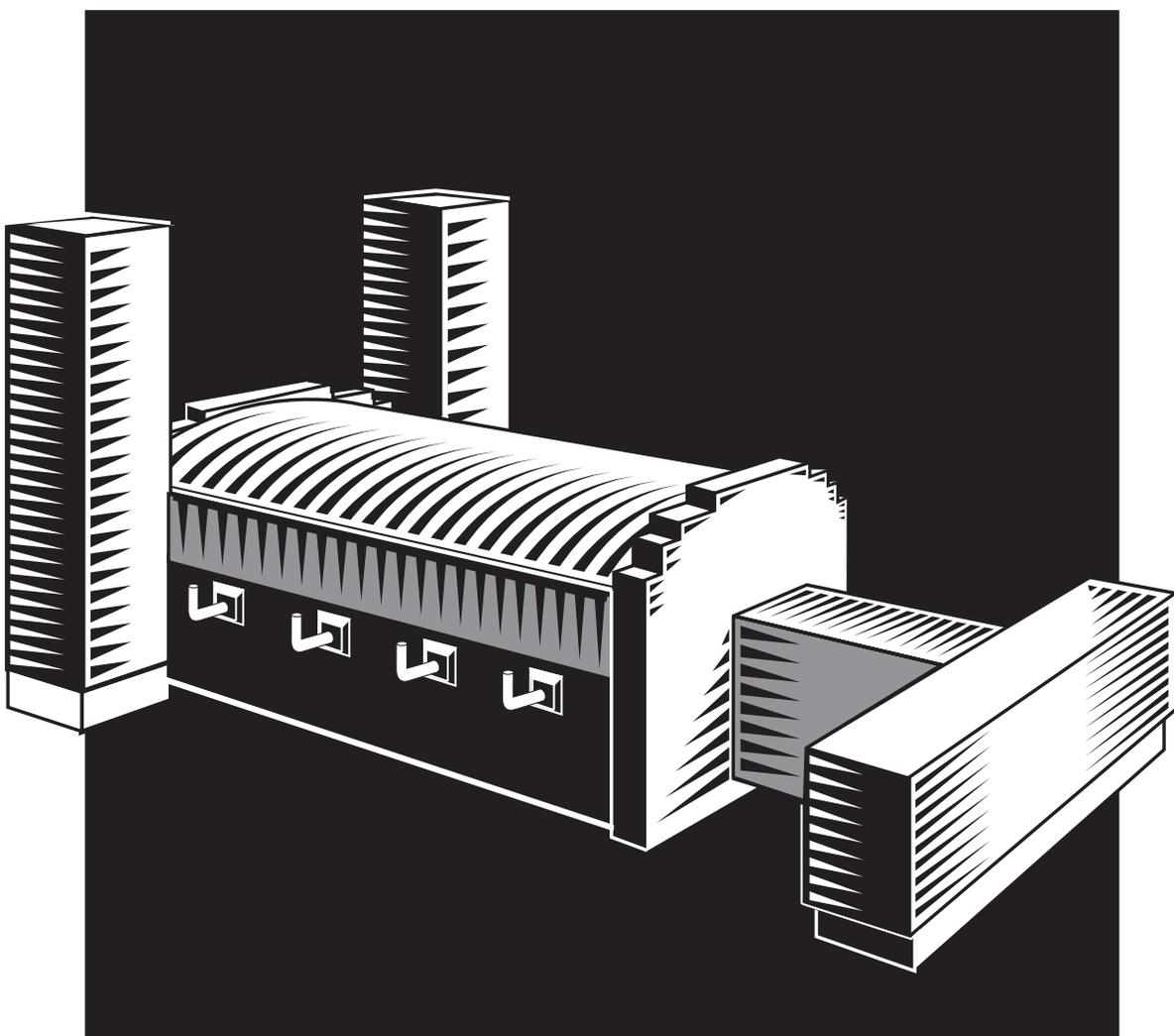


# *Glass*

## *Industry of the Future*

*Quarterly Status Reports*

*As of December 31, 2005*



U.S. DEPARTMENT OF ENERGY

02-GA50113-03

**Glass**  
**Industry of the Future**

*Quarterly Status Reports*

*As of December 31, 2005*

# Glass Industry of the Future

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ID14030	

***Development and Validation of a Coupled  
Combustion Space/Glass Bath Furnace  
Simulation***

Lottes: Argonne National Laboratory (w/ Techneglas)

Agr id:04895



**Background:** A substantial effort in the previous project was expended to develop a state of the art furnace model (GFM) that can be used to predict furnace performance. This validated model has been used by the industrial participants of the project to perform extensive parametric studies on their furnaces. These studies indicated that computer modeling is a cost effective method for improving furnace performance. In an effort to improve the performance of furnaces throughout the industry, the ensuing technical transfer program has been initiated to promote the usage of the GFM in the glass industry.

**Status:** Program progress is presented in accordance with the work breakdown structures adopted for the program. A brief summary of progress in tasks pursued during the last reporting period follows. Those tasks in italics are not applicable to the current quarter.

***Task 1: GFM brochure prepared and mailed to glass industry companies. (01/04 to 03/04)*** Completed.

***Task 2: Licenses for GFM available on ANL's software shop website (04/04)*** As of 31 December 2004, nineteen licenses have been issued through ANL technical transfer. A CD with the GFM was mailed to the licensees once ANL technical transfer notified the code developers a license had been signed.

***Task 3: GFM users group formed (05/04)*** Completed

**Task 4: Technical Support Provided to GFM Users (05/04 to 3/06)**

Technical support and ongoing development responsibilities for GFM were taken over by S.A. Lottes in March 2005. In the transition all pieces of the GFM package were reviewed, and areas where significant improvements could be made to increase marketability were identified. Major "ease of use" improvements and a new automatic cycling capability were reported in the April through June 2005 quarter. In the July through September 2005 period, new problems in robustness and numerical stability in both the melt space and combustion space components were identified and automated program state data collection and plotting was implemented to speed up isolation and resolution of problems. In the October through December 2005 period the new GFM monitoring capabilities were used to identify and initiate resolution of performance issues with the radiation heat transfer scheme in the combustion code, revamp the high level combustion space algorithm to speed up the computation, isolate and resolve a variety of minor combustion space problems, such as loss of solution precision on restart. The monitoring tools were also employed to identify a number of weaknesses in the melt code. Removal of a constraint requiring a positive heat flux into the melt over the entire melt surface yielded a pattern of oscillatory instability in cycling boundary conditions between melt and combustion space computations. A set of tasks was formulated to resolve or substantially

improve GFM performance with respect to these issues in the coming quarter.

Some of the performance difficulties in GFM are a consequence of attempting to solve a very complex computational fluid dynamics (CFD) problem within the memory and speed constraints of a single high end personal computer (PC). The existing direct solution approach of the radiation transport equation (RTE), though highly accurate due to minimal modeling assumptions, suffers from unacceptable discretization error in the wall exchange computation when confined to the resources of a PC. To resolve this issue, the RTE solution was split using a hybrid approach that retains the direct solve of the RTE over the volume to obtain direct heat flux from flames to walls and melt surface and uses a new enhanced enclosure radiation wall exchange algorithm to attain greatly improved accuracy in wall temperatures and total (wall and flame) heat flux to the melt surface.

A speed up by a factor of between 2 and 4 was achieved in the combustion code using new program monitoring data collection to reorganize distribution of computational effort among the fluid dynamics with combustion, radiation transport, and minor species calculations to greatly improve simulation solution efficiency. While this efficiency gain may lead to shorter run times, it may also need to be used to allow running with more refined grids to better resolve flow features to obtain acceptable accuracy. The convergence of the solution of transport equations for minor species and soot, which determines the volume radiation source distribution, was also checked and optimized in this process.

In air fuel furnace simulations, the radiation heat flux solution is very sensitive to soot production, distribution, and oxidation. To accommodate simulation with the resources of a PC, a reduced two step soot production and oxidation model is used that has four kinetic parameters. In air fuel furnaces, the magnitude of the total heat flux to the melt is very sensitive to the kinetic model soot parameters, and these parameters may need adjusting for different types of burners and furnace geometries. To provide a means to allow the user to set soot kinetic parameters for furnaces that are significantly different from those used for model validation, a new soot kinetic parameter calibration simulation mode has been implemented. The parameters can be calibrated using operating condition data from an existing furnace or design point conditions for a new design combined with an expected efficiency at the design point. In new designs, the calibrated soot parameters provide a reasonable baseline from which to test design variations to see whether performance improves or degrades. The soot calibration can also be done for oxy-fuel furnaces, however, soot kinetics are not nearly as significant in oxy-fuel furnaces because a large fraction of the radiation heat flux comes from the dominant combustion products, carbon dioxide and water vapor. New menu items are provided in the user interface for the new soot kinetic parameter calibration mode.

As part of the radiation model upgrade, some user control over the wall exchange radiation computation was added. For example, if the user's computer has sufficient memory, view factors computed from the grid geometry can be saved in memory to speed up the radiation wall exchange calculation, while if computer memory is limited, the user can set an option to recalculate view factors when needed. The capability to specify separate emissivities for walls, crown, and melt surface was also implemented.

In a continuing effort to improve ease of use, a significant number of minor improvements were made to the user interface.

***Task 5: Periodic meetings of CUG held to discuss code usage and results (05/04 to 01/05)*** In view of the change in personnel and the extensive improvements being made to the GFM code, the initial meeting of the CUG (Core User Group) has been delayed. The meeting date will be set during the next quarter.

***Task 6: Long-term code support mechanism established by CUG membership (02/05)***

**Plans for Next Quarter:**

Diagnosis and resolution of difficulties in achieving convergence in the melt simulation to more than one or two significant digits will be undertaken. The improved GFM melt code will then be used to find a strategy to stabilize and converge boundary coupling conditions when cycling between the combustion space and the melt codes. A list of other GFM improvements needed for a new release to trial users will also be addressed.

**Patents:**

The Glass Furnace Model software (GFM 1.0) was copyrighted (May 14, 2001).

The Glass Furnace Model software (GFM 2.0) was copyrighted (ANL-SF-01-030b) (May 17, 2002).

**Milestone Status Table:**

ID Number	Milestone Description	Planned Completion	Actual Completion	Comments
1	Brochure created and mailed	03/04	03/04	
2	Licensing becomes available via ANL software shop	04/04	04/04	
3	Technical support and upgrades provided to code users	11/04		Ongoing

**Budget Data:** (as of 9/30/03): The approved spending should not change from quarter to quarter. The actual spending should reflect the money actually spent on the project in the corresponding periods.

			Approved Spending Plan (\$K)			Provided to Date	Actual Spent to Date
Year/Budget Period			DOE Amount	Cost Share	Total	DOE Amount	DOE Amount
	From	To					
2004	January	March	70.0	n/a	70.0	250.0	78.2
2004	April	June	60.0	n/a	60.0		77.9
2004	July	Sept	60.0	n/a	60.0		56.0
2004	Oct	Dec	50.0	n/a	50.0	45.0	32.0
2005	January	March	10.0	n/a	10.0	110.0	8.9
2005	April	June					24.3
2005	July	Sept.					45.4
2005	Oct.	Dec.					55.0
		Totals	250.0		250.0	405.0	377.7

\*Program started officially 01/01/04.

***Advanced Oxy-Fuel Front-End System***

Mighton: Owens Corning

GO13091

## Quarterly Progress Report

**Project Title:** Development/Demonstration of an Advanced Oxy-Fuel Fired Front End

**Covering Period:** Oct 1 – Dec 31, 2005

**Date of Report:** Feb 1, 2005

**Recipient:** Owens Corning  
Columbus Rd., Rt. 16  
Granville, Ohio 43023

**Award Number:** DE-FC36-03G013091

**Industrial Partners:** Eclipse/CombustionTec, Kevin Cook  
BOC, Neil Simpson,  
Osram Sylvania, Tim Jenkins

**Contacts:** Steve Mighton, P. Eng. (740) 321-7633

**Project Team:** Elliot Levine (DOE Glass Industry Liaison)  
Brad Ring (DOE Project Officer)  
Carrie Capps (Project Monitor)  
Beth Dwyer (DOE Contract Officer)

### **Project Objective:**

The goal of this project is to develop and demonstrate an oxy-fuel combustion system for the front end of a fiberglass melter that will reduce fuel consumption by approximately 70% creating an operating savings of approximately 40% and significantly reduce NO<sub>x</sub> and CO<sub>2</sub> emissions.

### **Background:**

Glass melters have successfully used oxy/fuel burners to reduce emissions and operating costs. Glass melter front ends, consisting of refractory channels that deliver glass to the forming process have traditionally used air/gas burners. Conventional front end air/gas combustion systems supply an air/gas mixture to the burner. Due to safety concerns, the mixture is not preheated as is done for air in recuperative or regenerative melter combustion systems. As a result, a significant portion of energy is required just to heat nitrogen in the air to the temperature of the combustion space. Use of oxy/fuel burners in a front end eliminates the need to heat the nitrogen and generates a hotter flame that radiates energy with a shorter wavelength resulting in improved transmissivity characteristics. These factors create a more efficient radiant heat transfer into the glass and create the potential for improved thermal homogeneity.

## Background: cont'd

The resulting efficiency of a front end oxy/fuel combustion system is approximately 55% vs. only 15 to 30 % for an air gas system. In terms of gas consumption, an oxy/gas burner will use 65% to 70% less gas than an air/gas burner for the same heat input 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 is the same (65 to 70%). If nitrogen in the combustion space can be eliminated, the potential exists for lower NO<sub>x</sub> levels as well.

The hurdle to implementation of oxy/fuel burners in a front end is two fold and relates 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.

**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 in the past by others (Eclipse & BOC/BFH).

This project involves 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 allows one top fire burner, with higher flow, to replace 10 to 20 air/gas burners.

## **Status**

The project continues at step 13 of phase 3.

### Overall Project Plan

#### Phase 1

- 1.0 Develop conceptual designs of the oxy-fuel front end burner system
- 2.0 Perform computer modeling of the burner and block designs
- 3.0 Conduct single burner tests on a lab forehearth system
- 4.0 Develop oxy-fuel combustion systems to be integrated into front end
- 5.0 Perform computer modeling on combustion system integration
- 6.0 Conduct multi-burner tests on a lab forehearth system

#### Phase 2

- 7.0 Conduct field test of a single burner operation
- 8.0 Conduct field tests of multi burner operations
- 9.0 Conduct field evaluation of a production forehearth/channel

#### Phase 3

- 10.0 Design, engineering and system integration for field demonstration
- 11.0 Perform computer modeling on performance and glass quality
- 12.0 Prepare demonstration site for system installation
- 13.0 System installation and shakedown on a fiberglass melter front end.

## **4<sup>th</sup> Quarter 2005 Work**

### Demonstration site installation – Jackson TN

As of Dec 31st, the demonstration front end oxy/gas combustion system in Jackson, TN has been in operation a 17 months. No modifications to the combustion system were made in Jackson during the fourth quarter.

The installation of two sealed peephole assembly using high temperature glass that will allow inspection of burners without opening a peephole door was completed in the first week of November. A pyrometer was used to measure a temperature of 1160 F on the cold face of the sight glass, which . f 1160 F was acceptable for quartz glass. The peephole glass and screen were inspected 4 weeks and 6 weeks after installation. Gradual accumulation of a dry soot required cleaning of the glass at 6 weeks. The assessment of plant personnel of the sealed peephole has been favorable. The additional work to clean sight glasses every 6 weeks is more than offset by the improved safety and convenience of being able to conduct visual inspections without opening a peephole door and being exposed to sting out. Gasket deterioration due to disturbing the gasket while cleaning the glass may require a different type of gasket. The units will continue to be monitored periodically for any long term deterioration of components. Sealing the peephole did not impact NOX levels indicating air leakage elsewhere in the superstructure. If the plant can raise the matching 50% funding, the installation of sealed sight glass style peepholes may be considered for the Jackson installation.

No burner changes were made this quarter. Minor soot accumulation was addressed by briefly interrupting fuel flow on an “as necessary” basis.

### Full Scale Implementation at second plant – Guelph ON

The second full front end installation in Guelph ON has been in operation for 8 months.

### Other

Plans are being developed to introduce this technology at two other Owens Corning plants in 2006.

The project will be wrapped up in 2006.

## Plans for 1<sup>st</sup> Q 2005

A 3 way meeting with Eclipse, BOC and OC to establish a licensing arrangement for the technology was rescheduled to Feb 9, 2006

## Patents

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 application is now inactive

Filed patent applications directly for: Korea, Brazil, Canada, India, Mexico, Norway

LOW HEAT CAPACITY GAS OXY FIRED BURNER

US application filed June 9<sup>th</sup> 2004

Filed PCT application, now inactive

Filed patent applications directly for Brazil, EU, Japan, Korea, Mexico, Norway, Canada, China, India

## Publications/Presentations

No publications or other presentations have been made this quarter.

A presentation on project results is scheduled for the American Ceramic Society meeting in May 2006.

## Budget Data

Total project spending is anticipated to be \$ 1,775,794

Project Spending and Estimate of Future Spending							
Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays	Cumulative
	Start	12/31/05	Note 1	\$855,309		\$855,310	\$1,710,619
1Q06	1/1/06	2/20/06	\$32,587		\$32,588		\$1,775,794
<b>Totals</b>			\$32,587	\$855,309	\$32,588	\$855,310	\$1,775,794

***Energy Efficient Glass Melting:  
The Next Generation Melter***

Rue: Gas Technology Institute

GO13092

## QUARTERLY PROGRESS REPORT

**Project Title** Energy-Efficient Glass Melting - The Next Generation Melter

**Covering Period** October 1, 2005 through December 31, 2005

**Date of Report** February 6, 2006

**Recipient** Gas Technology Institute  
1700 S. Mt. Prospect Rd.  
Des Plaines, IL 60018

**Award Number** DE-FC36-03GO13092

**Subcontractors** A.C. Leadbetter and Son, Inc.  
Fluent, Inc.  
Praxair, Inc.

**Other Partners** NYSERDA – project sponsor  
GTI Sustaining Membership Program (SMP) – project sponsor  
Gas industry through FERC funding – project sponsor  
Corning, Incorporated  
Johns Manville  
Owens Corning  
PPG Industries, Inc.  
Schott Glass Technologies, Inc.

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**Project Team**

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## Project Objective

The objective of this project is to demonstrate a high intensity glass melter, based on the submerged combustion melting technology. This melter will serve as the melting and homogenization section of a segmented, lower-capital cost, energy-efficient Next Generation Glass Melting System (NGMS). After this project, the melter will be ready to move toward commercial trials for some glasses needing little refining (fiberglass, etc.). For other glasses, a second project Phase or glass industry research is anticipated to develop the fining stage of the NGMS process. Overall goals of this project are:

- Design and fabrication of a 1 ton/h pilot-scale submerged combustion glass melter,
- Extensive melting of container, fiber, flat, and specialty glass formulations,
- Detailed analysis of the product glasses,
- Preparation of a Fluent-supported CFD model of the melter to be used in parallel with further development of the NGMS technology,
- Physical modeling of the NGMS process to determine energy savings, cost savings, environmental improvements, and use of waste heat for production of needed oxygen,
- Development of a commercialization plan and timeline for further, needed components and integration of the NGMS technology.

The Work Breakdown Structure and schedule are presented below. The project team recognizes that further work will be needed after this project to bring the critically-needed NGMS into industrial use. To expedite that development, the work in this project will focus in three areas needed to demonstrate the melting and homogenization steps of the NGMS technology and to prepare for further work to commercialize NGMS. These work areas are:

- Design, fabrication, and operation of a pilot-scale melter with analysis of product glass,
- Supported CFD modeling on the melter that is available to all users,
- Physical modeling and energy balances for the full NGMS with specific planning for further steps leading to commercial implementation.

Work in each project year is divided into Tasks with milestones at the end of many of the Tasks. The integrated Task Schedule enables project team members to assign labor appropriately and to follow a critical path to reach all milestones and objectives toward the overall goal of design, modeling, demonstration, and analysis of this melting technology.

Task		Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	Modeling	[Orange bar spanning all 12 quarters]											
2	Melter Design	[Orange bar spanning all 12 quarters]											
3	Procurment	[Orange bar spanning all 12 quarters]											
4	Physical Modeling	[Orange bar spanning all 12 quarters]											
5	Fabrication	[Orange bar spanning all 12 quarters]											
6	Shakedown	[Orange bar spanning all 12 quarters]											
7	Test Planning	[Orange bar spanning all 12 quarters]											
8	Testing - Parametric	[Orange bar spanning all 12 quarters]											
9	Melter Modification	[Orange bar spanning all 12 quarters]											
10	Second Test Series	[Orange bar spanning all 12 quarters]											
11	Analysis	[Orange bar spanning all 12 quarters]											
12	Toward Commercialization	[Orange bar spanning all 12 quarters]											

Milestones are placed at the end of many project Tasks to help sponsors and team members evaluate project technical progress on time and financial tracking. The milestones shown below will serve throughout the project as a gauge to successful completion of the work.

Year 1 Milestones	<ul style="list-style-type: none"> <li>• Complete CFD model to be used by team members to design pilot scale melter</li> <li>• Design pilot scale melter</li> <li>• Procure all equipment and components for the melter in preparation for fabrication</li> </ul>
Year 2 Milestones	<ul style="list-style-type: none"> <li>• Fabricate and shake down of the pilot scale melter</li> <li>• Prepare test plan including compositions of glasses to be melted</li> <li>• Finish all pilot scale melting tests and collect samples for analysis</li> <li>• Complete detailed analyses of product glass properties and quality</li> </ul>
Year 3 Milestones	<ul style="list-style-type: none"> <li>• Modify melter, as needed, for second test series</li> <li>• Finish second test series, including at least one long term test, and all glass analysis</li> <li>• Finalize CFD model of the melter usable by all CFD operators</li> <li>• Finish physical material and energy balance model of next generation melting system (NGMS) process including utilizing waste heat for oxygen production</li> <li>• Complete plan for commercialization, including needed developments and stages</li> </ul>

Go-no-go decision points are placed at the end of the first and second years of the project. At these times, the project team and sponsors have the opportunity to assess project progress and decide on continued work in the next phase (or year) of the project. The project team has every confidence that all project technical targets and milestones will be reached.

- The Year 1 go-no-go decision point criteria for continuing work will be design of the pilot scale melter and procurement of equipment and components on schedule and budget.
- The Year 2 decision point criteria for continuing work will be completion of pilot scale testing with glass formulations from all four industry segments and analyses of the product glasses.

### Background

Any new melter must perform at least as well as refractory melt tanks by all technical, cost, operability, and environmental criteria while providing tangible benefits to the glass maker. A partial list of this daunting set of criteria, by category is shown below.

<u>Criteria Category</u>	<u>Specific Criteria</u>
Technical	High thermal efficiency, ability to make any glass formulation, can handle needed temperatures and oxidation conditions, meet glass quality requirements, integrates with batch handling and forming processes
Cost	Low melter cost, low maintenance cost, low energy cost, inexpensive environmental regulation compliance

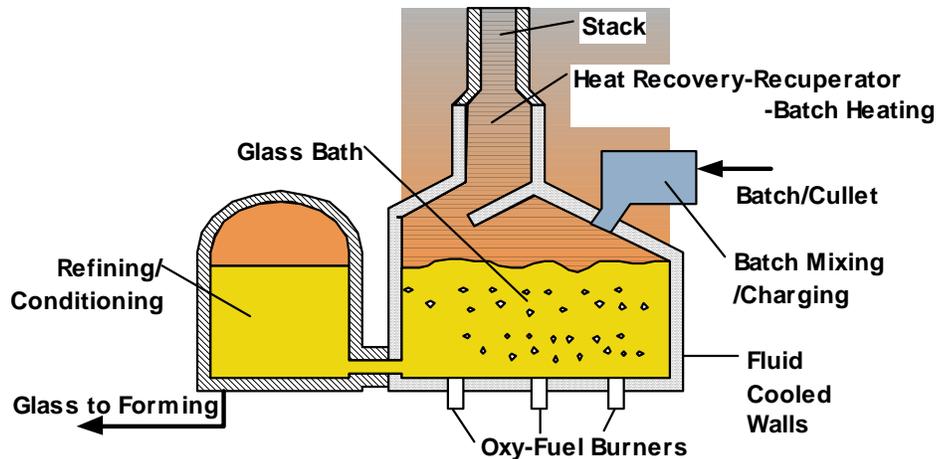
Operability	Scalable from 25 to 700 ton/day, reliable, stable operation, easy to idle, ability to start and stop, ease of access and repair, fast change with glass formulation and color, no moving parts to be abraded by the glass
Environmental	Low air, water, and solid waste, recycle-friendly

The search for a lower-cost glass melter has led technologists to suggest a segmented melting approach in which several stages are used to optimize the melting, homogenization, and refining (bubble removal) instead of the current practice of using a single, large tank melter. In this segmented approach, separately optimized stages for high-intensity melting and rapid refining are expected to reduce total residence time by 80 percent or more. This approach to melting has come to be known as the Next Generation Melting System (NGMS).

The project team has identified submerged combustion melting (SCM) as the ideal melting and homogenization stage of NGMS. This is the only melting approach that meets and exceeds all the performance characteristics of refractory tanks and also provides large capital and energy savings to the glass industry. Submerged combustion melting is a process for producing mineral melts in which fuel and oxidant are fired directly into the bath of material being melted. The combustion gases bubble through the bath, creating a high heat transfer rate to the bath material and turbulent mixing. Melted material with a uniform product composition is drained from a tap near the bottom of the bath. Batch handling systems can be simple and inexpensive because the melter is tolerant of a wide range in batch and cullet size, can accept multiple feeds, and does not require perfect feed blending.

SCM was developed by the Gas Institute (GI) of the National Academy of Sciences of Ukraine and was commercialized a decade ago for mineral wool production in Ukraine and Belarus. Five 75 ton/day melters are in operation. These commercial melters use recuperators to preheat combustion air to 575°F. All melters operate with less than 10 percent excess air and produce NO<sub>x</sub> emissions of less than 100 vppm (at 0 percent O<sub>2</sub>) along with very low CO emissions. A photo of a commercial SCM unit in Belarus is shown below.

In SCM (shown below), fuel and oxidant are fired directly into the molten bath from burners attached to the bottom of the melt chamber. High-temperature bubbling combustion inside the melt creates complex gas-liquid interaction and a large heat transfer surface. This significantly intensifies heat exchange between combustion products and processed material while lowering the average combustion temperature. Intense mixing increases the speed of melting, promotes reactant contact and chemical reaction rates, and improves the homogeneity of the glass melt product. The melter can handle a relatively non-homogeneous batch material. The size, physical structure, and especially homogeneity of the batch do not require strict control. Batch components can be charged premixed or separately, continuously or in portions.



A critical condition for SCM operation is stable, controlled combustion of the fuel within the melt. Simply supplying a combustible fuel-oxidant mixture into the melt at a temperature significantly exceeding the fuel's ignition temperature is insufficient to create stable combustion. Numerous experiments conducted on different submerged combustion furnaces with different melts have confirmed this. Cold channels are formed that lead to unstable combustion and excessive melt fluidization. A physical model for the ignition of a combustible mixture within a melt as well as its mathematical description show that for the majority of melt conditions that may occur in practice, the ignition of a combustible mixture injected into the melt as a stream starts at a significant distance from the injection point. This, in turn, leads to the formation of cold channels of frozen melt, and unstable combustion. To avoid this type of combustion, the system must be designed to minimize the ignition distance. This can be achieved in three ways: 1) by flame stabilization at the point of injection using special stabilizing devices, 2) by splitting the fuel-oxidant mixture into smaller jets, and/or 3) by preheating the fuel/oxidant mixture.

Several types of multiple-nozzle air-gas burners that meet these requirements have been designed and operated industrially by the GI Ukraine. The burner is attached to the bottom of the bath with the main body outside the furnace. Only the surface around the exhaust of the slotted combustion chamber is in contact with the melt. Based on the research data available on thermal and fluid dynamic stability of the combustion chamber, a model for calculating the

design parameters of submerged burners has been developed. GTI has extended this work to oxy-gas burners and found them to be stable during lab-scale melting of several materials including mineral wool, sodium silicate, and cement kiln dust.

Material in the SCM melt chamber constantly moves against the walls. A typical refractory surface would rapidly be worn away by the action of the melt. To address this, the melting tank is constructed of fluid-cooled walls that are protected by a layer of frozen melt during operation. This frozen layer is constantly formed and worn away during operation. The industrial SCM units used water-cooled walls. The project team intends to use high temperature fluids for cooling to allow useful heat to be recovered from this coolant. The heat flux through the frozen melt layer is determined by the properties of the processed material and the temperature and turbulence of the melt. It is, therefore, undesirable to superheat the melt because this increases the heat flux through the walls. Also, heat flux is lower with oxy-gas firing because melt turbulence is greatly reduced. Under normal operating conditions for silica melts, the oxy-gas heat flux is 7700 Btu/ft<sup>2</sup>·h, equal to 2 x 10<sup>6</sup> Btu/h heat loss for a 75 ton/day melter. These values are relatively independent of the temperature of the coolant as any increase or decrease in the coolant temperature is accompanied by a compensating change in the thickness of the lining. Heat flux for a refractory tank is lower at 1800 Btu/ft<sup>2</sup>·h, but with much greater surface area, the refractory tank loses more heat (2.55 x 10<sup>6</sup> Btu/h).

Special care must be taken to minimize fluidization of the melt which creates a large amount of droplets. These droplets, especially small ones which are formed when bubbles split, can be thrown out of the melt to a significant height. Consequently, the exhaust ducting must be protected from being covered by the frozen melt. In our design, this issue is resolved by removing combustion products through a special separation zone. In the separation zone, exhaust gas is forced to change direction and drop all liquid carryover droplets. The roof of this zone is sloped so droplets can easily be returned to the melter. This approach also reduces the necessary fluid-cooled surface area around the melting zone.

GTI holds the exclusive, world-wide license to SCM outside the former Soviet Union. Recognizing SCM's potential, GTI has operated a laboratory-scale melter with oxy-gas burners and produced several melts. Evaluation of the process has shown its potential for glass production when combined with other technologies for heat recovery, batch handling, refining, and process control. The photo above shows melt collection from GTI laboratory SCM testing.

Waste heat recovery is critical to reach high energy savings with NGMS. Adaptation of Praxair's Oxygen Transport Membrane (OTM) technology to the melter will be evaluated in this project. Praxair has been the world leader in the development of oxygen transport membrane (OTM) technology. The OTM technology is based on a class of ceramic materials that, when operated at temperatures above 500°C, can separate oxygen from air with infinite selectivity. Because of the high temperature of operation, opportunities exist for integrating OTM oxygen production with the glass melting process to utilize waste heat. This integration is expected to result in increased energy efficiencies, reduced oxygen costs and emissions, and potential carbon dioxide sequestration.

Praxair's efforts will focus on developing and simulating OTM processes that would be ideally suited for glass melting furnaces. A multitude of process configurations will be designed. Of these processes, the top two or three configurations will be selected based on process

efficiency, emission levels, simplicity, and level of integration. A preliminary economic analysis then will be performed on the selected process cycles.

The Glass Industry Technology Roadmap cites the need for a less capital intensive, lower energy cost, and cleaner way to melt glass. Incremental changes to current melting practices will not stop the loss of furnaces, jobs, and companies to the competition from alternative materials and international glass makers. The Roadmap sets high strategic goals of 20 percent cost reduction, six sigma quality, 50 percent decrease in the gap between actual and theoretical energy use, and 20 percent decrease in air emissions. At the same time, the Energy Efficiency technical area calls for 'New Glass melting technologies'. This project addresses the following Needs expressed in the Roadmap:

- Accurate validated melter model (Energy Efficiency) – developed and supported by Fluent
- Improved thermal efficiency (Energy Efficiency) – the gap between actual and theoretical energy use is decreased by 50 percent
- Superior refractory materials (Energy Efficiency) – over 80 percent of refractory is eliminated because refractory walls are replaced with fluid-cooled walls with heat recovery
- Lower production cost (Production Efficiency) – melter cost at 55 percent lower, energy cost 23 percent lower, and glass production cost (capital, labor, and energy) 25 percent lower
- Decrease air emissions (Environmental Performance) – 20 to 25 percent decrease in air emissions from higher efficiency while NO<sub>x</sub> is reduced over 50 percent (to under 0.35 lb/ton)

This project will demonstrate that the submerged combustion melter is ideally suited for technical and cost reasons, and better suited than any other melting approach, to be the melting and homogenization stage of an NGMS process. Also, the quality of glass produced and the flexibility of the melter to integrate with other processes will expedite development and commercial application of the full NGMS process. After this project, the melter will be ready to move to commercial trial for fiberglass and other glasses needing little or no refining. For other glasses, glass industry research or a Phase II project is expected to demonstrate rapid glass refining and to integrate the NGMS melting and refining stages.

Development of a new glass melting technology is a challenging undertaking, and no attempt to replace refractory tank melters has succeeded in the last 100 years. SCM, however, has been operated as an industrial-scale mineral wool melter for the last decade and has proved highly reliable. The industrial units are air-gas fired, but GTI has demonstrated smooth operation of oxy-glass burners on a 300 lb/h melter with several siliceous melts. This experience provides a solid basis for extending SCM to industrial-glass production.

A number of hurdles must be overcome to develop SCM into the NGMS melter and to develop the full NGMS process. The wide glass making, combustion, modeling, and engineering knowledge and experience of the project team assure the technical feasibility of this technology. No other project in recent memory has captured the commitment of such a large portion of the glass industry. This strong support makes clear that there is a great need for a revolutionary new melting technology and that these glass industry experts believe the melting technology to be demonstrated in this project is technically feasible and meets all the cost savings, energy reduction, emissions reduction, and operability needs of the glass industry.

## **Status – Work This Quarter**

Work carried out this quarter was focused on additional melts with the new tap piece, CFD modeling, and final pilot SCM unit design. This quarter was the first quarter in Year 3 of this three year project. Areas of most attention this quarter included

- Lab-scale SCM testing with a strong focus on collecting operations and product glass data to facilitate fabrication of the pilot-scale nominal 1 ton/h SCM unit,
- Analysis of lab-scale melter test results with several glass compositions,
- Final design of pilot melter design including instrumentation,
- Mathematical and computer CFD modeling including hydrodynamics and heat balances,
- Review of the Praxair OTM work on the project.

The glass company consortium agreement has served well as a basis for all parties including GTI, Corning Incorporated, Johns Manville, Owens Corning, PPG Industries Inc., and Schott North America, working well together. With GTI taking the lead in testing and modeling and a smaller role in analysis of samples, the other consortium members have focused on:

- Corning - LCD batch provider, fabrication of platinum tap piece (twice), analysis of LCD glass,
- Johns Manville - E glass and fiberglass scrap provider, sample analysis,
- Owens Corning - Advantex glass provider, provider of transformer and power pack for tap piece, sample analysis, CFD modeling,
- PPG - CFD modeling support for the melter and for new tap piece designs,
- Schott North America - Tap piece design, tap piece shake-down testing, sample analysis,

Along with consortium member direct support, all members have attended meetings, reviewed analyses, discussed pilot SCM design, and provided financial support.

The Praxair Oxygen Transport Membrane (OTM) work has been delayed because Praxair analyses showed that OTM would not be a good fit for SCM. Further review has shown that the initial intended OTM application may not be attractive, but other applications may provide energy and cost benefits. A re-scaled OTM effort, with NYSERDA support was evaluated this quarter.

## **Mathematical modeling**

Mathematical modeling this quarter included continuation of CFD work by Fluent and continued hydrodynamic calculations of melt flow patterns and heat loss calculations.

Fluent modeling was begun with development of CFD code to describe the mixing and flow patterns in the oxy-gas fired SCM unit. Originally, work was to focus initially on the air-fired mineral wool melters, but this route was determined to not provide a reasonable baseline for future CFD modeling of the oxy-fired glass melting undertaken in this project. During this quarter, CFD modeling was underway, and the following work was completed. An important note is that Fluent is focusing on improvements to the CFD code to provide a better tool for SCM modeling. The project team, including engineers at GTI, Owens Corning, and PPG, is carrying out the modeling of specific SCM cases.

## **Fluent Modeling Developments**

### **Concept Simulation**

Research on the FLUENT model of the GTI pilot melter continued at both GTI and Fluent this quarter. The preliminary scoping efforts with the two-dimensional axisymmetric model were discontinued in favor of a 3-D, single-burner model encompassing roughly one-sixth of the melter. Grigory Aronchik at GTI studied burner optimization, heat losses through cooled walls, and a design variation using a flat-flame burner in the feeding area. Andrey Troshko at Fluent developed several versions of the one-burner model with a fine mesh in the burner orifice and investigated how best to combine the VOF multiphase method with combustion. Due to inherent instabilities, the most successful method was to simulate single-phase combustion, then “patch” equivalent inlet gas temperatures onto an unreacting VOF simulation.

Initialization and start-up methods were also investigated. Due to the high initial gas velocities, the maximum practical time step size for the VOF analysis was found to be about 0.0001 sec. Therefore, for the upcoming final analyses of the entire pilot melter, the CFD committee agreed to adopt a multi-step approach for computational efficiency reasons. This approach includes the single-burner VOF analysis to derive equivalent plume momentum and thermal source terms, followed by a single-phase simulation of the entire liquid glass bath. These two steps can be manually iterated back and forth as needed to converge on bulk temperature profiles and source characteristics.

The strategy for the pilot melter CFD analysis can be summarized as follows:

1. 3-D, single-burner (one-sixth melter) single-phase oxy-gas combustion using FLUENT eddy dissipation model;
2. 3-D, single-burner (one-sixth melter) VOF transient analysis of several large bubbles, with no batch particles and combustion approximated as boundary conditions from (1);
3. 3-D, three-burner, half-melter geometry assuming one symmetry plane with gas effects approximated as (possibly steady-state) equivalent heat/momentum sources from (2);
4. Discrete Phase Model (DPM) for transport and dissolution of solid batch and residence time distribution, as a follow-on analysis to (3).

A representative result from the single-burner model is presented in Figure 1. This cross-section through the burner centerline shows the emission of a new gas bubble while an earlier bubble is breaking up at the free surface. The observed temporal spacing, or bubble period, is on the order of one second. FLUENT case files demonstrating the latest refinements were distributed to the CFD Committee.

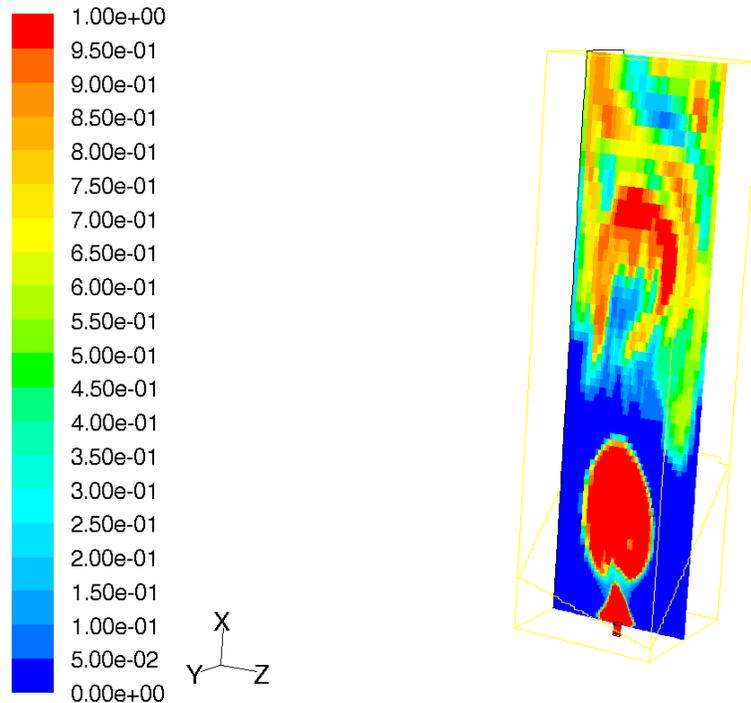


Figure 1. Representative result from single-burner test model (volume fraction of gas)

### Simulation Tool Research and Development

Project-specific software R&D was paused this quarter as the analysis approach continued to evolve, and since the task target budget was already exceeded (see Table 1). Discussions confirmed the feasibility of using DPM for only a few representative large particles for tracking purposes, while modeling the majority of the batch mass with the conversion reaction as a continuum in the liquid (melt) phase. This approach can be implemented using existing features of FLUENT.

### Fluent CFD Work Management

On November 3, Lewis Collins attended the project team meeting at GTI. The meeting's main purpose was to review pilot melter design details and distribute drawings leading to final approval for fabrication by the glass consortium. Drawings were obtained and modeling questions about the pilot feed and cooling system were resolved. The team agreed to baseline John Manville's E glass for CFD analysis purposes and to test that glass first (March target date) to provide early correlation results for the model. Bruno Purnode provided a specification of pilot melter instrumentation needs that consolidated the input from the CFD Committee regarding the model tuning and correlation purposes. This specification included video imaging of the melt free surface for bubble frequency observation.

The CFD Committee met by teleconference on October 26 and in person at the November meeting at GTI. CFD modeling strategy and plans were discussed and approved, per Fluent's Q3 progress report. It was agreed to give up on predicting formation and transport of: (a) small bubbles, (b) NO<sub>x</sub>, and (c) soot. As an interim stepping-stone to the full melter, it was

agreed to develop the three-dimensional, one-sixth model with a single burner as described above under Task A, ignoring the small inlet/outlet flows into this rectangular region.

The cumulative Fluent efforts on this project as of the end of the quarter are summarized in Table 1 in terms of labor hours. An Excel spreadsheet file is being submitted to GTI along with this report that provides additional information, prior period data, and graphical charts. Based on the subcontract period of performance (1-May-04 through 31-Jul-06), the Fluent sub-project was 74% complete by schedule at the end of this reporting period.

Table 1. Fluent task status as of 12/31/05

SOW	Task Description	Staff	Budget hours	Actual hours
A.1a	Develop an initial model of the SCM and evaluate performance based on information provided by GTI <i>at project initiation</i> using FLUENT 6.1.	AT	150	179
A.1b	Study design alternatives based on direction from team.		50	0
A.2	Refine and re-run model as more mature design information becomes available	RLC	50	20
A.3a	Support FLUENT use by team members	AT	100	61
A.3b	Provide FLUENT licenses to Schott	ERF	0	2
A.3c	Conduct two-day SCM-focused training workshop at mutually agreed venue	AT	50	33
A.4a	Using enhanced tool from Task B, conduct final CFD analysis of melter, validate with operating data from GTI.		200	0
A.4b	Investigate scale-up to production scale, optimization of design details		100	0
B.1	Identify and prioritize CFD technology gaps and FLUENT enhancements	AD, RLC	80	60
B.2a	Investigate cost/accuracy trade-off; extend and calibrate Eulerian method to represent SCM conditions	HL	100	236
B.2b	Prepare SRS with cost estimates, review with team, finalize and integrate with FLUENT development cycle	AD, ERF, RLC	50	44
B.3a	Implement new SCM features in FLUENT prototype (development version)	AKV	1990	2683
B.3b	Verification testing and draft documentation		300	0
B.3c	Port to team members' platforms and distribute prototype		50	0
B.3d	Obtain suggestions and defect reports from team usage, process validation results from A.4, and incorporate improvements in software		100	0
C.1	Participate in team telecons and 2 one-day team meetings per year	AD, RLC	100	161
C.2	Quarterly technical reports, final report, and technical paper contributions	ERF, AD, RLC	200	89
<b>TOTALS</b>			<b>3670</b>	<b>3568</b>

The Fluent level of effort was relatively low this quarter because charges to the project had begun to exceed the authorized funding. (In January 2006, the Fluent subcontract was amended to formally add the planned Year 3 funding.) With the expended funding at about 70% of the project total, Fluent is now in a position to accelerate efforts for the remainder of the period.

## CFD Work Issues and Resolution

Considerable progress was made on the issues cited last quarter: a reference glass type was established, feed and cooling system characteristics were clarified, the free surface experimental imaging for the pilot melter was specified, and several model improvements were made. Table 2 summarizes the remaining important issues and our plans to resolve them. GTI responded to last quarter’s feedback by initiating procurement of a major computer upgrade for the CFD work.

Table 2. Summary of outstanding CFD issues and resolution plans

Issue	Proposed resolution
1. Batch particle size distribution is unknown	Discuss material specifications with Johns Manville, which is providing the “reference” E-glass for melting tests. Correlate with Alfred Univ. database [1].
2. Temperature at combustion bubble surface may be high enough to induce some glass vaporization and/or new reactions.	Conduct further research to assess the likelihood, and if it occurs, how to approximate in the model.
3. Local batch (solid phase) volume fraction approaches 1.0 at feed inlet, but DPM cannot handle values above 0.1.	Research a hybrid method for batch representation, involving a combination of DPM and an equivalent liquid-phase reaction to simulate melting effects.
4. Obtaining residence time distribution with complete physics is computational cost-prohibitive for this application.	Four-step analysis method as outlined in this report, under Task A. Iterate between steps manually as needed for reasonable efficient approximations.
5. GTI computer resources are inadequate for the full 3D model.	GTI to procure 16-processor Linux cluster for project use.

The representation of the glass batch properties remains partially unresolved. Although the initial pilot tests are expected to use relatively small “instantly melting” particles, in the long run, the plan (and touted advantage) for SCM technology is to enable melting of much larger batch or cullet particles. This pilot-versus-production difference could have very significant effects on the key CFD results and should be investigated if time permits.

## Mathematical Modeling for the Pilot-Scale SCM

With selection of the final design for the pilot-scale melter, CFD modeling cases this quarter focused on energy balances, temperature profiles, and heat transfer evaluation of various melter configurations. A large number of cases have been calculated, but for proprietary reasons, only a few cases are outlined below. Every effort has been made to make assumptions representative of the working melter. Conclusions from running these CFD cases include:

- The best flow patterns (those with particles required to traverse lengthy convective flow loops around the burner) were established around single burners earlier, and temperature distributions and heat loss from walls for these patterns were evaluated.
- Multiple burners are preferred for heat transport, temperature uniformity, and surface splashing reasons

- While particle flow patterns around multiple burners are not as well established (are more chaotic) than around a single burner, multiple burners create acceptable, well-established particle convective flow paths when the burners are physically far enough apart
- Wall effects can be significant on particle flow patterns, and corners on a rectangular melter serve as poorly mixed zones that should be avoided in the melter design

One sample CFD case calculation showing temperature patterns and mixing paths was presented in more detail in the last quarterly report. Variations in temperature and melt viscosity have a significant impact on particle flow patterns and residence time distributions. The heat transfer calculations undertaken this quarter are outlined below. Calculations are still in progress, so no detailed results will be presented here. Detailed results will be presented in the next quarterly report.

### Basis For Heat Transfer Calculations

One-sixth part of pilot melter is considered as a subject of modeling (Fig. 1; The “Horizontal line” is explained in section “Numerical results”). That part of the pilot melter is called “section” below. The section is provided with one burner located at the distance of 15cm (6”) from the cooled wall and at equal distances of 20cm from the side boundaries of the section. For the purpose of estimating the influence of the distance between the burner and the cooled wall on heat loss values, in the last case the burner has been moved at the distance of 30cm (12”) from the wall. The firing rate is 1.5 MMBtu/h. The section is filled with the glass melt with the nominal level of 1m (3 ft).

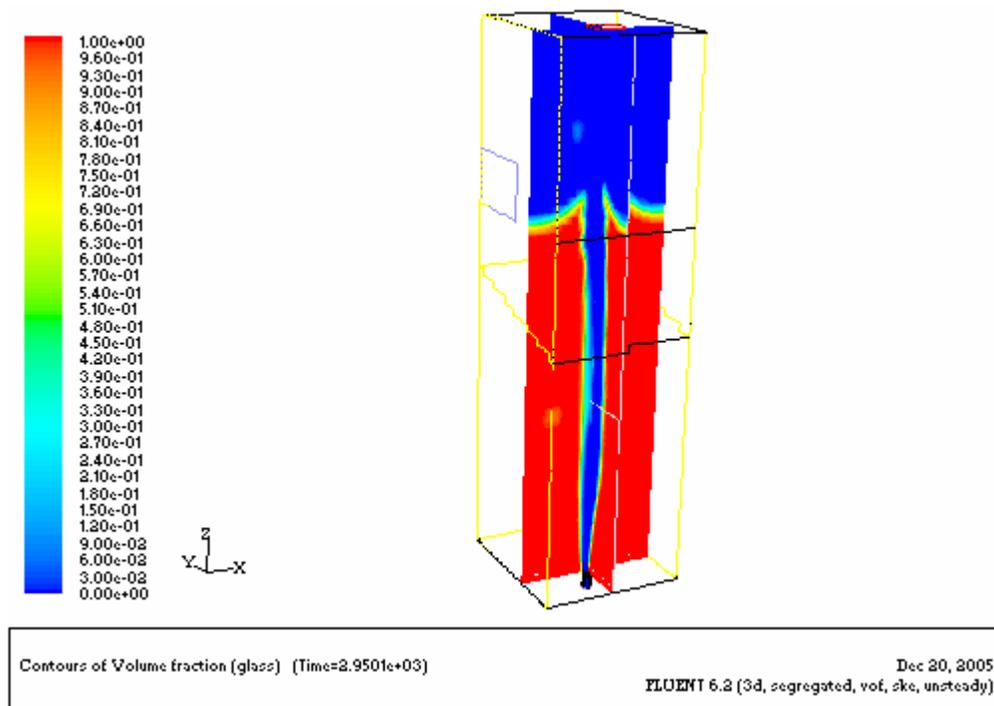


Figure 2. Temperature Profile Calculated Between Burner and Melter Wall

## Main simplifications

The following simplifications have been used:

- 1 Radiation heat transfer has not been considered directly. An effective thermal conductivity has been used instead of that.
- 2 Three planes of symmetry surround the section: one water-cooled wall, water-cooled floor, and water-cooled roof.
- 3 Incoming and outgoing flows of the glass melt of 167 kg/h through rectangular windows in sidewalls are imposed. The incoming flow temperature has been chosen of 1475K based on heat balance analysis to provide reasonable heating of glass in the section.
- 4 Real gas jets have been substituted by jets with artificial physical properties similar to those used in previous models.

Calculations are preliminary at this time on heat transfer. For that reason, calculated values and graphs are not being presented in this quarterly report. Results will be presented in the next quarterly report. A set of interim conclusions have been made, and they are summarized below. These interim conclusions may be changed significantly with more accurate calculations.

### Heat Transfer Calculation Interim Conclusions

1. Average heat loss value of about  $150 \text{ kW/m}^2$  seems to be reasonable estimate for submerged combustion melters.
2. Heat loss values are much greater for the parts of walls below the glass melt level than for those above the glass melt level (approximately  $250 \text{ kW/m}^2$  vs.  $30 \text{ kW/m}^2$ ).
3. Exact “frozen glass” layer cannot be obtained at given glass melt temperature even without refractory.
4. Reachable maximum glass melt viscosity in the boundary layer is only about 1.5 times greater than that for the rest of the melt (200 vs. 140 poises). Much higher viscosity can be reached without refractory, but it results in extremely high and inappropriate heat loss level despite of the fact that glass melt thermal conductivity is much less than the refractory thermal conductivity.
5. Nonexistence of a “frozen glass” layer results in glass melt’s motion near the walls with velocity, which is approximately equal to corresponding value of distance from the wall (5 mm/s at the distance of 5 mm, etc).
6. Since moving glass melt cannot serve an isolator of the refractory from mechanical and chemical influence of the melt, determination of appropriate minimal glass melt viscosity (and/or velocity profile) near the cooled walls becomes a key point of optimal refractory design.

## **Lab-Scale Melter Final Testing**

A series of four melt tests were conducted in the first quarter of 2005: three tests with soda-lime glass and one test with LCD glass. A summary of each test was presented in an earlier quarterly report. The soda-lime glass was made from a typical batch blend provided by CertainTeed, and the LCD batch was a 4-component, non-alkali glass composition provided by Corning, Inc. to GTI. By conducting tests with soda-lime and LCD glass, the project team demonstrated successfully that the SCM unit is capable of melting the lowest temperature 'soft

glass' (soda-lime) to the highest melting temperature 'hard glass' melted industrially. The tests were made in the batch lab melter, and batch feed and melt removal were inconsistent because of the techniques and components used. The project team focused all efforts after these tests on conducting tests with a new platinum discharge pipe and on preparing for installation of the pilot melter with controlled and continuous batch feed and melt discharge. Other activities have included implementation of new safety procedures, additional data collection, and CFD modeling. The CFD and mathematical modeling work is described above. All other work conducted this quarter on the melter is described below.

#### Additional Data Collection

The project team is now using a National Instruments' Labview system for all data collection. This same system will be used for both the lab-scale SCM unit and the new pilot-scale SCM unit currently being designed. All data, including temperatures, pressures, flows, and voltages will be collected and stored. The needed modules were purchased and installed this quarter in preparation for installation of the pilot-scale SCM unit.

One of the most difficult measurements to make is the melt temperature. A normal ceramic coated platinum thermocouple will fail because of the thermal shock experienced during and after an SCM test. The project team ordered a tri-plex thermocouple last quarter that is clad in an outer platinum sheath. This platinum sheath prevents thermal shock failure of the underlying ceramic covering of the thermocouples. The intent is to measure melt temperature by the wall and then at two positions of 2 and 4 inches into the melt. The tri-plex thermocouple was received this quarter and installed.

The tri-plex thermocouple was inserted through a sidewall port into the melt. Initial data was excellent and sheath cracking was avoided. Unfortunately, the thermocouple tip was too close to the oxy-gas flame in the small lab-scale melter. This caused the weld at the tip to fail. The team will redesign the internal thermocouple to enter the melt through the melter crown. This will provide a better thermocouple placement and long sensor life.

#### Rebuilt Burners and New Burner Design

After connecting many tests with the original oxy-gas burners during this project and before this project, one of the burners developed a hole. Examination found that the problem was a result of poor fabrication standards practiced by the Ukrainian machinists. GTI rebuilt both burners with standard pipe and tube components. This ensured that the gaps for the pipe-in-pipe gas and oxygen flows are uniform. Testing showed the new burners operated much more stably than the original burners. Subsequent tests with soda-lime glass found the new burners operate stably over a wide 8:1 turn-down ratio. The new burners worked well and reliably for all tests conducted this quarter.

Burners for a submerged combustion melter should maintain a very stable, short flame. The project engineers felt a modified burner design could improve the stability of the flame and produce a shorter flame. A shorter flame allows more time for combustion products to heat the melt, and are therefore more desirable. Several new burner designs were modeled for mixing patterns, and a reliable, simple design was selected. Detailed engineering drawings were made of this new burner design, and the drawings were sent out for fabrication. The new burner design was tested in the batch SCM unit last quarter. The main feature of the new burner design is to provide faster and more uniform gas-oxygen blending. Results found that the burner

produced a very loud combustion process and no real benefit toward a shorter flame. Testing, did however, indicate ways in which mixing can be improved and the flame can be shortened. A new burner modification was completed this quarter and sent out for fabrication bids. This second burner modification will be built and tested next quarter.

#### New Platinum Discharge Pipe

The project team agreed that a platinum-rhodium discharge tap pipe was the ideal method to remove glass from the submerged combustion melter. This device provides several important advantages over other melt tapping methods. First, the pipe can be heated electrically to precise temperatures, allowing operators the ability to control glass viscosity and flow rate through the pipe. Second, the pipe can shut off glass flow simply by removing electrical heating. Third, restoring electrical heating can restore melt flow. Fourth, the pipe can be extended into the melter beyond the water cooled wall, the refractory layer, and the frozen glass layer on the refractory, so that homogeneous, fully melted glass can be removed through the pipe. Fifth, the operation is much safer and more stable than the previous methods used to remove melt from the SCM unit.

The project team, led by Carsten Weinhold of Schott, designed the new tap piece. A plan was devised to test the new tap piece on the lab-scale SCM unit and to then move it to the new pilot-scale SCM unit. The tap piece will enable the project team to meet one of the primary project goals of obtaining a continuous, controlled product melt stream with any glass composition desired.

Glass companies consider the platinum discharge pipes they use to be proprietary. Therefore, the pipe designed for the SCM was intentionally designed to not conflict with known, proprietary designs. The pipe consists of an outer shell with an inner platinum pipe. The inner pipe extends through the outer pipe in a horizontal position leaving the melter. The inner pipe then undergoes a 90 degree bend and extends downward to a nozzle. Two flanges are used, one against the melter wall and one above the nozzle. The tap piece is set in castable refractory and then encased in insulating bricks held in a steel frame. The pipe is designed for flows up to 660 lb/h. This is sufficient for lab-scale tests. After successful demonstration, the pipe will be modified for flows up to 1500 lb/h when used with the new pilot-scale SCM unit being designed.

Basic drawings for a first pipe design were completed, and the tap was fabricated by the Corning Metal Shop. Owens Corning supplied a transformer to power the pipe and sent engineers to GTI during installation and initial testing. The first test with the new discharge pipe was conducted last quarter with soda-lime batch as the feed.

Unfortunately, the tap piece failed during the first test. The melter was started, and molten glass was started through the tap. But the tap failed almost immediately, with an open circuit. The test was ended, and the tap was disassembled by removing the refractory and examining the pipe. The inspection showed the tap failed at the 90 degree bend. Melt leaves the melter parallel to the floor and then goes through a 90 degree bend to flow vertically downward through a nozzle. The elbow was found to fail, not at the welds, but at the inside of the elbow. Analysis confirmed that the elbow had overheated. No thermocouple was on the elbow, but the bend is clearly the hottest spot on the pipe. Better care needed to be taken to avoid taking the elbow over 2650°F. The photographs below show the tap piece in place on the melter, the tap piece when heated, and the spot where the tap piece failed. The tip of the nozzle can be seen in the first picture just behind one of the coiled green thermocouple wires.



Figure 3. First Tap Piece (a) in place on lab-scale melter, (b) being heated, and (c) after failure from excess heat

The project team realized the tap piece worked but needed to be rebuilt to avoid the hot spot at the elbow. The second tap piece was similar to the first. But the rebuilt piece has a larger internal cross sectional area, has a thermocouple welded to the hot spot at the elbow, and has redesigned flanges for more uniform temperature distribution and avoidance of overheating. The second version of the tap piece was fabricated by Corning from drawings by Schott and installed in the GTI lab-scale melter last quarter.

#### Lab-Scale Testing

Three tests were conducted at the end of last quarter. The first test was with soda-lime glass. The second test was with LCD glass, and the third test was a repeat test with soda-lime glass. Samples were submitted to the laboratory for analyses and will be reported next quarter.

For the first soda-lime test, there were three thermocouples on the tap piece; one on each leg and one at the elbow. The tap worked perfectly and a controlled flow of product glass was obtained as seen in the photograph below from that test. The thermocouples were found to vary significantly, with the elbow thermocouple, as expected, approximately 200°F above the other two thermocouples. In this test, the tri-plex thermocouple showed that glass temperature at the

wall is much lower than glass further inside the chamber, but the glass temperature past the wall boundary layer is uniform.



Figure 4. Soda-Lime Glass Flow From Tap During Melter Operation

The second test was with a high melting point non-alkali LCD glass provided as batch from Corning. The team was able to successfully melt this glass and to collect glass from the tap. Several things were learned in this test. First, the tap needed to be driven to near the operation limit, with the elbow thermocouple at 2675°F. This was expected since the glass has such a high melting point. The tap for the new pilot unit will not have an elbow with the hot spot design, so the team expects to melt LCD glass much more easily. Second, the glass was difficult to remove from the tap nozzle. This is because the nozzle temperature (measured with a pyrometer) is not surrounded with refractory. From the nozzles' top to tapered tip, the temperature decreased by almost 300°C. This will also be addressed in the pilot unit with an insulated tip to avoid heat loss. A torch is used to establish glass flow. Use of the torch and the high temperature the tap nozzle can be seen in the photograph below. The other photograph shows the tap piece after the LCD glass test.



Figure 5. LCD Glass Flowing From Tap and Tap After LCD Melt Test

The third test was made with soda-lime batch. The thermocouples on the vertical and horizontal legs of the tap piece were broken clearing the tap of glass after the LCD test. The third thermocouple, the crucial one at the elbow, remained functional and was used for tap piece control. This test confirmed the ease of operation with soda-lime glass. This test also confirmed that the melt thermocouple must be inserted away from the burners in order to survive

Results from these three tests showed glass could be steadily collected. Product glass analyses found the glass to be homogeneous with no stria or stones. Results also found that no glass components were volatile. Even the most volatile component, sodium, was not volatilized.

Three tests were conducted this quarter. All three tests were made using an E glass batch. The feed was carried out in a batch mode while discharge was continuous for 2 to 4 hours from the tap. The batch compositions charged to the melter included the following -

- E glass - Advantex scrap test (10/6/05)
  - 520 lb - E glass batch
  - 300 lb - Advantex LOI woven scrap
  - 0 lb - NzO tracer
- E glass test (10/18/05)
  - 950 lb - E glass batch
  - 2.2 lb - ZnO tracer
- E glass - E glass matt scrap with high LOI test (11/10/05)
- 815 lb - E glass batch
  - 100 lb - E glass wool matt scrap with high LOI (>16%)
  - 1 lb - ZnO tracer

The tap worked well in all tests. Sampling was carried out every 10 to 30 minutes. Al elements except boron were found to be non-volatile and stable in the melt. Boron was lost from the melt in all three tests. Boron loss of 15 to 35% was observed, and the loss continued as melt was held at temperature. The project team is concerned about boron mobility and will pay attention to this during upcoming pilot-scale melting. Lower melt temperatures, steady instead of batch feeding, and shorter residence times are all expected to provide lower boron

volatilization. Examples of stability of glass components are given for silica composition in the different melts in the plots below. While values showed variability, no trends with longer melter residence time were detected.

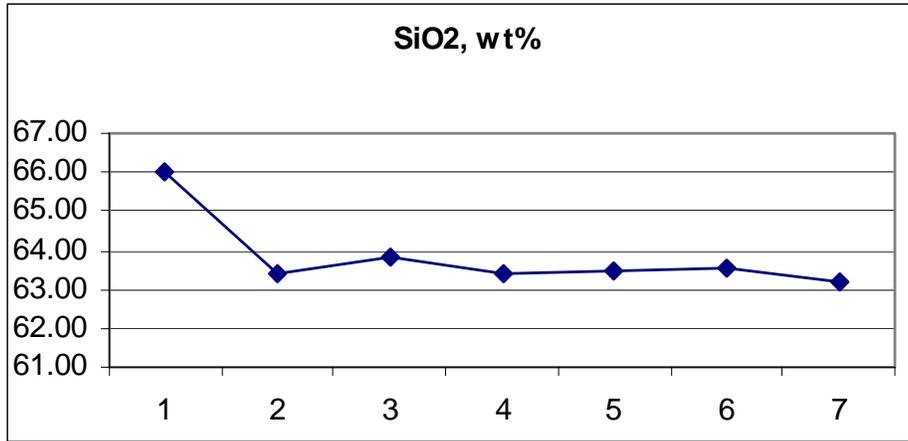


Figure 6. Silica in Product Glass (E Glass Plus Woven Scrap 10/6/05) vs. Time, Samples 30 Min. Apart. Scrap OC Advantex Fiber Added Between Samples 1 and 2

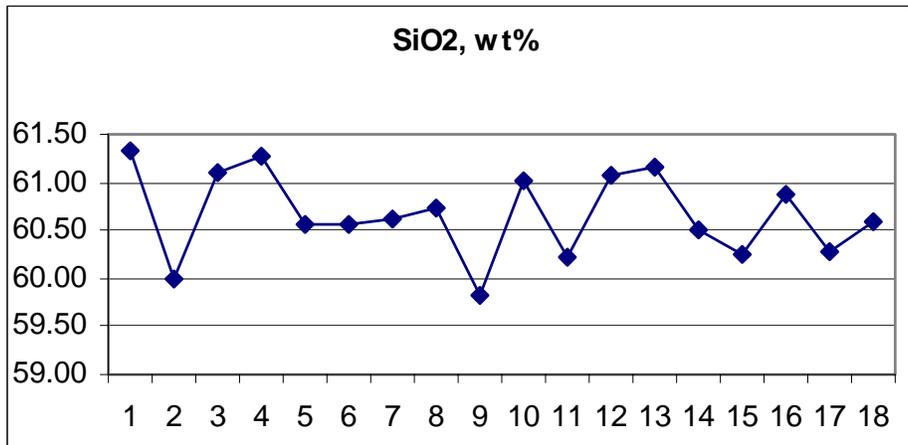


Figure 7. Silica in Product Glass (E Glass 10/18/05) vs. Time, Samples 10 Min. Apart.

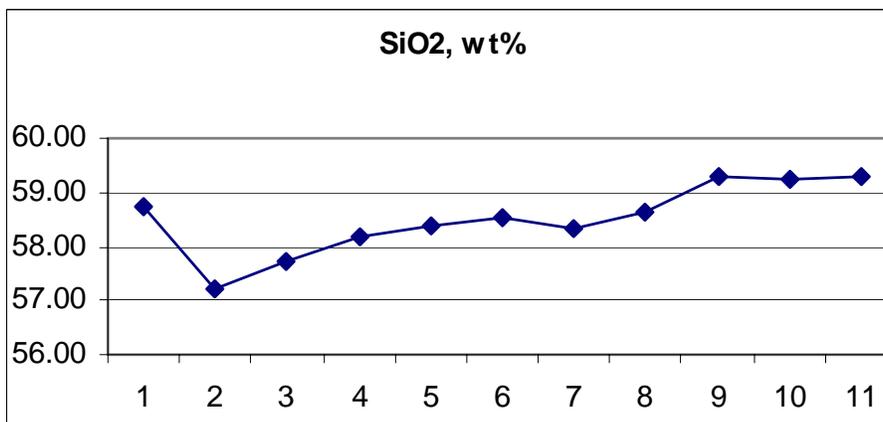


Figure 8. Silica in Product Glass (E Glass Plus E Glass Matt Scrap with High LOI 11/10/05) vs. Time, Samples 10 Min. Apart. Scrap JM Wool Matt Added Between Samples 1 and 2

The final test conducted this quarter was made by melting E glass from batch and adding a high LOI matt scrap (16.5% LOI) made from the same glass composition. The Figure below shows that all product glass samples taken before and after the matt scrap was added have very low LOI. No visible carbon particles were found in the product glass. This is an encouraging result suggesting the submerged combustion melter may be an excellent means to recycle scrap fiberglass back to cullet, no matter how much resin is on the scrap.

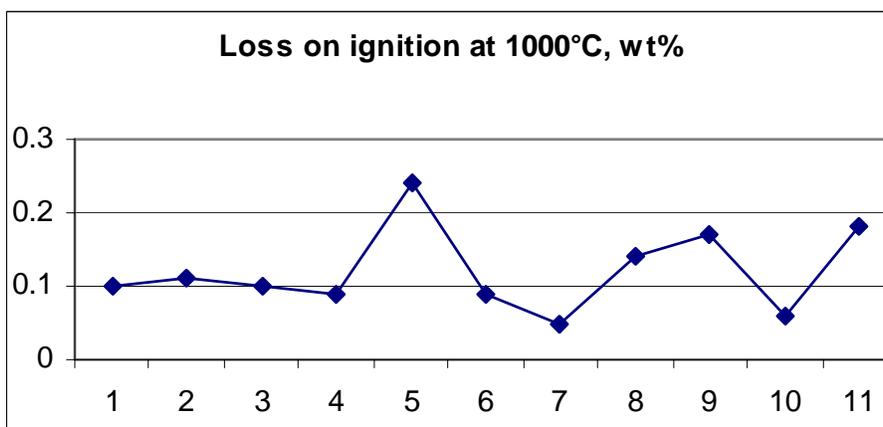


Figure 9. LOI in Product Glass (E Glass Plus E Glass Matt Scrap 11/10/05) vs. Time, Samples 10 Min. Apart. Scrap JM Wool Matt Added Between Samples 1 and 2

### Pilot Melter Design

The project team collected all available information from physical modeling, CFD modeling, lab SCM testing, and Ukrainian experience to provide input for the continuous, pilot SCM design. The consortium team members met this quarter to review preliminary pilot melter designs and to make final modifications. The objective is to design and fabricate a highly flexible 0.5 to 1.0 ton/h SCM unit with continuous feed and continuous melt discharge. The analysis was completed and the final design was selected this quarter. Details of the design will be provided after patent applications have been filed. Presented below are the primary design

parameters selected and the rationale for those selections. Design concept work was completed this quarter, and work was begun on the detailed engineering drawings. The design was intentionally selected to utilize all existing support components installed with the lab-scale SCM unit. The feed system, the exhaust gas system (with fans and baghouse), the utilities supplies (gas, oxygen, electricity, and water), and the data acquisition systems will all be used with only minor modifications. This will simplify and speed installation of the new pilot-scale SCM unit.

The design philosophy behind the pilot-scale SCM unit is:

- Maximum ‘flow element’ path length with no bypass to discharge - Burners must be spaced far enough apart so that convective flow paths form around them and particles (flow elements) do not pass around any of the burners.
- Minimized surface to volume ratio - Since heat is lost from the water-cooled walls and the viscosity is high along the cooled walls (giving poorer mixing zones), the amount of wall surface area is to be as small as possible. This is addressed by choosing the length to width ratio of the tank appropriately.
- Avoidance of ‘corners’ or stagnant zones that concentrate unmelted or poorly melted batch and may serve as sites for devitrification of some glasses - A cylindrical melt tank design is not preferred because particle flow path optimization and heat distribution can not both be optimized. Therefore, a rectangular tank with no 90 degree corners is preferred. This means no 90 degree corners along the sides or where the sides meet the bottom of the melt chamber.
- Maximized symmetry - Symmetry has been shown in both physical and CFD modeling to be a key parameter in optimizing flow patterns in an SCM unit. For that reason, burners will be placed in designed, optimized patterns in the melt chamber, and options will be provided to study different burner patterns as desired.
- Minimized convective heat loss to walls - Convective heat loss is maximized by higher velocity melt close to the melter walls. At the same time, placing burners too far from the walls leads to poor uniformity of temperature across the chamber. To balance these two undesirable conditions, burners must be placed at appropriate distances from the walls, not too close and now too far away. The CFD modeling work is guiding this design parameter.
- Short, intense oxy-gas flame - Oxy-gas flames provide preferred heat transfer when flames are short and very stable. For that reason, burners will be used that meet this criterion. This ensures the combustion is completed in the bottom of the melt, and combustion gases have the needed opportunity to transfer heat to the melt as they pass upward toward the melt surface. Also, stabilized flames prevent burner pulsing and serve as an added feature to prevent melt flowing downward into the burners. Multiple burners are used so that heat is distributed uniformly through the melt, surface area between combustion products and melt is maximized, and kinetic energy of each burner is in the desired range. If kinetic energy is too low, melt particle flow patterns are not established around the burners. If kinetic energy is too high, hot spots are created and excessive melt surface disturbance and splashing occurs.

The pilot-scale SCM will have the following features:

- Capacity of 1000 to 2000 lb/h - capacity will vary for different glass compositions and different melt depths

- Continuous feed - using two different feed systems, one based on dropping batch into the melter and the other based on pushing batch through a horizontal pipe or slot into the melter
- Continuous discharge - using newly designed platinum discharge pipe. The discharge pipe used in the lab-scale SCM tests will be redesigned and rebuilt for the pilot-scale unit so larger flows and more uniform discharge pipe temperature profiles are achieved.
- Operation with wide range of glass batch and batch compositions. The intention is to use three glasses - soda-lime, E glass, and LCD glass as the baseline glasses. Scrap fiberglass, which is of particular interest to the consortium will also be melted.
- Water-cooled walls lined with 1 to 2 inches of high-alumina rammed refractory - with refractory thickness designed to minimize heat loss and to enable a frozen layer of glass to form on the walls during operation
- Fully instrumented with data collection - operation to be in manual mode with data collection to be in automatic mode. Instrumentation includes all flows, voltage and amps to the tap piece, temperatures (including melt temperature), pressures, and melt level.
- Burner firing rate up to 9 MMBtu/h divided among 6 burners - with the tank bottom designed to be removable so that alternative burner patterns can be studied
- Flexibility
  - Multiple feed options
  - Two discharge positions
  - Melt depth from 2 to 4.5 ft
  - Burner pattern of multiple burners
- Full data collection and control through National Instruments Labview interface - extension of the system already in place for the lab-scale SCM unit
- Sensors - A list of the wide range of sensors to be installed on and around the melter is presented below. All data will be digitally collected using Labview software.

Gas and oxygen flow	Into all 6 burners
Gas and oxygen pressure	Into each burner
Water flow	Into each melter panel
Differential pressure	At melter flue exhaust
Melt temperature	Internal thermowell
Temperatures	Gas, oxygen, water, tap, exhaust gas, refractory
Nuclear level gauge	Average bed height
Digital cameras	Melt surface and tap
Voltage, amps	Tap transformer control
Weights	Batch feed rate

## Oxygen Transport Membrane (OTM)

Engineers from Praxair and GTI met this quarter to discuss Praxair's analysis of applying their OTM technology to the NGMS process. After careful technological and economic analysis, Praxair has concluded that OTM is not a competitive means to produce oxygen for SCM or the NGMS process. Other oxygen production methods are more reliable and cost effective. Praxair is preparing a report describing their analysis procedures and results. This report will be completed next quarter.

### Plans for Next Quarter

Work will be carried out next quarter on a number of project activities. The primary focus will be on completing tests in the lab-scale melter, completing detailed engineering drawings of the pilot-scale melter, beginning installations of pilot-scale melter components, and CFD modeling.

**Modeling.** All major activities will continue next quarter by Fluent regarding CFD development. The pilot melter reference model and solution method will be extended as summarized in Table 3, based on the guidance from the CFD Committee. The immediate next step is to finalize the combustion method, ensuring that the corresponding boundary conditions are realistic. The FLUENT development work will target those enhancements that can aid the chosen simulation approach.

Table 3. Pilot melter analysis completion schedule

Two-phase hydrodynamics	Complete
Heat transfer - basic version	Complete
Temperature-dependent viscosity	Complete
Refined water-cooled walls	Complete
Combustion and emissions	Jan-06
Refined radiation model	Feb-06
Third phase: batch transport & dissolution	Mar-06
Melter design variations as needed	Apr-06
Scale-up plant geometry	May-06
Small bubble nucleation & entrainment	Not planned
Melt chemistry	Not planned

Physical modeling work has been halted as the project team focuses on fabrication of the pilot-scale SCM unit, CFD modeling, and final testing in the lab-scale SCM unit. The results from physical modeling have been confirmed by CFD calculations. Additional physical modeling work will be conducted if additional data is needed to confirm design decisions or to validate results from CFD work.

A consultant, Dr. Grigory Aronchik, at GTI is conducting mathematical support for both physical and CFD modeling. CFD modeling will be the main focus of the modeling effort next quarter. The emphasis will be on developing better understanding of wall heat losses, modeling bubbles and combustion chemistry, and improving understanding of heat transfer mechanisms.

Cases will be expanded to incorporate hydrodynamics, glass temperature-viscosity properties, heat balances, temperature profiles, and limited combustion. Temperature-viscosity modeling will be included in the cases for preferred configurations. This modeling will provide important insights into the final configuration of the 2000 lb/h pilot-scale melter (burner positions, exact dimensions, tap discharge location, burner firing rates, etc.). Specific work next quarter in CFD modeling will remain the same as last quarter and will include:

1. Numerical issues running cases using the implemented DO radiation model with the Eulerian multiphase model.
2. Numerical issues of improving turbulence dispersion of bubbles for multiphase models will be researched. The current models for turbulence dispersion may not be adequate and might need some enhancement for this application. Our plan is to conduct a literature survey on the existing models and to develop a new turbulence dispersion model to capture the effects of bubbles on turbulence more accurately.
3. The GAMBIT mesh will continue to be refined as necessary based on the CFD results of the model.
4. A new GAMBIT and FLUENT model will be evaluated and enhanced for the pilot melter being developed. Fluent will work collaboratively with GTI and other consortium members to come up with modeling requirements and the details of the simulations that will be needed. It is expected that both physical modeling and numerical modeling will guide the final design parameters for the pilot melter. The boundary conditions, material properties, and other model parameters for this FLUENT model will be developed jointly by Fluent and the consortium members.
5. The FLUENT model will be refined as the simulation progresses, and may include modifications to the following:
  - burner inlet boundary conditions for air/gas velocity, temperature, mass fractions, etc.
  - boundary conditions for heat transfer on the walls to capture the cooling effects
  - exhaust boundary conditions
  - addition of a batch inlet boundary condition
  - addition of batch melting modeling
  - glass and gas properties

The model will be modified to allow the user to change some of the boundary conditions and material properties. An attempt will be made to capture the effect of radiation using the optically thick assumption (Rosseland approximation).

**Pilot SCM Melter Assembly.** GTI and A.C. Leadbetter designed and constructed the pilot melter system. This system currently uses the lab-scale melter along with other equipment sized from the pilot melter. The larger 1 ton/h melter design concept work was completed last quarter with the start of fabrication drawings. This work was modified this quarter and efforts

next quarter will involve finishing the detailed engineering drawings. Pilot-scale SCM construction is planned for next quarter. This will include the melter, the burners and combustion control system, sensors and control equipment, an improved platinum discharge pipe, and a more reliable feeder system. Shake-down testing will be not next quarter, but the following quarter (early in 2006).

The platinum discharge pipe and the triplex melt thermocouple were tested on the lab-scale melter this quarter. The tap worked well but must be redesigned and re-built next quarter for higher pilot-scale SCM flow rates. The triplex thermocouple will be re-built next quarter to come into the melt from above and provide more reliable readings. The peripheral units (batch hopper, feeder, baghouse, melt removal, sample collection, etc.) were installed last year and are being used in tests with the smaller 300 lb/h SCM unit at GTI. All major support systems, including the oxygen, water, gas, water, electricity, and Labview data collection are now installed and operational. After initial burner shakedown, the smaller, existing lab melter has been used for tests the last two quarters. These small-scale test results, along with physical and CFD modeling results, have been used as input to the pilot SCM design process. The 1 ton/h melter is being designed, fabricated, and installed for much more extensive testing in 2006.

Data processing will continue next quarter. This will include collection and/or translation of relevant SCM papers and publications, further discussions with Prof. Piore when needed (but not planned at present), and calculations and designs by Dr. Olabin of the Gas Institute of Ukraine. Dr. Olabin will continue the 1 ton/h melter design work that is already underway. Articles related to compatible rapid refining techniques will also be collected and reviewed. Calculations will be conducted next quarter to optimize wall design (with refractory) to minimize heat loss and to determine the pluses and minuses of specific burner patterns, mixing patterns, and heat transfer to the melt.

Peripheral questions continue to be evaluated. These include determining any potential for devitrification in the SCM unit and assessing the possibility of metal contamination of the glass by melt reaction with the melt chamber walls. Literature will be reviewed. Experts will be consulted. Lab experiments, if needed, will be set up and carried out, probably by the glass company partners. Devitrification can be minimized by decreasing 'corners' in the melter where glass is not at high temperature and is not moving. The pilot-scale melter design will minimize 'corners' by eliminating all 90 degree angles.

**Testing.** The lab-scale melter (300 lb/h) system with complete feed, discharge, sampling, exhaust gas cleaning, baghouse, and control system will be not be operated next quarter. Tests last quarter and this quarter with the new tap piece included soda-lime, LCD, E, scrap continuous fiber, and scrap matt glasses. The new tap worked very well. All data was collected via Labview software. Samples of product glasses are being analyzed by GTI and several glass company partners (Corning, Owens Corning, Johns Manville). Some of the analyses were completed this quarter. The remaining analyses will be completed next quarter, and all data and test results will be consolidated next quarter.

## **Patents**

GTI holds world-wide rights to the submerged combustion melting technology outside the former Soviet Union. GTI also holds a patent covering portions of the technology. A new patent covering the combustion system used for oxy-gas firing was completed and submitted with the U.S. Patent Office in April, 2004. This can be found under the U.S. Patent Office

Application 20050236747. A new patent application covering SCM design and operation is planned for the next quarter.

The project team has formed a consortium to develop the NGMS technology. GTI has agreed to provide the glass company members of this consortium royalty-free rights to submerged combustion melting for glass production. In return, the glass company consortium members have agreed to support the project with cash, man-hours, testing assistance, modeling, and technical support. Other companies will be able to license the technology from the developing consortium. This arrangement is considered the most efficient means to rapidly develop, commercialize, and disseminate the NGMS and submerged combustion melting technology. The consortium agreement is a blueprint for multiple parties to work together on a technology of value to each of them. Lawyers for team members resolved final points and the agreement is signed and active. This consortium represents the first time such a large segment of the U.S. glass industry has worked together on a project, and a number of issues have been clarified to avoid legal concerns in the future.

**Publications/Presentations**

A number of presentations and papers have been published regarding submerged combustion melting and the NGMS technology. A presentation was made at a GMIC workshop held after the 7<sup>th</sup> International Conference on Glass Fusion held in Rochester, NY in July, 2003. A paper was presented at the second Natural Gas Technology Conference in Phoenix, AZ in February, 2004. A presentation was made at the DOE ITP project review meetings in June, 2004 and September, 2005 (last quarter). An introductory presentation was also made at the DGG, Germany Glass Society, meeting in Nurenburg, Germany in June 2004. A presentation was made at the American Ceramic Society (ACerS) Glass and Optical Materials Division (GOMD) in Port Canavreal, FL in November, 2004. Presentations are planned for the first quarter of 2006 to the management and senior technical staffs of all five glass consortium member companies. These presentations will be made at the glass companies (not at GTI) to focus attention on the project and to expand support for continued NGMS development after completion of this project.

**Milestone Status Table**

This project is divided into twelve Tasks over a three-year period. Tasks 1 through 4 are scheduled for Year 1 (Phase I). Tasks 5 through 8 are scheduled for Year 2 (Phase II). Tasks 9 through 12 are scheduled for Year 3 (Phase III). Project work began this quarter on the Year 3 effort and is expected to be complete on time and budget. Thirteen milestones have been defined covering the full project. Progress toward milestone completion is shown below.

Mile-stone	Milestone Description	Planned Completion	Actual Completion	Comments
1	Initial working CFD model written and tested	Sept. 2005		On-going but complete
2	Design pilot scale melter	June 2004	June 2005	Completed this quarter
3	Procure equipment for pilot scale melter	Sept. 2004		Continued this quarter
4	Fabricate pilot scale melter	March 2005		Completed last Quarter and continuing next quarter for larger pilot

				melter
5	Prepare test plan	March 2005		Completed this quarter
6	Complete pilot scale melting tests and collect samples	July 2005		Completed this quarter
7	Complete all sample analyses	Sept. 2005		Completed this quarter
8	Modify melter as needed	Dec. 2005		Complete April 2006
9	Complete second test series	June 2006		
10	Finalize CFD modeling and physical modeling	Aug. 2006		
11	Complete OTM analysis	June 2006		
12	Complete development plan	Sept. 2006		

### Budget Data

The DOE contract was dated September, 2003, and work began in Oct. of 2003. The NYSERDA contract for co-funding was finalized last quarter. Gas industry co-funding through FERC funds for \$700,000 are in place. The SMP portion of gas industry co-funding is in place during years 2 and 3 of the project. The glass industry consortium has finalized the consortium agreement and billings are continuing based on the planned schedule. GTI has entered into identical contracts with each of the six glass company partners. The overall project budget, and spending to date, is shown below. Only cash funding is shown. In-kind cost-sharing by Praxair, Fluent, and the five glass company partners is not shown.

Phase / Budget Period			Approved Spending, \$K			Actual Spending, \$K		
			DOE Amount	Cost Share	Total	DOE Amount	Cost Share	Total
	From	To						
Year 1	10/03	9/04	1311	850	2161	1192	178	1370
Year 2	10/04	9/05	1335	300	1635	1376	637	2013
Year 3	10/05	9/06	1186	300	1486	228	2	230
<b>Total</b>			<b>3833</b>	<b>1450</b>	<b>5283</b>	<b>2796</b>	<b>817</b>	<b>3613</b>

### References

1. Seward, T.P., and Vascott, T., eds. (2005), *High Temperature Glass Melt Property Database for Process Modeling*, Westerville, Ohio: American Ceramic Society, ISBN 1-57498-225-7.

***High Intensity Plasma Glass Melter***

Gonterman: Plasmelt

GO13093

**QUARTERLY PROGRESS REPORT  
12-31-05**

**Project Title:** High-Intensity Plasma Glass Melter

**Covering Period:** 10/1/05 to 12/31/05

**Date of Report:** January 28, 2006

**Recipient:** Plasmelt Glass Technologies, LLC  
2845 29<sup>th</sup> Street  
Boulder, CO 80301

**Award Number:** DE-FC36-03GO13093

**Subcontractors:** James K. Hayward  
N.Sight Partners, LLC  
Laboratory of Glass Properties, LLC  
Integrex Analytical Laboratories  
Dr. Scott Parker  
Robert Kirkland

**Other Partners:** AGY  
Johns Manville

**Contact(s):** J. Ronald Gonterman, 270-524-5110, [Ron@plasmelt.com](mailto:Ron@plasmelt.com)  
Michael A. Weinstein, 303-530-2727, [Mike@plasmelt.com](mailto:Mike@plasmelt.com)

**Project Team:** Elliott Levine (DOE Glass Industry Liaison)  
Brad Ring (DOE Project Officer)  
Carrie Capps (Project Monitor)  
Beth Dwyer (DOE Contract Officer)  
Matea McCrav (DOE Technical Analyst)

**Project Objective:** Develop an efficient 500 lb / hr transferred arc plasma melting process that can produce high quality glass suitable for processing into a commercial article.

**Background:** The purpose of this project is to demonstrate the energy efficiency and reduced emissions that can be obtained with dual torch DC plasma transferred arc-melting system. Plasmelt Glass Technologies, LLC was formed to solicit and execute the project, which will utilize a full-scale test melter system. The system is similar to the one that was originally constructed by Johns Manville, but Plasmelt has added significant improvements to the torch design and melter system. The original JM design has been shown to achieve melt rates 5 to 10 times faster than conventional gas or electric melting, with improved energy efficiency and reduced emissions. This project began on 7/28/2003.

## **EXECUTIVE SUMMARY**

During the Fourth Quarter, the level of melting trial activity has been significantly increased. Since we are nearing the end of our project funding, we have focused our work on only the most important glass trials to attempt to demonstrate the broader range of glass compositions that can be melted via plasma melting.

Results of many of the recent intensive melting trials have shown that plasma melting is indeed applicable to broader compositional ranges. During the first two years of the Project, Plasmelt has focused most heavily on glasses of interest to its two cost share partners, e.g. E-glass, S-glass, and E-glass fiber scrap. Most of our efforts have targeted these narrow compositional ranges in order to develop and demonstrate as much progress toward a process that is capable of yielding high quality glass with minimal defects that can compare favorably to standard glasses melted using conventional gas/electric technologies. We have indeed demonstrated high glass quality sufficient to be able to fiberize E-glass in a re-melt process at one cost share partner facility.

The work this quarter has included glasses with high alkali, zero boron and fluorine, and high levels of zirconia used in a variety of end-use products and market applications including acid resistance used in battery separator mats, alkali resistance used in concrete applications, low emissions fiberglass reinforcements, low dielectrical glass used in electronics, microfiber filtration glass, lighting glass, and a mineral composition used in a wide variety of end user applications. Each of these glasses was batched in Boulder with a rented Eirich mixer to avoid any problems with batch segregation during transport of the mixed batch. The objective of each of these melts was to attempt a 100 - 150 #/hr melt trial to evaluate the melting performance and glass quality.

Although each reconnaissance trial of each glass only lasted 1 to 2 days (due to limited funds), we have gained insight into the breadth of glasses that can be melted with minimal efforts as well as other more challenging glasses that do melt and give on-composition glasses—but with less quality than is required. For these latter more challenging glasses, it is our opinion that further focused process development and further optimization of these glasses can yield successes comparable to our successful efforts on E-glass.

A final DOE report will be written before the official end of this project on 7/27/06.

**<End of Executive Summary>**

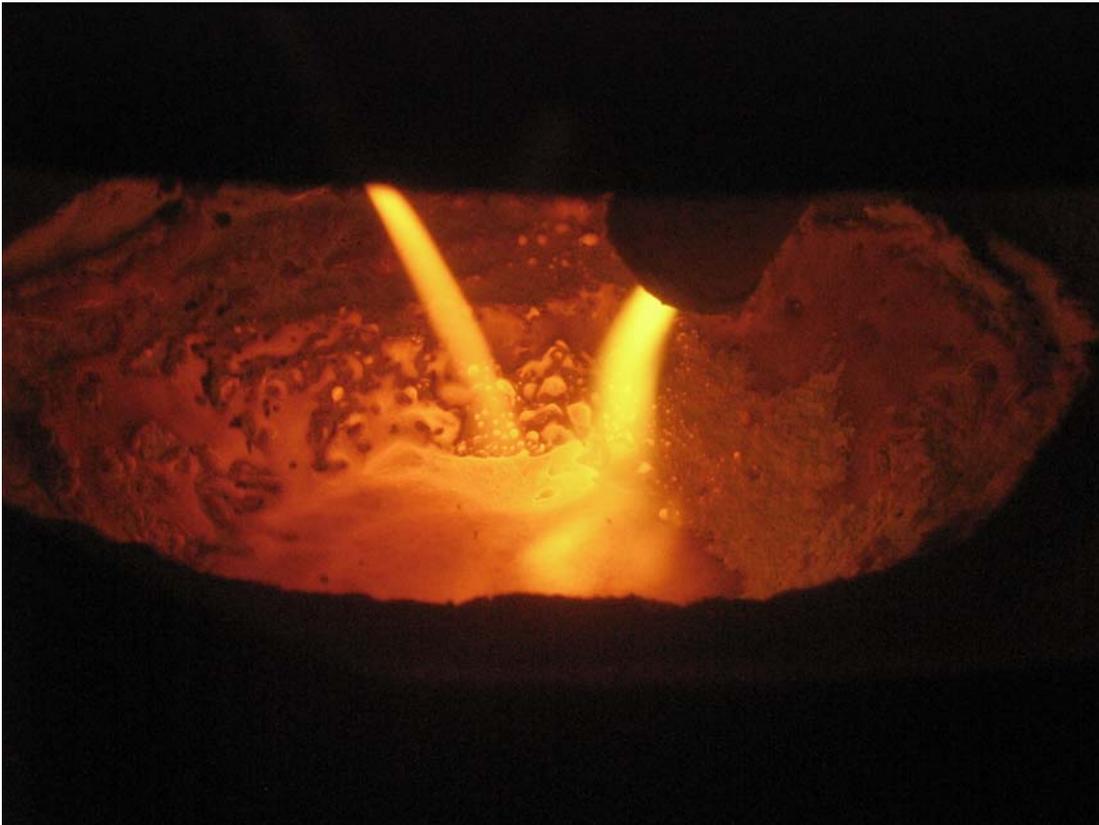
## TECHNICAL CHALLENGES

From the previous Johns Manville work, several critical technical obstacles were known to exist with the plasma-based glass-melting process:

- I. Torch life and stability
- II. Glass Quality
- III. Maximum throughput of the melter system
- IV. Energy efficiency

### I. Torch Life and Stability

Torch lives are influenced by both design and operation. Our intensive screening process has yielded a design for a 5/8" diameter torch that shows good stability and reliability. This design has been designated the "standard 5/8 torch" and is now being used for all glass melting experiments. High potential has been shown for this design to be capable of producing 250-350 #/hr of E-glass. Based on trial results, higher glass melting throughputs up to 500 #/hr will likely require modifications to a larger diameter torch. A new design 3/4 inch torch has been initially tested. Although it shows promise in its early stage of development, there is still much work to be done to fine tune this design. The current melting operation using the baseline torch designs is shown below:



**Plasma Torches in S-Glass Melting Operation**

Initially, a goal of 100 hours of torch life was established for the project. Thus far, incremental improvements to design and major improvements to the operation have currently evolved to a torch with a demonstrated life of more than 20 + hours. Several of these torches were still in good operating condition when they were removed from service. Many of the life improvements made thus far relate to the operation of the torches. Several process configurations have been identified that can significantly shorten the torch life and cause premature failures. We continue to improve our understanding of the relationship between this torch operation and energy efficiency, heat transfer, batch bowl configuration, proximity of the torch tips to the batch pile, separation of the torches from each other, and the power settings. Even with our improved understanding, there remains a significant technical challenge to reach the 100-hour goal.

## **II. Glass Quality**

### **4<sup>th</sup> Quarter, 2005--EXPLORATORY GLASS MELTING TRIALS**

A broad range of glass compositions was melted in the plasma melter. The purpose of these trials was to establish compositions that are good candidates for plasma melting and to understand the limitations of other compositions. Trials were run for one to three days for each on the following compositions:

- S-glass—a high strength glass fiber composition; one trial run 11-3-05.
- C-glass—a fiberglass composition known to have good chemical resistance to mineral acids; two trial runs conducted on Saturday 11-5-05.
- Low DK glass—a composition, which is known to have low dielectric constant and low dissipation factors, that is useful to the electronics industry; two runs conducted on 11-8 and 11-9-05.
- AR-glass—a fiberglass composition known to have good resistance to highly alkaline environments such as concrete reinforcement; two runs conducted on 11-7 and 11-8-05.
- Low Flux E-glass without boron & fluorine—an E-type fiberglass composition that is being used in the fiberglass industry to lower emissions and batch costs; one run conducted on 11-7-05.
- B-glass—a composition used for fine fiber that is known to possess good properties for micro-filtration products; three runs conducted on 11-10 and 11-11-05.

All glasses melted well and drained from the plasma melter. The quality of the glasses ranged from high quality (on-target chemical composition, no visible batch stones, minor-to-zero cord) to low quality (high levels of unmelted batch and/or melt segregation with evidence of abundant silica scum formation and cord). For perspective, it should be noted that we have been working with the plasma melter to optimize the melting of E-glass for approximately one year before we successfully demonstrated high quality E-glass fibers. It has become evident to us that the plasma melter's operational parameters

must be tailored to accommodate the different compositions with their different melting characteristics. Each glass has its own requirements and therefore, each time a new composition is melted, the optimal process setup on the melter must be determined through trial and error. These trials may require several iterations. So, to be able to demonstrate a successful high quality glass trial upon the first attempt is remarkable. Likewise, not being able to demonstrate such high quality glass in one or two days has no real strategic significance.

We remain optimistic that each of these more challenging glasses can be successfully melted via plasma melting if sufficient time is invested in optimizing the melter setup and the glass formulations. However, due to the short time remaining on our funded project, we plan no such further DOE Project Trials.

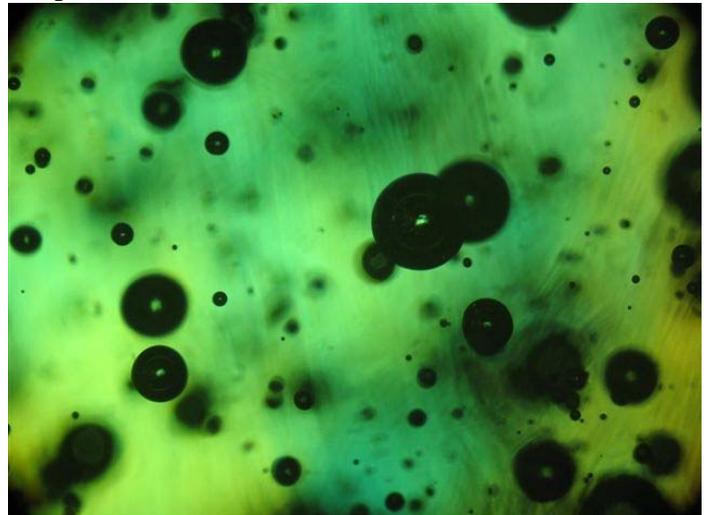


**C-GLASS**—Melting trials were conducted on Saturday, 11-5-05. Within the experimental process conditions used, the first glass stream appeared within two minutes after light off and good quality glass samples were produced using the standard process setup protocols. Each glass patty was examined with a polarized light microscope to document the levels of batch stones and cordiness. Overall, the quality of the C-glasses was high, although it was seedy.



**C-glass patties collected during 11-5-05 melting trial**

Petrographic analysis showed that these C-glass patties contained no batch stones or other crystalline material. Abundant seeds are in evidence. Some minor cordiness is present. Overall, the glass ran well and was of good quality. We believe this glass was of a comparable quality to the E-glass that was successfully fiberized earlier in the year.



**C-glass photomicrograph @ 40X showing overall good quality with low levels of cord, zero batch stones, and abundant seeds**

**AR GLASS**—Trials were conducted using a commercially available composition for AR Glass. Several other versions are also commercially available. AR Glass is known to devitrify easily during production operations, so care must be exercised to keep the cooling rates high to avoid crystallization of the glass during the draining operations. Overall, the glass melted and drained acceptably.

During the first of two runs, considerable difficulty was encountered with the torch operations. Two outages of the torches were traced to unstable purge gas flow through an error in the construction of the torch orifices. After correcting the problem, the torches

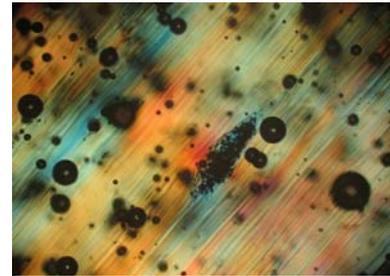
were re-lit and proceeded to melt with no further issues. These torch issues were unrelated to AR Glass.

Glass quality, as determined by petrographic inspection, was generally poor under the melter setup conditions that we used. Unusually high corrosion of the moly orifice materials was in evidence and was exhibited as reddish-streaked moly-contaminated glass, especially abundant upon startup. As the run progressed and glass began to flow routinely, the reddish glass ceased. The  $\text{MoO}_3$  content at normal glass throughputs was determined to be only 50 ppm. Therefore, during the routine melting it appears that moly contents are no greater than the range demonstrated previously on E-glass. Startup seems to be the only issue.



**AR Glass showing oxidized molybdenum from startup glass**

Glass quality was poor throughout the run. Numerous examples of incompletely melted batch were in evidence in most glass samples. The fine streaks of cordy glass typically contained abundant unmelted zircon grains. (Zircon is a batch ingredient used to supply zirconia to the AR Glass formulation.) The root cause of the poor glass from this run is not known, but can be determined in follow-up runs. Suspects include incomplete mixing of the batch as well as short-circuiting in the melter due to an un-optimized process setup for this unusual composition. On a positive note, there was no evidence of devitrified glass even though this glass is well known to have a high crystal growth rate below the liquidus temperature.

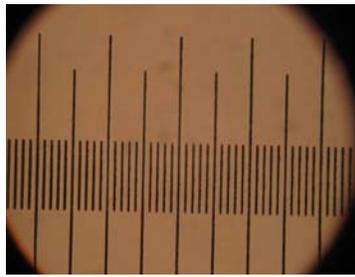


**Photomicrograph @ 40X showing multiple cords, seeds, and unmelted batch stones**

**LOW FLUX E-GLASS** without boron/fluorine—This glass is currently receiving high interest from several companies in the fiberglass industry since it has lower batch costs and emissions. During the one trial run conducted on 11-7-05, we never truly achieve a stable process setup so the run itself is not truly indicative of the ability of the plasma melter to successfully melt and drain a low-flux E-glass. Instabilities exhibited themselves as fluctuating glass head, torch instabilities, surging glass throughput rates, and temperature fluctuations.



**Low Flux E-glass showing clusters of unmelted batch silica grains (cristobalite)**



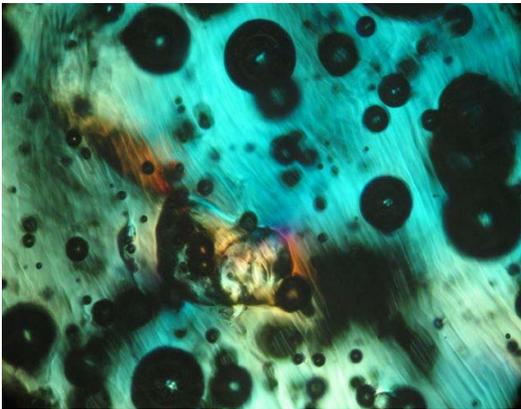
**Reference scale with each division = 0.01mm**

All of these process problems allow glass to short circuit the melter. It is predictable that the glass samples produced during these runs had quality problems from batch stones, cords, and very high seed

levels. There were brief periods during the trial of significantly improved glass quality, especially for the first portion of the melting trial. This trial should be re-done before any meaningful conclusions can be drawn.

**S2 GLASS**—A trial was conducted on S2 Glass on 11-3-05. Earlier S2 Glass trials have been conducted in which severe silica scum buildup became worse over time, resulting in serious cristobalite scum defects being continuously fed thru the drain orifice. Although the mechanism is not proven, it is our working hypothesis that the high plasma temperatures result in a very hot surface layer of glass that allows premature melting of the individual ingredients in S-glass---magnesite, alumina, and silica. Premature melting does not allow good mixing and the normal glass chemical reactions. Since fused silica has a lower density than S-glass, the high silica scum tends to rise to the surface and float on the melt pool. Once a scum layer is formed, it is virtually impossible to recover from this seriously segregated condition. Prevention of scum formation is the key.

The other possible mechanism is that the mixed S Glass batch has segregated in the barrels during transit from South Carolina to Colorado. Segregations of silica flour may contribute to high silica glass, which could also be continuously fed to the exit orifice to generate never-ending batch defects. To test this latter mechanism, we remixed the S2 mixed batch barrels in the Eirich mixer. If segregation was important, this re-mixing should prevent any further silica stoning.



**S2 Glass photomicrograph @ 40X showing cristobalite (silica) scum**

Results were no different from this re-blended S Glass batch than from standard South Carolina drummed batch. Numerous cristobalite stones were present in the Eirich-mixed batch. Batch segregation is not responsible for any of the silica scum problems with S Glass. We have concluded that the silica segregation due to the premature melting of silica flour is the over-riding mechanism causing the high incidence of silica (cristobalite) defects in S Glass.

**LOW DK FIBERGLASS**—Several fiberglass companies have developed or are developing commercial versions of a low dielectric glassfiber for use in electronics applications. We selected one composition that is sold in the marketplace and conducted a melting trial.

The selected glass is a very high boron (20-24% B<sub>2</sub>O<sub>3</sub>) version that is designed to have a low loss factor (i.e. low permittivity) and a low DK (dielectric constant). Since this glass had such high boron content, we elected to evaluate two different batch formulations with

different borates—boric acid and Vitribor (both materials produced and supplied by US Borax). These two melting trials were conducted on 11-8 and 11-9-06.

The glass melted and began draining in 6 minutes from start up. It became immediately apparent that the corrosion rate with the molybdenum orifice was very high, resulting in substantial quantities of black or streaked glass. High effluent was in evidence from the melter as the boron escaped as both particulates and volatiles. A stack plume was visible.

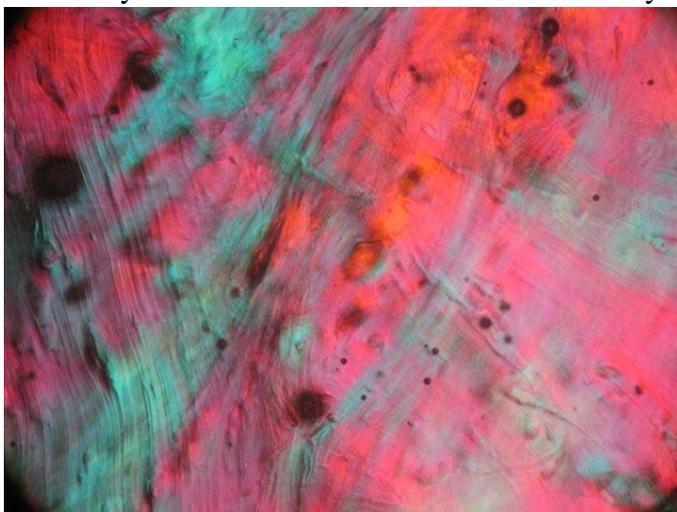
Early in this trial, we discovered a leaking water jacket in the melter, which was allowing water (steam) to be added continuously to the melter atmosphere and batch. However, the quantity was so low that we deemed the operation safe. The trials were continued with this leak without further incident.



**Suite of Low DK Glass patties produced during the plasma melting trial**

The suite of glass patty samples shows the range of streaked and black discoloration caused by moly corrosion. Even the best patties had some contamination. The worst were totally opaque. The exact corrosion mechanism is not understood.

Petrographic analyses were performed on all glass patties. The glass was the lowest quality of any glass ever melted in the plasma melter. Abundant unmelted batch, scum, and heavy cord were much in evidence. The only redeeming attribute of this glass was its near zero seed level.

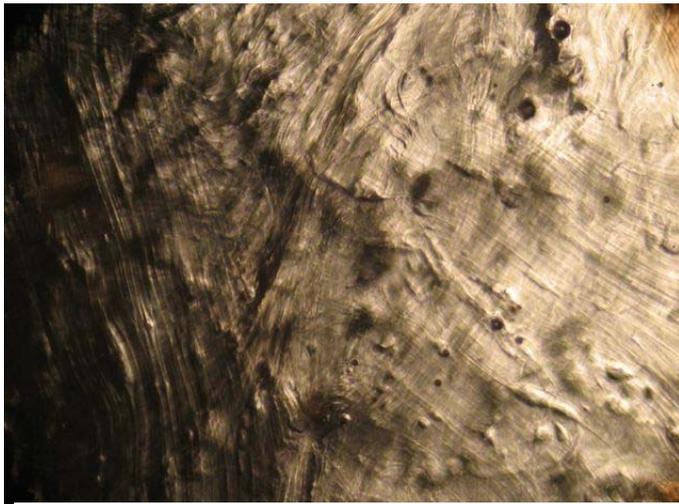


**Low DK Glass photomicrograph @ 40X with crossed nicols**

This glass was, by far, the lowest seed level of any glass ever melted in the plasma melter.

Photomicrographs of the glass patties showed a chaotic complex mixture of heavy cord and unmelted crystals from batch as well as scum. This photo was taken under crossed polarized light and shows the highly

stressed cordy condition of the glass.



**Low DK Glass photomicrograph @ 40 X with plane polarized light**

This photomicrograph was taken (same area as above) with a plane polarized collimated light source to highlight the cordiness and high relief, resulting in the tremendous differences in the refractive index of the glass.

**CONCLUSIONS FROM THE LOW DK GLASS TRIALS**—Results of this glass trial were poor and we were unable to conduct a side-by-side comparison between the two borate sources. Too many extraneous factors prevented a good comparison. The high boron content of this glass renders it unsuitable to be melted in a hot top glass melter. The high surface temperatures of the plasma melting unit cause severe melt segregation, high volatilization and cordiness, and poor quality glass. Significant modifications must be made to the process before this family of compositions can be successfully melted using the plasma concept.

But, we only attempted this glass melting trial for about one hour, so more work should be conducted before a final conclusion is drawn.

### **OVERALL CONCLUSIONS OF THE MELTING TRIALS OF EXPERIMENTAL GLASSES**

1. The plasma melter can successfully melt a broad range of glasses compositions. The process setup for the melter must be tailored to the individual idiosyncrasies of each glass. One setup (such as the typical E-glass process setup) is not suitable for other glasses of different melting characteristics.
2. Both E-glass and C-glass can be easily melted with a quality that is suitable for successful low-break fiberizing. Further process development is needed to establish the highest throughput and most energy efficient configuration for these two glasses.
3. High sodium glasses can be successfully melted in the plasma melter. Soda retentions of 99% have been demonstrated for some glasses containing high alkali levels (e.g. 12%

Na<sub>2</sub>O). This represents a key breakthrough, since earlier experiments with plasma melts had suggested very high alkali losses exceeding 50%.

4. Glasses containing high melting components (such as zircon, alumina, magnesia) are susceptible to melt segregation. The plasma melter operating conditions must be further optimized to produce fiberizable high-quality glass. Examples of these glasses include AR, S Glass, and Low Flux E-glass.

5. For the plasma melter to successfully melt glasses with a high boron >20% or other highly fluxed glasses (such as frits), further plasma melting process modifications must be made to reduce melt segregation and volatilization. This work is beyond the scope of this project but will be pursued later with private funding. We remain optimistic that there is a solution to this issue.

6. Based on these results to date, it is clear that the plasma melter concept applies to a wide variety of glass compositions and formulations. Some can be successfully melted easily with the melter process setup similar to the "E-glass configuration", whereas other compositions and formulations require significant modification to the setup.

### **QUALITY OF E-GLASS THAT WAS MELTED AND FIBERIZED—Previously Reported Work**

Certainly, one of the most important technical challenges of this program is to demonstrate the potential for producing the best quality glass from the plasma melting process without the need for downstream refining and processing. The development of further refining processes is beyond the scope of this project. Although there is a finite probability that a separate refining process step will be required for plasma-melted glass to achieve the highest quality of glass, the goal of this program is to make this determination based on glass quality data and to quantify how much refining is actually accomplished within the plasma melter itself.

During the second quarter, we have completed a major glass quality evaluation of the plasma-melted glass. During two extended E-glass plasma-melting runs on April 11 and 12, 2005, several hundred pounds of glass were melted and formed into nuggets. These nuggets were shipped to AGY's facility for subsequent fiberizing trials.

### **AGY FIBERIZING EXPERIMENTS**

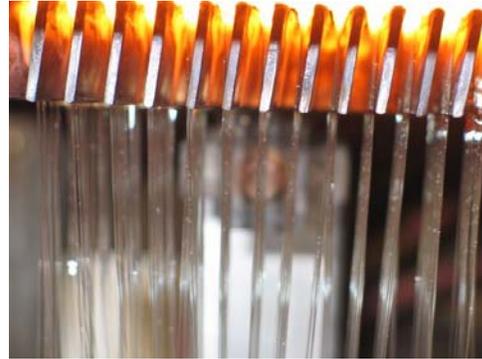
There are numerous lab techniques and numerous approaches to defining and characterizing glass quality. However, in our experience, one of the more stringent, practical, and relevant tests is to continuously fiberize glasses in small diameter multi-hole bushings as are commonly used in the production of continuous filament commercial fiberglass. The stresses encountered during attenuation are sufficiently large that any discrete micro-defects from seeds, stones, or cords will cause the strength level of the fibers to be exceeded and the filaments to suffer breakages and interruptions to the process. In short, this fiberizing process is an excellent metric of glass quality.

Since the two cost share partners for the High Intensity Plasma Glass Melter are both fiberglass companies, we initially have elected to use this method of characterizing the quality of the glass. One of the cost share partners, AGY, has agreed to conduct these trials in their commercial facility. Their commercial fiberizing process currently uses E-glass marbles, which are re-melted in single-position melters / bushings. Since this commercial process is currently set up to automatically process bulk containers of marbles, the nuggets were used as a marble-substitute to conduct these trials.

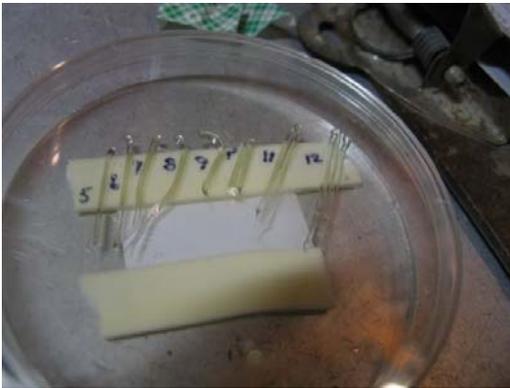
### **FIBERIZING TRIAL RESULTS**

E-glass nuggets were re-melted and fiberized in AGY's Huntingdon, PA commercial fiber forming facility. A team of AGY and Plasmelt representatives were on-site to coordinate and monitor these fiberizing trials, which were conducted on April 27 and 28, 2005.

Nuggets were fed to a marble re-melt bushing for more than 15 hours. Fiberizing was continuously conducted.

**Nuggets Produced in Boulder Lab****Close-up of Fibers Being Formed**

The fiberizing position was continuously monitored by at least one team member. Interruptions were logged. These interruptions can be caused either by a non-glass related process origin or a defect in the glass. Glass defects can often times be retrieved if a skilled operator is able to witness and collect the bead containing the defect. During these fiberizing trials, all glass beads associated with these interruptions were collected and inspected via a polarizing microscope.

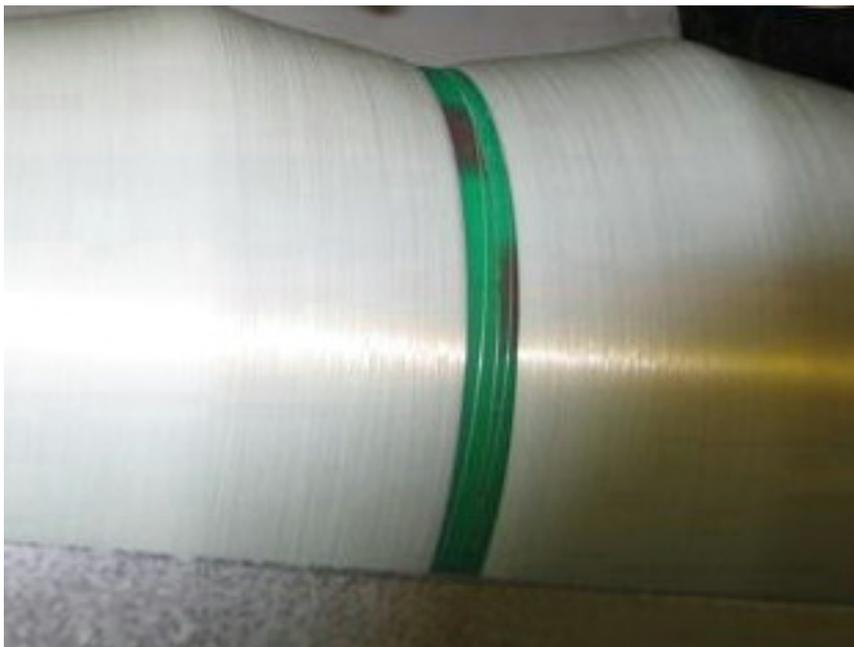
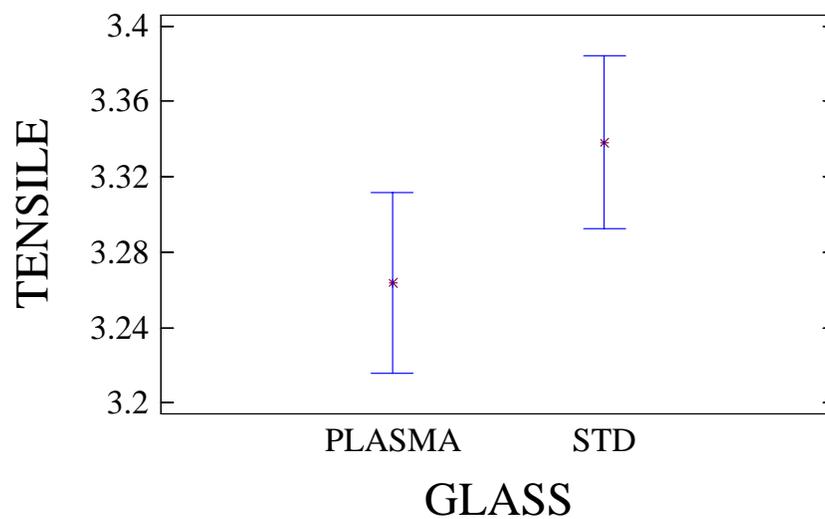
**Glass Beads with Defects Collected During Fiberizing Trials**

### **HUNTINGDON FIBERIZING TRIAL RESULTS**

- Coarse filament products greater than 10 microns in diameter ran without breaking.
- Fine filament products (5 to 6 microns) ran with high breaks.
- Intermediate products (7 to 9 microns) ran with moderate breaks.
- Several full fiber packages were made on 7 and 10 micron products.
- All microscopic inspections showed that the breaks were caused by beading -- all identifiable bead breaks were caused by seeds.

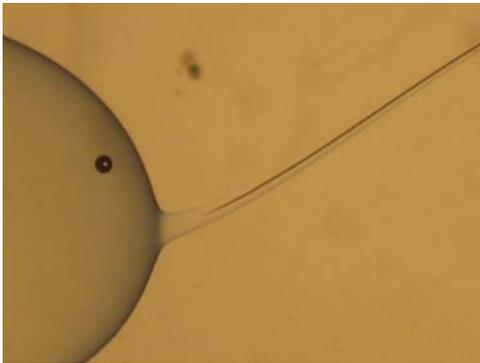
### **TENSILE STRENGTH TESTING SHOWED NO STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN PLASMA-MELTED GLASS AND STANDARD GLASS**

### Means and 95.0 Percent LSD Intervals



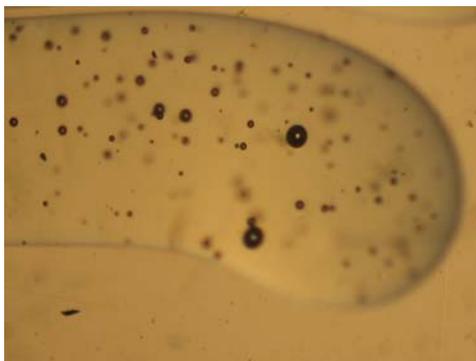
**FIBERGLASS YARNS WOUND ONTO FORMING PACKAGES USED TO TEST TENSILE STRENGTH OF PLASMA-MELTED GLASSFIBERS**

*TYPICAL SEED BREAKS AS STUDIED BY MICROSCOPIC ANALYSIS  
(100x magnification)*



***DARK LINES IN FIBER TIPS ARE HOLLOW FILAMENTS (seeds/bubbles)  
THAT LIKELY CAUSED THE FIBER BREAKOUT***

- There was no evidence of batch stones, devitrification, refractory, or molybdenum metal in any of the beads collected during the study.
- Seed levels were very high. Seed checks done in the Huntingdon Lab on four samples ranged from an estimated 800 to 3,000 or 4,000 seeds/oz.



***HIGH SEED LEVELS OF TYPICAL E-GLASS BEADS***

**UNANNEALED NUGGETS PRODUCED ON 4/11 SHOWING TENDENCY TO EXPLODE UPON HEATUP**



- The plasma-melted glass is known to be high in seeds due to the very short dwell time of molten glass in the plasma melter.
  - The 4/11/05 unannealed nuggets had a tendency to fracture and explode as they were re-heated in the marble boot
- Nuggets made in Boulder on 4/12/05, which were partially annealed, were less susceptible to thermal shock during re-heating in the marble melter.
  - These nuggets were generally acceptable for the re-melt process in Huntingdon.

### IMPLICATIONS OF AGY FIBERIZING TRIAL RESULTS:

- In order to improve energy efficiency and to understand the relationship between melter operation and glass quality, the higher throughput trials that were previously planned for the plasma melter are the next logical step.
- As the first attempt to fiberize plasma-melted glass, this trial is successful. To our knowledge, no other company in the world has successfully made continuous glass fibers from plasma melted glass, i.e. neither the previous Johns Manville project nor efforts related to an extensive and costly program that was conducted in the late '90s by British Glass.
- **The major barrier to glass quality during this trial was high seeds. Thus, the need to conduct the refining project, as proposed to DOE by Plasmelt-AGY-GAF is now conclusively supported with trial data.**
- The absence of batch stones, moly, or devitrification or any other defects in this plasma-melted glass is very encouraging.
- The tensile testing results, which showed that the plasma-melted glass and the glass melted in standard production operations, indicate that the glass quality is acceptable for some products made with continuous fiber forming operations.
- The encouraging E-glass results form a good foundation upon which to build for the upcoming S-2 Glass nugget runs that have been requested by AGY as their next technical priority.

### CHEMICAL ANALYSIS OF NUGGETS

In order to document the glass composition of the nuggets used in these fiberizing trials, several lots of glass were submitted for chemical analysis, which was performed at the Integrex Labs in Granville, OH. Results of these analyses are shown in the table below.

Time of Production	Plasma-Melted E-glass Produced in Boulder, CO Lab					"STANDARD" E-glass
	4:38 - 4:52 PM	5:54 - 6:09 PM	6:54 - 7:05 PM	7:51 - 8:00 PM	8:55 - 9:09 PM	
SiO <sub>2</sub>	54.39	--	54.32	--	54.27	<b>53.55</b>
Fe <sub>2</sub> O <sub>3</sub>	0.279	--	0.279	--	0.278	<b>0.26</b>
FeO	0.133	--	0.133	--	0.127	<b>0.09</b>
TiO <sub>2</sub>	0.57	--	0.57	--	0.57	<b>0.58</b>
Al <sub>2</sub> O <sub>3</sub>	15.06	--	15.01	--	15.00	<b>14.78</b>
Cr <sub>2</sub> O <sub>3</sub>	0.01	--	0.01	--	0.01	
CaO	23.05	--	22.91	--	23.07	<b>22.35</b>
SrO	0.167	--	0.166	--	0.165	
MgO	0.52	--	0.52	--	0.51	<b>0.52</b>
Na <sub>2</sub> O	0.33	--	0.37	--	0.37	<b>0.64</b>
K <sub>2</sub> O	0.03	--	0.04	--	0.03	
Fluorine	0.21	0.25	0.27	0.29	0.30	<b>0.45</b>
B <sub>2</sub> O <sub>3</sub>	5.42	5.56	5.57	5.66	5.67	<b>6.94</b>
MoO <sub>3</sub>	0.0054	0.0079	0.0049	0.0043	0.0082	
CuO	0.004	0.005	0.005	0.004	0.004	
SO <sub>3</sub>	<0.01	--	<0.01	--	<0.01	

**NOTE: All values are expressed as weight %.**

Results of these analyses indicate:

1. The plasma-produced glass is “on-composition,” except for a somewhat greater depletion of volatile components: boron, fluorine, and alkali.
2. In these results, there is a slight trend to lose more volatiles early in the glass melting run and less as the whole melting system reaches more of a steady state later in the run after 3 to 4 hours of operation.
3. Compared to standard glass melted in traditional melters, the plasma-melted glass is slightly more reduced as shown by the presence of higher levels of FeO.
4. The level of trace metals from the process is monitored by the MoO<sub>3</sub> and CuO levels. These metals are present in the 0.004 to 0.008% level in the glass.

After the completion of the AGY E-glass fiberizing trials, we held a planning meeting with them to review their trial results and to outline the next steps. AGY has requested that Plasmelt’s emphasis should now shift from E-glass high throughput to S-glass melting. This shift involves having Plasmelt conduct several reconnaissance melting trials in order to define the process setup that will allow S-glass to be melted and subsequently fiberized with the same good glass quality as was demonstrated in the E-glass work.

We have now begun these S-glass reconnaissance trials. Preliminary results show that greater than 200 pounds per hour is achievable, but glass quality is inferior due to the formation of a high silica scum on the melt surface. This scum is continuously feeding high silica defects into the melt pool, which results in all of the S-glass patties having a high number of cristobalite (SiO<sub>2</sub>) defects. We continue to perform melting experiments to help understand and circumvent this melt segregation problem. Alternate raw materials are being explored as a means to avoid unwanted silica scum formation.

Exploratory melting trials have also been conducted on other glasses of interest to the glass industry. One such trial was made of a lighting tube glass composition. These exploratory trials did result in a limited quantity of off-composition glass being produced. Chemical analysis showed this glass to be seriously depleted in the volatile components such as Na<sub>2</sub>O, K<sub>2</sub>O, and B<sub>2</sub>O<sub>3</sub>. The basic issue with melting this glass is that its viscosity was very high and flow out the orifice was impeded. Additional melting time and temperature was provided to the melt while the optimal orifice diameter was being determined. This additional time/temperature no doubt played a major role in depleting the volatiles and other runs are being planned to test this hypothesis. We are currently reviewing these trial details to arrive at an understanding of the cause and effect. Further trials with this composition are planned for later this quarter to demonstrate that a change in the plasma-melting process setup can retain more of these volatiles. We also will perform additional, albeit limited, trials of additional glass compositions of interest to the glass industry as we continue our goals of demonstrating wide applicability of this melting technology to the US glass industry. Our current level of funding does not allow any extensive investigation into these other compositions, however.

### **III. Maximum Throughput of the Melter**

All of the initial E-glass melting trials have been conducted in the 50-350 #/hr range. The method used for establishing throughput is by hand collecting patties, annealing, then weighing. These patties are collected for known times in the 15 second to 60 second range. Pull control is generally established by selecting the appropriate diameter of the opening of the fixed orifice, by the viscosity curve of the glass, and by the glass temperatures. Since most runs have been made with E-glass with a fixed batch chemistry, the only indirect control on glass flow rate through the orifice is by controlling temperature of the glass near the orifice.

Early trials have established the ability of the process to deliver exit glass with temperatures as high as ~3300°F. These conditions are achieved by some combination of power level through the torches, torch proximity to the batch / glass, and the torch-to-torch spacing. Within the throughput range that is being used in this process, batch feed-rate also has some influence, albeit a secondary one.

At this time, a “hands-off” process has been demonstrated in excess of 6 hours on several occasions. These longer trials had glass throughputs nominally in the range 50-250 #/hr. Numerous short runs have also been successfully completed. Automatic data logging equipment is being used routinely to log all process conditions during glass melting trials. Temperature monitoring is provided with a Mikron I.R. detector. This sensor is entrained on mirrors that reflect the glass stream at the bottom of the moly orifice support cylinder. Before the end of the project, higher throughput trials are planned on one or more of the glasses currently under study.

### **IV. Energy Efficiency**

The stated goal of the program is to achieve a melt rate of 4.1 MBTU/hr melting efficiency. That number was selected as a stretch goal over the previously demonstrated work completed at Manville.

All glass melting runs made during the 2<sup>nd</sup> Quarter of 2005 were made at the lower throughput range (75 to 200 #/hr) to emphasize glass quality and process stability. It was these lower throughput runs that have successfully allowed us to demonstrate good fiber forming test performance during the AGY fiberizing trials, which were highly dependent on good glass quality. Now that we have successfully demonstrated these good fiberizing trials, a higher priority will be placed on demonstrating higher energy efficiency during the final phase of the project. We are still committed to demonstrating a high throughput / high energy efficiency process as one of our important objectives.

### Brief Review of Past Energy Efficiencies from Previous Reports:

Based on this previous work, it is known that the increased power efficiencies will be achieved at higher throughputs. The increased efficiencies at the higher throughputs are primarily due to the ohmic heat transfer mechanism that is realized by the amperage and torch position. It is only possible to operate in these positions at the higher feed rates.

The highest throughput run to date was ~350 pounds per hour. This yielded the highest efficiency. The average operational conditions at this level were:

- 415 Volts
- 712 Amps
- 295 kW

To calculate the energy used per pound of glass:

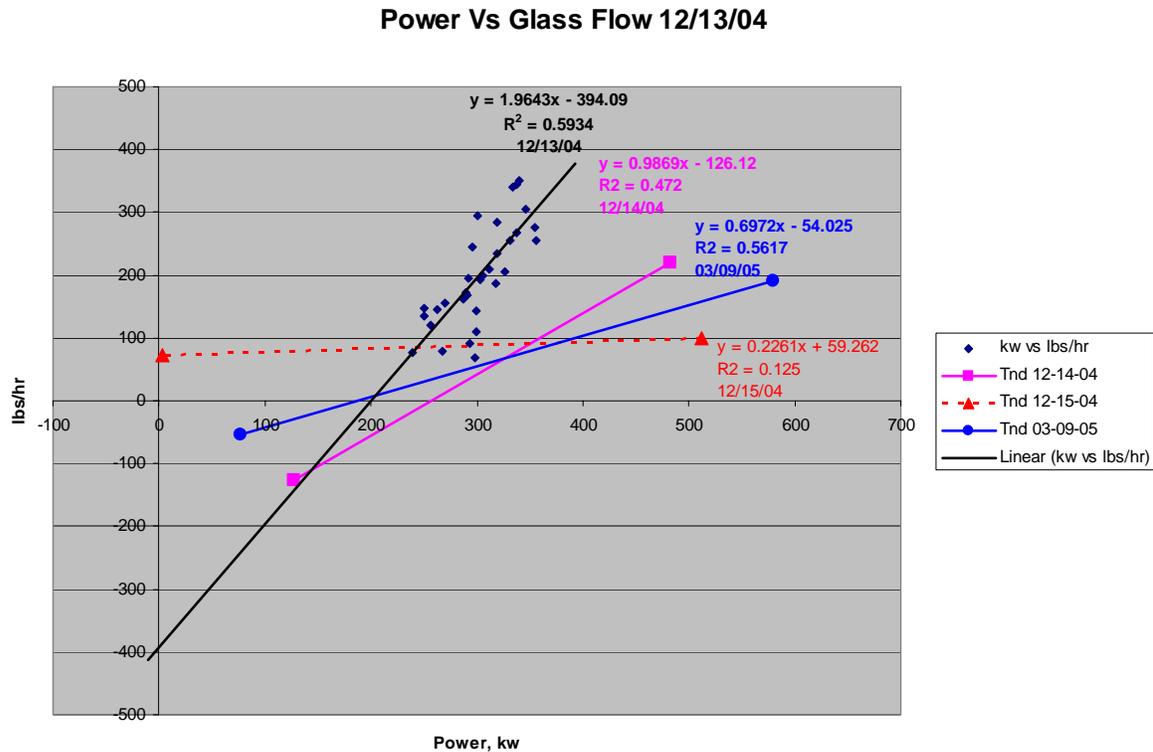
$$Power = Volts \times Amps = 415v \times 712a = 295kW$$

$$kW / Pound\ of\ Glass = \frac{295kW}{300lbs/hr} = .98 \frac{kW}{lbs/hr}$$

$$1kW = 3412.4BTU/hr$$

$$0.98 \frac{kW}{lbs/hr} * 3412.1 \frac{btu}{hr} = 3343.9 \frac{btu}{lbs} \Rightarrow 6.69MBTU/ton$$

The graphic below reflects the process throughput and energy efficiency relationship that we have deduced thus far (for E-glass only):



Major conclusions from these E-glass data are:

1. The best fit line for the 12-13-04 data shows an energy usage of approximately 1.16 kwh per pound of glass (300 # divided by ~ 350 kwh).
2. The best actual data points show ~350 #/hr @ ~340 kwh or ~ 0.97 kwh/pound of glass.
3. There is wide scatter in the data as shown by the  $R^2$  value of 0.59.
4. Trend lines are somewhat different for different dates. These differences are normal and result from the process setup (torch positions, power, feed position, etc.) are all very influential on the slope of the curve.
5. Since these data were collected on a plasma melting process that has not yet been optimized, we fully anticipate that optimization will yield even better efficiencies at the higher throughputs that are planned for May-July trials.

## ACCOMPLISHMENTS

Without elaboration, below is a list of program accomplishments to date.

1. All lab infrastructure has been installed including the glass melter, batch feed system, exhaust gas system, plasma torch system, all electrical power and control systems, cullet handling, and process monitoring.

2. More than 50 torch designs have been evaluated. A standard 5/8 torch has been designed that is in routine use and allows the process to run continuously in a stable hands-off mode for > 4 hours.
3. A process has been demonstrated that is capable of continuously melting glass in the 200 to 250 pounds per hour for several hours.
4. The standard 5/8 inch torch has been used to briefly operate the process at pull rates of ~ 350 #/hr.
5. Brief runs have been conducted in excess of 500 pounds per hour, but these were not stable and in-control operations. We have concluded from these experiments that a larger torch is required and work has been initiated on a 3/4 inch torch.
6. Preliminary chemical analyses of glass, which was collected on 6-16-04, show that overall, the analyzed glass samples were essentially on-composition, with somewhat higher losses of boron and fluorine.
7. Several preliminary assessments have been made of several E-Glass patties produced during trials. These generally show a very high seed count, some cord, and occasional un-melted batch stones.
8. The best glass quality was demonstrated on a glass sample that was melted for 20 minutes with no flow from the exit orifice. These samples have been selected as our baseline glass quality against which all future improvements will be judged.
9. Several glass trials have produced glasses with nearly the same quality as the baseline glass, but invariably, they have also included minor moly streaking.
10. Contamination from moly has been a serious problem until recently. We have now successfully defined the process boundary limits to circumvent the production of black/streaked glass. This accomplishment has been a major step forward.
11. Torch lives have improved dramatically from a few minutes on the initial designs to several hours on the current standard 5/8 torch. The torch with the longest service life thus far is >20 hours.
12. Energy consumption has on average been about 6.7 MM BTU/ton. This efficiency is much worse than the target 4.1 MM BTU/TON of glass, but is primarily related to our low throughputs thus far in the program.
13. The environmental impact of the process has not yet been assessed. However, using commercial E-glass batch ingredients, the dustiness of the initial system is known to be high. Significant work is planned for later in the project to focus on quantifying and reducing the particulate emissions as necessary.
14. A market study has been completed. Candidate early adopters have been identified. Discussions are on-going with these companies.
15. Melting trials have shown that the system is capable of melting 200 #/hr of S-2 Glass.
16. We have developed a preliminary understanding of the process settings and how these may relate to the ability to maintain a stable melting operation.

17. The design, construction, and operation have been completed for a refractory glass delivery channel that will transport the glass from the melter exit orifice to the processing area.
18. A patty-making machine has been installed and rendered operational in the Boulder Lab. Although further work is still required to improve consistency, we have now essentially demonstrated the capability to make glass patties.
19. Several preliminary methods for glass flow control have been identified.
20. One exploratory glass melting trial has been completed on a frit composition that is commercially produced by a US glass company. This company has expressed interest in working with Plasmelt to more fully assess the benefits of plasma melting technology for their operations.
21. Approximately 400 # of good quality glass nuggets have been produced from a two-day period when the melting operation was very stable. These nuggets were shipped to AGY for further fiberizing trials.
22. Fiberizing trials have been completed by AGY. Results showed good fiberizing performance for fibers with a filament diameter of 10 microns or greater, poor fiberizing performance (due to highly seedy plasma melted glass) of filament diameters of 5 to 6 microns, and moderately good performance for filaments in the 7 to 9 micron range.
23. Exploratory runs have been made on high strength fiberglass (S-glass) and lighting glasses melted in the plasma melter.
24. Exploratory runs have been completed on a broad range of glass compositions including C-glass, S-glass, AR-glass, Low DK glass, B-glass, and a mineral composition glass.
25. Further trial work is in progress to develop and refine the orifice design that is critical to controlling glass flow from the melter.

**BUDGET / FINANCIAL**

As of December 31, 2005, the project funds are nearly exhausted. Only a small amount of money remains to fund the writing of the final report and for funding the last few trials.

**Budget Data** (as of 12/31/05): The actual spending should reflect the money actually spent on the project in the corresponding periods.

<b>Project Spending and Estimate of Future Spending</b>							
<b>Quarter</b>	<b>From</b>	<b>To</b>	<b>Estimated Federal Share of Outlays*</b>	<b>Actual Federal Share of Outlays</b>	<b>Estimated Recipient Share of Outlays*</b>	<b>Actual Recipient Share of Outlays</b>	<b>Cumulative</b>
	Start	12/31/05	Note 1	\$1,273,926.73	Note 1	\$563,037.02	\$1,836,963.75
1Q06	1/1/06	3/31/06	\$38,429.27				\$ 38,429.27
2Q06	4/1/06	6/30/06					
3Q06	7/1/06	9/30/06					
4Q06	10/1/06	12/31/06					
1Q07	1/1/07	3/31/07					
Etc.							
<b>Totals</b>			\$38,429.27	\$1,273,926.73		\$563,037.02	<b>\$1,875,356.00</b>

**FOOTNOTES:**

**Note 1:** Actual Fed Share of Outlays for this period is calculated as follows:

Amt of total \$ spent from Plasmelt QB Accounting System Report (dated 9/30/05) minus AGY cash contributions,

i.e.  $\$1,273,926.73 = \$1,455,499.57$  (from QB 12/31/05 Rept) minus  $\$181,572.84$  (AGY cash as of 12/31/05)

**Note 2:** Amount of Total Federal Share Reflects the increase in DOE funding by \$100,000 to total \$1,312,356 plus Recipient Share by \$43,000=\$563,000.

**General Note:** DOE Laboratory partner spending should not be included in the above table. If a DOE Laboratory is a partner, report their spending and spend plan information in the table below (use separate tables if multiple DOE Laboratories are involved).

**General Note:** The information in this table should be consistent with the information provided in section 10 of the quarterly financial status reports (SF269 or SF269A).

**Note 1:** Leave blank. Only the actual DOE/Cost Share amounts spent through 3/31/05 are needed.

**Note 2:** Amount for this quarter and subsequent quarters should be updated as necessary on a quarterly basis. Estimates need to be provided for the entire project. If spending for a given quarter is different than estimated, then the remaining quarter's estimates should be updated to account for the difference. Total DOE and Cost Share amounts should be the same as the Award amount.

**Plans for Next Quarter:**

Write a final report before the project officially closes on 7/27/06.

**Patents:** N/A

**Publications/Presentations:** N/A

**Milestone Status Table:** This should be a complete list of project milestones, anticipated completion dates and actual completion dates. The milestone identification number should correspond to the task numbers in your agreement to aid in tracking (example below).

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
M 1	Project Startup: Establish WBS and Schedule, operating agreements, IP Terms, subcontract agreements	10/31/03	10/31/03	Complete
M 2.1	Melter Design: Develop Project Request Documents, specifications, materials lists, engineering packages	10/31/03	10/31/03	Complete
M.2.2	Laboratory Preparation: Identify candidate facilities, sign lease agreements, establish environmental permits	12/31/03	10/31/03	Complete. Notification of environmental Exemption Letter received from Colorado DPHE
M.2.3	Construct Melter: Subcontract fabrication and construction, install melter at site	12/31/03	2/29/04	Most of the delay due to major change in the building electrical system upgrade by Xcel Energy. Melter construction and fabrication are now complete.
M 3	Market Survey	5/31/04	5/31/04	Work is complete.
M 4	Melter/Process Test Program: Startup and operation at 500 #/hr rate [GO/NO GO DECISION], preliminary energy balance, preliminary report	7/27/04		350 #/hr has been achieved. But not on a routine basis. All Year 2 efforts have been focused on glass quality and away from high throughput low glass quality runs.
M 5	Assess Glass Quality: Patty Making Installation, Patty Production, and Fiberizing Testing [GO/NO GO DECISION]	1/31/05	4/30/05	Fiberization and fiber product testing completed. Good fiber forming performance for 10 micron and larger fibers. Good tensile testing results of plasma-melted glass.
M 6.1	Optimization: Process refinement, energy balance updates [GO/NO GO DECISION]	6/30/05	In progress	Optimization is an on-going priority. Recent glass melting focused on demonstrating the broad glass compositional capability of plasma melting.
M 6.2	Final Reporting to DOE	Before end of project on 7/27/06		

***Measurement and Control of Glass Feedstocks***

Weisberg: Energy Research Company, ORNL

ID14030

## QUARTERLY PROGRESS REPORT

**Project Title:** Measurement and Control of Glass Feedstocks

**Covering Period:** October 1, 2005 through December 31, 2005

**Date of Report:** January 31, 2006

**Recipient:** Energy Research Company  
2571-A Arthur Kill Rd.  
Staten Island, NY 10309

**Award Number:** DE-FC36-01ID14030

**Subcontractors:** Oak Ridge National Laboratory

**Other Partners:** PPG Industries  
Fenton Art Glass

**Contact(s):** Arel Weisberg, Ph.D.  
(718) 608-0935  
aweisberg@er-co.com

**Project Team:** DOE-HQ Contact: Elliot Levine  
Contract Specialists: Brad Ring, Beth Dwyer

**Project Objective:** Energy Research Company (ERCo) is developing an on-line sensor for controlling the quality of glass feedstocks, both batch and cullet. In the case of batch, the sensor can determine whether or not the batch was formulated accurately, and serve as part of a feedback loop in the plant to control glass quality. In the case of cullet feedstocks, the sensor can serve as part of a system to sort cullet by color and ensure that it is free of contaminants.

**Background:** The Glass Industry Technology Roadmap<sup>1</sup> emphasizes the need for accurate process and feedstock sensors. Listed first under technological barriers to increased production efficiency is the "Inability to accurately measure and control the production process." ERCo's LIBS sensor addresses this need by giving plant operators critical knowledge of their batch composition. In plants where cullet is used in glass production, the LIBS sensor can provide color sorted cullet free of contaminants,

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<sup>1</sup> Available at: <http://www.oit.doe.gov/glass/pdfs/glass2002roadmap.pdf>

including those contaminants that are not detectable using current optical based color sorters.

LIBS utilizes a highly concentrated laser pulse to rapidly vaporize and ionize a small amount of the material being studied. As the resulting plasma cools it radiates light at specific wavelengths corresponding to the elemental constituents (e.g. silicon, aluminum, iron) of the material. The strengths of the emissions correlate to the concentrations of each of the elemental constituents. This technology has been successfully demonstrated in ERCo's LIBS laboratory for both batch analysis and cullet sorting. In the upcoming year, designs of prototype sensors for installation at the program's industrial partners will be developed.

**Status:**

Work on the program was suspended this quarter pending the arrival of the remaining funding from DOE.

**Plans for Next Quarter:**

The remaining program funds were delivered in January, so work will resume this quarter to finish building the improved sample chamber. This will be followed by installing the sensor upgrade at PPG, performing the in-plant shakedown, and training PPG personnel to use the completed batch analyzer.

**Patents:** N/A

**Publications/Presentations:**  
N/A

**Milestone Status Table:**

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
1	Laboratory Development			
1.1	Facility Modification	9/30/01	9/30/01	
1.2	Testing	3/31/02	2/28/02	
1.3	Initial Software Development	3/31/02	3/31/02	
1.4	Performance Evaluation	3/31/02	3/31/02	
2	Sensor Fabrication			
2.1	Facility Construction	9/30/02	8/31/02	
2.2	LIBS Testing	8/31/03		Ongoing to add capabilities
2.3	Modifications to PPG Facility	12/31/03	3/31/04	
2.4	Procure System	6/30/04		Ongoing to add capabilities
3	Sensor Testing			
3.1	Testing at PPG	2/28/05		Commenced in 6/04
3.2	System Integration	12/31/04	8/24/04	

**Budget Data** (as of date):

<b>Project Spending and Estimate of Future Spending</b>							
Quarter	From	To	Estimated Federal Share of Outlays*	Actual Federal Share of Outlays	Estimated Recipient Share of Outlays*	Actual Recipient Share of Outlays	Cumulative
	Start	6/30/04	Note 1	904,873.18	Note 1	784,137.42	1,689,010.60
3Q04	7/1/04	9/30/04	Note 2	1,109,175.19	Note 2	784,137.42	1,893,312.61
4Q04	10/1/04	12/31/04	1,127,725.19	1,109,175.19	984,137.42	784,137.42	2,789,183.19
1Q05	1/1/05	3/31/05	1,438,813.00	1,129,178.00	1,680,008.00	1,605,006.00	2,734,184.00
2Q05	4/1/05	6/30/05	-	-	-	-	-
3Q05	7/1/05	9/30/05	-	-	-	-	-
4Q05	10/1/05	12/31/05	-	-	-	-	-
1Q06	1/1/06	3/31/06	1,228,375.02		1,680,007.00		-
<b>Totals</b>			<b>1,228,375.02</b>	<b>Note 3</b>	<b>1,680,007.00</b>	<b>Note 5</b>	<b>Note 7</b>

\* Update quarterly

**General Note:** DOE Laboratory partner spending should not be included in the above table. If a DOE Laboratory is a partner, report their spending and spend plan information in the table below (use separate tables if multiple DOE Laboratories are involved):

**Note 1:** Leave blank. Only the actual DOE/Cost Share amounts spent through 6/30/04 are needed.

**Note 2:** Amount for this quarter and subsequent quarters should be updated as necessary on a quarterly basis. Estimates need to be provided for the entire project. If spending for a given quarter is different than estimated, then the remaining quarter's estimates should be updated to account for the difference. Total DOE and Cost Share amounts should be the same as the Award amount.

**Note 3:** This should match the amount on the SF269A section 10.c. Column III (10.j. Column III on the SF269).

**Note 4:** This should match the amount on the SF269A section 10.c. Column II (10.j. Column II on the SF269).

**Note 5:** This should match the amount on the SF269A section 10.b. Column III (10.i. Column III on the SF269).

**Note 6:** This should match the amount on the SF269A section 10.b. Column II (10.i. Column II on the SF269).

**Note 7:** This should match the amount on the SF269A section 10.a. Column III (10.d. Column III on the SF269).

**Note 8:** This should match the amount on the SF269A section 10.a. Column II (10.d. Column II on the SF269).

**DOE Laboratory Spending Table (if applicable):**

<b>DOE Laboratory Partner Spending and Estimate of Future Spending</b>					
Quarter	From	To	Estimated DOE Lab Amount*	Actual DOE Lab Amount	Total
	Start	6/30/04	Note 1	155,000.00	155,000.00
3Q04	7/1/04	9/30/04	Note 2	0	0
4Q04	10/1/04	12/31/04			
1Q05	1/1/05	3/31/05			
2Q05	4/1/05	6/30/05			
3Q05	7/31/05	9/30/05			
4Q05	10/1/05	12/31/05			
1Q06	1/1/06	3/31/06			
Etc.					
<b>Totals</b>				<b>155,000.00</b>	<b>155,000.00</b>

\* Update quarterly

**Index of Award CID Numbers**

**Index of Award CID Numbers**

Agr id:04895 .....	1	GO13093.....	4
GO13091.....	2	ID14030 .....	5
GO13092.....	3		