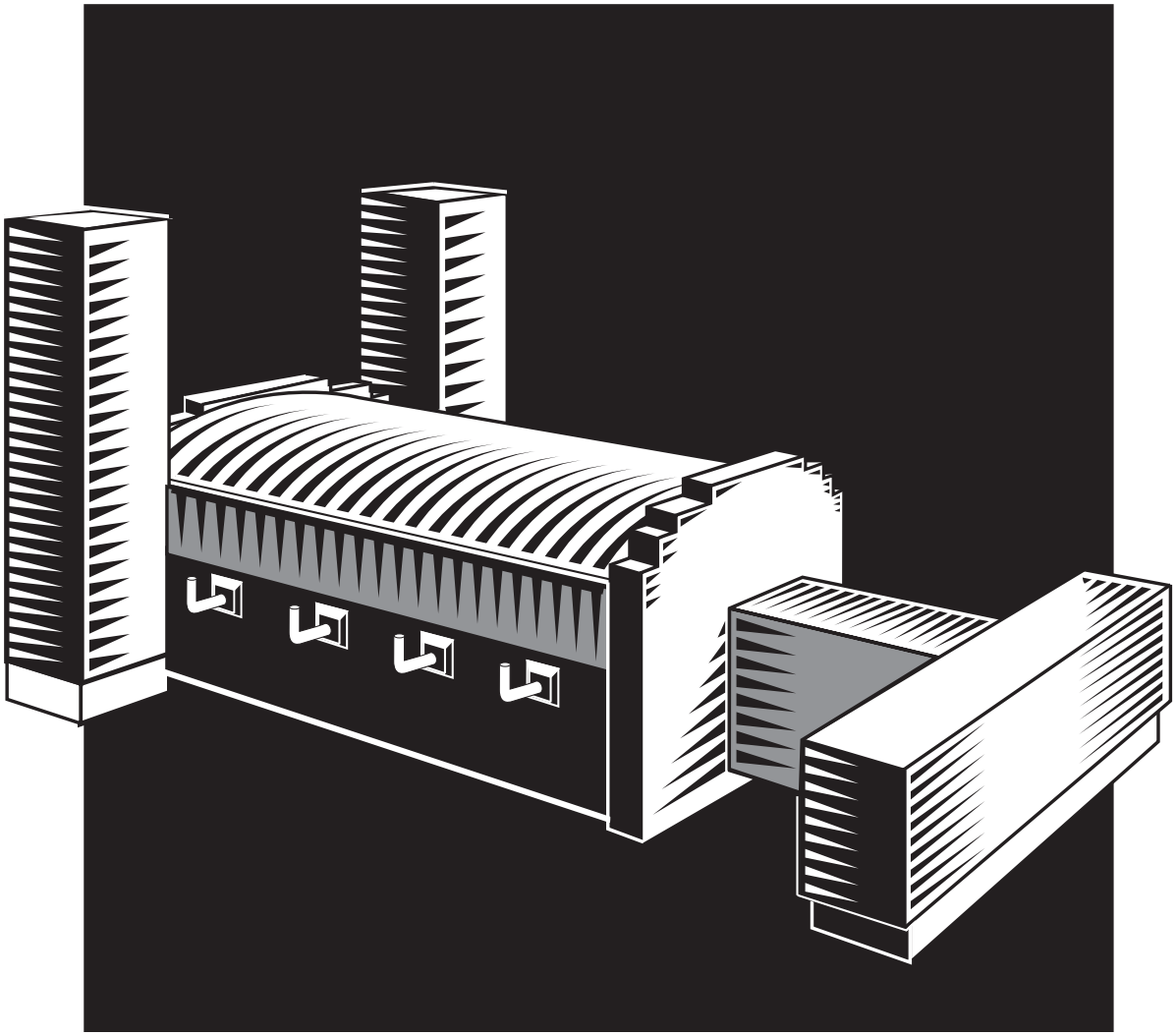
Glass Industry of the Future

Quarterly Status Reports

As of June 30, 2006



U.S. DEPARTMENT OF ENERGY

02-GA50113-03

Glass

Industry of the Future

Quarterly Status Reports

As of June 30, 2006

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Glass Projects

Development and Validation of a Coupled Combustion Space/Glass Bath Furnace Simulation 1
Lottes: Argonne National Laboratory (w/ Techneglas)
Agr id:04895

Energy Efficient Glass Melting: The Next Generation Melter 2
Rue: Gas Technology Institute
GO13092

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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

QUARTERLY PROGRESS REPORT

Project Title: Glass Furnace Model (GFM) Technology Transfer Program

Covering Period: 1 April 2006 through 30 June 2006

Date of Report: 27 July 2006

Recipient: Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Award Number: *Follow-on Program to DE-SC02-97CH10875 and DE-SC02-00CH11037*

Other Partners: Techneglas, Libbey, Inc., Osram-Sylvania, Owens Corning, Visteon

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Project Team: *Elliot Levine, OIT DOE-HQ contact; Matea McCray, DOE-ID, Project Mentor*

Project Objective: The objectives of the program are to transfer the ANL-developed Glass Furnace Model (GFM) to the glass industry and to promote its widespread use by providing the requisite technical support to allow effective use of the code. Project objectives will be accomplished through the following actions. A brochure will be prepared that describes the capabilities of the code and the support that will be provided to the user. The brochure will be mailed to a broad spectrum of glass industry representatives. The GFM code will be placed in ANL's Software Shop on the internet and will be readily available for licensing on-line through the laboratory's Office of Technology Transfer. Technical support will be provided to the code users and a GFM code user group (CUG) will be established. Every licensee will automatically become a member of the CUG and will be entitled to receive technical support at no cost throughout the duration of the technology transfer program. The level of support provided is expected to allow the licensee (user) to become proficient in the use of the code. The CUG members will meet periodically to discuss their experience and the results derived from the use of the code. Further improvements in the code that evolve from the technical support activity will be incorporated into the source code. At the conclusion of this program, the CUG members will be expected to define a mechanism that they would implement for provision of any additional support they may need in the long term.

Background: A substantial effort in the previous project was expended to develop a 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 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 6/06)

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 January to March 2006 quarter, a major effort was completed to resolve the most significant technical issues that were preventing convergence of the new automatic coupled cycling mode between the combustion and melt spaces. This effort involved all of the GFM components, but focused on improving numerical convergence in the melt and developing a cycling control and relaxation algorithm that would damp large oscillations in the melt and combustion space coupling conditions and lead to successful convergence of a coupled, cycling furnace simulation.

In the April to June 2006 quarter, new GFM documentation was written and a number of additional refinements and improvements were implemented to resolve issues that arose in testing GFM upgrades completed in the previous quarter. These improvements are listed below.

The melt code improvements included the following:

- added a "Summary of the Simulation" file giving users a summary of simulation case results including overall energy and mass balances
- improved and reorganized several of the text and Runplot data files to include more information and added capability to collect that information
- added a means to make many of the diagnostic and progress status data collection and file output optional and under user control
- added a means for users to adjust relaxation factors used to stabilize the simulation runs for highly nonlinear problems
- changed grid files to include length and width of the main furnace chamber to resolve a problem in interpolating coupling conditions between the combustion space and melt when refiners or doghouses are part of the furnace geometry
- added user defined tables for determining cullet and batch specific heat as a function of temperature

The combustion code improvements included the following:

- added a "Summary of the Simulation" text file file giving users a summary of simulation case results including overall energy and mass balances
- improved and reorganized several of the text and Runplot data files to include more information and added capability to collect that information
- added a means to make many of the diagnostic and progress status data collection and file output optional and under user control
- added a means for users to adjust relaxation factors used to stabilize the simulation runs for highly nonlinear problems
- improved GUI <-> CFD communications by adding timers in various code sections to force communication breaks limiting the

computation time between status feedback or response to user input during a simulation
- Changed the radiation calculation so that emission from the volume is calculated more frequently between full radiation calculations, which improves numerical stability and the convergence rate in the combustion space

The graphical user interface and control program improvements included changes to support improvements in the combustion and melt codes in addition to several new user convenience features:

- added new VB form for user to specify what extra summary and progress data to collect during simulations
- added new VB form for user to select what GFM documentation to view via the help menu
- added length and width of main chamber to grid files
- made the RunPlot program more user friendly by adding a legend and a right mouse click to show user display options
- updated and created new GFM user documentation

In a continuing effort to improve ease of use, a significant number of additional 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:

With successful completion of coupled combustion and melt automatic cycling testing, the upgrades in GFM implemented since March 2005 were judged to be sufficient for a new version copyright. Documentation of the new version, GFM 4.0, will be completed, and a technology transfer plan will be initiated to promote the use of GFM 4.0 in industry and academia via a new trial use offering.

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 6/30/06): 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	42.4
2005	January	March	10.0	n/a	10.0	110.0	8.9
2005	April	June					2.2
2005	July	Sept.					45.4
2005	Oct.	Dec.					55.0
2006	Jan.	March				75.0	73.1
2006	April	June					38.0
		Totals	250.0		250.0	480.0	477.1

*Program started officially 01/01/04.

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	April 1, 2006 through June 30, 2006
Date of Report	August 11, 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 Objective

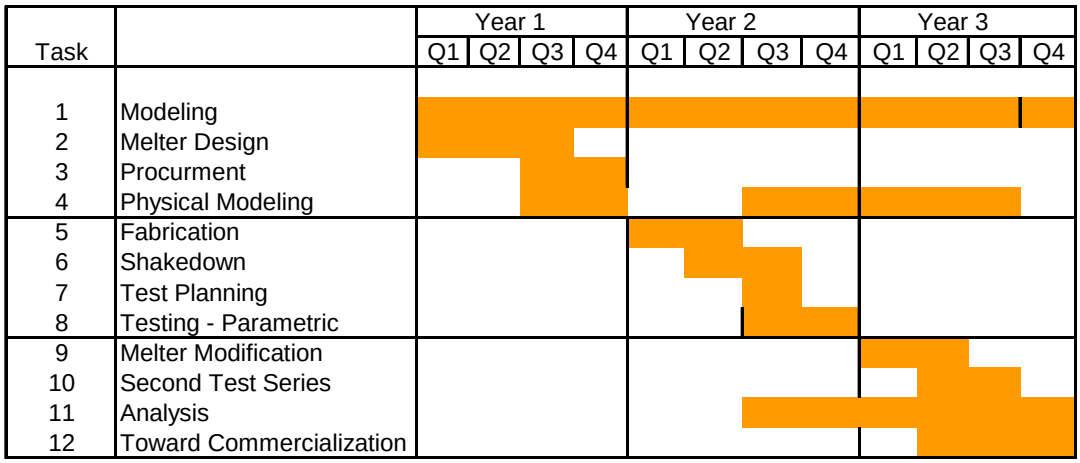
The objective of this project is to demonstrate a high intensity glass melter, based on the submerged combustion melting technology. This melter will serve as the melting and homogenization section of a segmented, lower-capital cost, energy-efficient Next Generation Glass Melting System (NGMS). After 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.



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	• Complete CFD model to be used by team members to design pilot scale melter • Design pilot scale melter • Procure all equipment and components for the melter in preparation for fabrication
Year 2 Milestones	• Fabricate and shake down of the pilot scale melter • Prepare test plan including compositions of glasses to be melted • Finish all pilot scale melting tests and collect samples for analysis • Complete detailed analyses of product glass properties and quality
Year 3 Milestones	• Modify melter, as needed, for second test series • Finish second test series, including at least one long term test, and all glass analysis • Finalize CFD model of the melter usable by all CFD operators • Finish physical material and energy balance model of next generation melting system (NGMS) process including utilizing waste heat for oxygen production • Complete plan for commercialization, including needed developments and stages

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.

Criteria Category	Specific Criteria
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

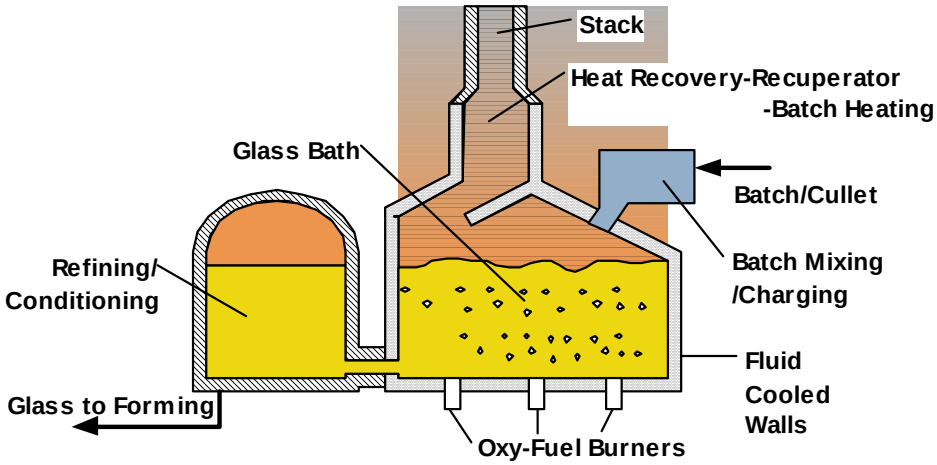
Operability	Scalable from 25 to 700 ton/day, reliable, stable operation, easy to idle, ability to start and stop, ease of access and repair, fast change with glass formulation and color, no moving parts to be abraded by the glass
Environmental	Low air, water, and solid waste, recycle-friendly

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_x emissions of less than 100 vppm (at 0 percent O_2) 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 $Btu/ft^2 \cdot h$, equal to 2×10^6 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 $Btu/ft^2 \cdot h$, but with much greater surface area, the refractory tank loses more heat (2.55×10^6 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 500ºC, 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_x 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 final analyses of melts with the new tap piece conducted last quarter, CFD modeling, and initial pilot SCM unit fabrication. This quarter was the second quarter in Year 3 of this three year project. Areas of most attention this quarter included

- Lab-scale SCM test analyses with a strong focus on reviewing the data to optimize final design of the pilot-scale nominal 1 ton/h SCM unit,
- Final review of pilot melter design including instrumentation,
- Ordering most major components for the pilot-scale melter, start of melter panel fabrication, and initial test cell preparations.
- Mathematical and computer CFD modeling including hydrodynamics and heat balances with a focus on means to reduce wall heat losses,
- Revision of the work scope for the Praxair OTM work on the project,
- Visits to several of the glass consortium member companies with presentations to increase project awareness, to obtain direct engineering and management feedback, and to discuss schedules for testing with the pilot-scale melter.

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 last quarter and initiated this quarter.

Mathematical modeling

Mathematical modeling this quarter included continuation of CFD work by Fluent and continued hydrodynamic calculations of melt flow patterns, but mainly 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. With reference to the three-step analysis strategy presented in Figure 1 (see last quarter's report for details), the Step 1 methods were finalized and the first exploratory Step 2 runs were completed.

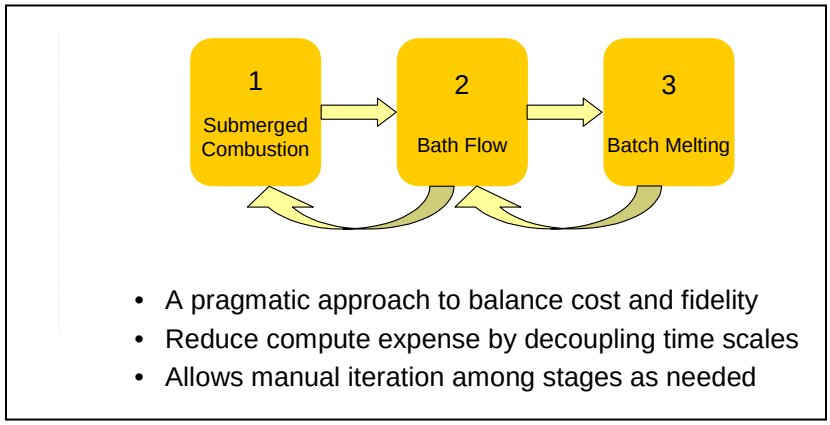


Figure 1. Top-level CFD analysis strategy

The preliminary Step 1 runs completed last quarter had suffered from stability issues that stalled the calculation after about 13 s of simulation time, among other problems. Moreover, a large cold spot was predicted on the melter floor near the burner. After discussion, the CFD Committee concluded this result was unphysical and identified a set of model changes that succeeded in eliminating the phenomenon and stabilizing the simulation. The most important changes were adding radiative absorption coefficient of 400 m^{-1} to the glass phase and limiting the glass/gas viscosity ratio to an arbitrary maximum of 10,000 for numerical conditioning reasons. The former value, suggested as typical by Bruno Purnode of Owens-Corning and corroborated by the literature [1], resulted in the elimination the cold spots while the latter value was instrumental in stabilizing the simulation.

In addition, an improved setting was activated for handling the combination of low-speed melt flow and high-speed gas flow within the same FLUENT domain. This approach selects the renormalization group (RNG) k-ε turbulence model with a special option named the Differential Viscosity Model, which avoids spurious artificial viscosity in the large laminar-flow regions of the melt. (See Fluent's Q3 2005 report for further description.)

With these changes, the axisymmetric VOF simulations proved to be very stable and rapidly equilibrated to a periodic bubbling flow within about six seconds. The temperature field presented in Figure 2 for a particular time of 25 sec confirms the elimination of the cold spot. (Note that the bulk temperature away from the burner is influenced by the inflow boundary

condition at the outer circumference of this small break-out region, which is artificially held at 1300 K, subject to future adjustment based on Step 2 results.)

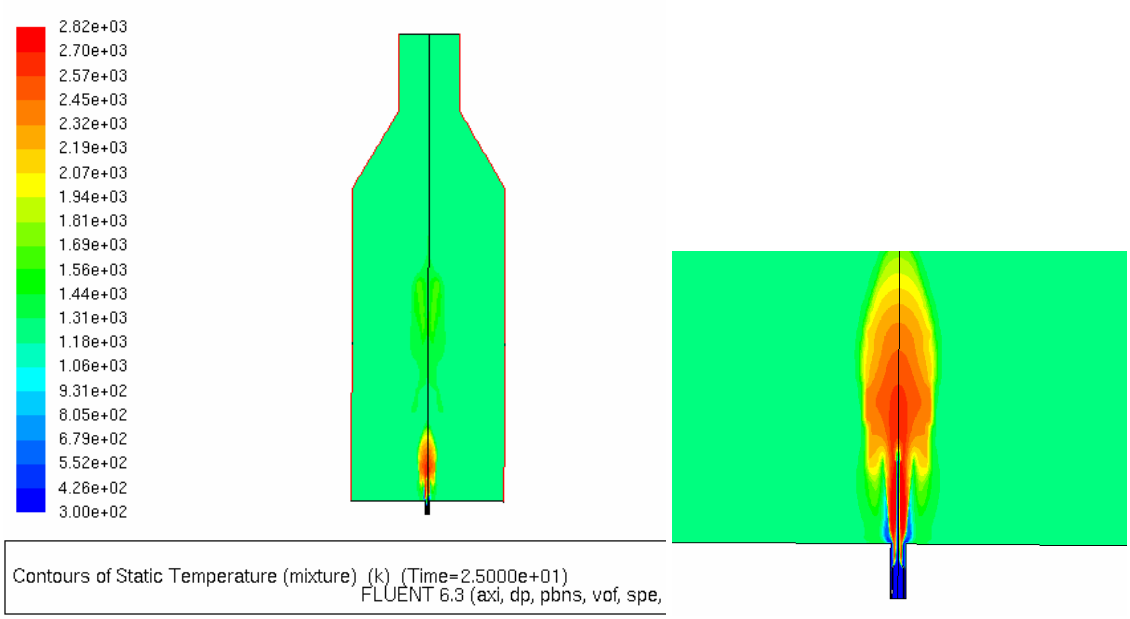


Figure 2. Step 1 analysis – contours of mixture temperature (K) at t = 25 s
(L – entire model; R – close-up in burner region)

With the previous convergence difficulties overcome, longer-duration Step 1 runs were accomplished this quarter. Figure 3 presents the time-averaged liquid volume fraction based on 30 sec of simulation. (At this writing, run-time has been successfully extended to more than 40 sec, comprising more than 50 combustion bubbles.) These results continue to predict a small tunnel of gas on the burner centerline that is almost never interrupted (i.e., pinched off into discrete bubbles) by molten glass, because the bubbles are so closely-spaced. However, as the inset in Figure 3 shows, the analysis refinements have led to a somewhat narrower and smoother tunnel region, while continuing to exhibit the "necking" of the bubble-dominated region near the melt surface. It should be remembered that these contours reflect the presence of only the primary combustion bubbles, not any small satellite bubbles that may persist throughout the melt.

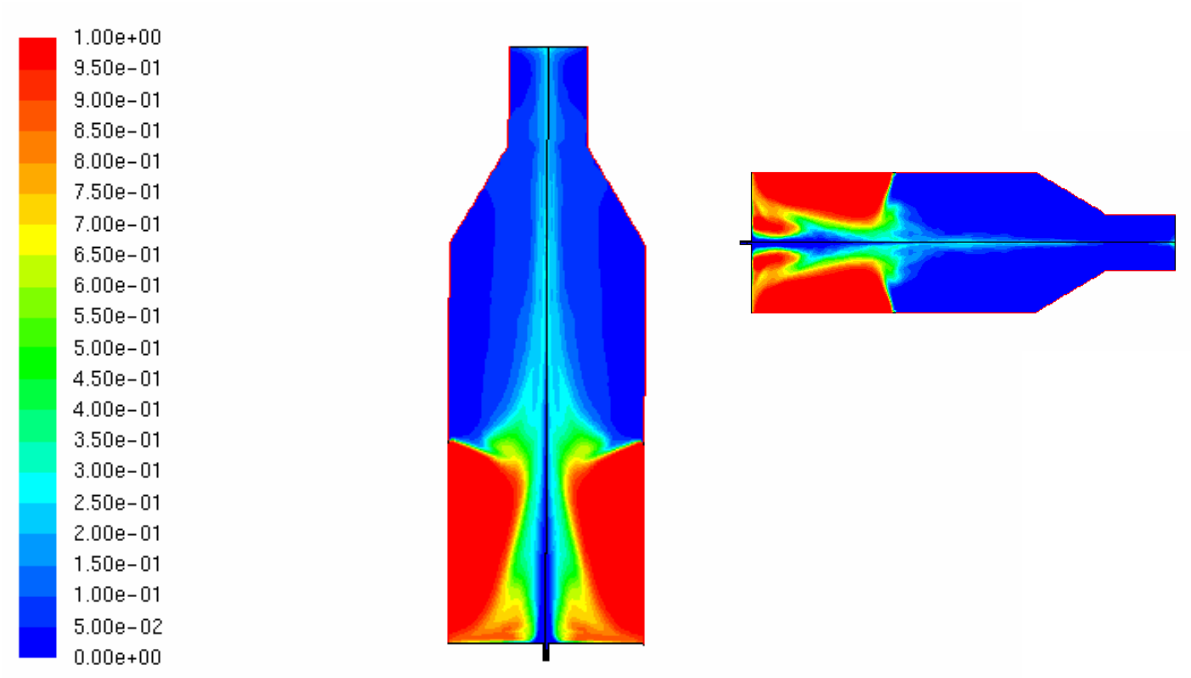


Figure 3. Step 1 analysis – time-average of volume fraction of glass
(smaller inset, on side, shows result of previous model for comparison)

Simulation Tool Research and Development

Project-specific software R&D this quarter continued to refine the source terms that form the forward connection between Steps 1 and 2. The focus was on the quasi-steady approach using the time-averaged Step 1 results. The time-averaging utilities for computing equivalent source terms were finalized. The utility code consists of two parts: a FLUENT user-defined function (UDF) that performs the averaging calculations, and a Scheme routine that repeatedly reads in the saved FLUENT data files and executes the UDF.

Within the region having glass volume fraction less than $\alpha = 0.2$ (in Step 1), steady momentum and energy sources were imposed on the single-phase melt flow as follows:

$$S_v(\vec{x}) = C_v\left[V^*(\vec{x}) - V(\vec{x})\right]$$
$$S_e(\vec{x}) = C_e\left[T_f^* - T(\vec{x})\right]$$

where C_v = 1.0E6 kg/m^3-s
C_e = 2.4E4 W/m^3-K
V = vertical component of velocity
T = temperature
$\vec{x}$ = position vector

In these equations, the asterisk indicates the time-averaged values from the Step 1 analysis, and the subscripts *v* and *e* indicate vertical momentum and energy, respectively. Figure 4 shows an example of the curve-fitting of the Step 1 results to determine the shape of the source

region based on the $\alpha = 0.2$ criterion. At the melter floor, entrainment effects cause this region of significant gas content to spread out to a diameter more than double the nominal burner diameter. Then the source region diameter gradually reduces with increasing height in the melt.

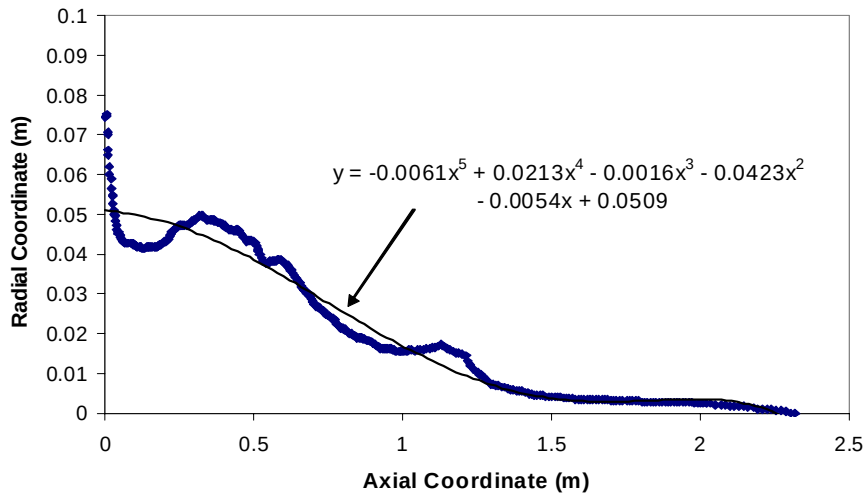


Figure 4. Fitted source region shape based on Step 1 VOF results

Mass, momentum, and energy sources representing the exhaust gas plume from each burner were also imposed in a small cylindrical region directly above the free surface, based on known gas flow rates. At the melter wall, a series of Committee discussions led to an assumed heat transfer coefficient of 100 W/m-K as an appropriate preliminary value to represent the composite thermal resistance of the refractory, steel wall, and cooling water. The assumed water jacket temperature (average over the entire melter) which constitutes the ambient environmental temperature for the simulation is 300 K.

Preliminary results of Step 2 analysis with the baseline E glass and the imposed sources are presented in Figures 5 through 7. The overall time-averaged velocity pattern (Figure 5) exhibits three distinct plumes on each half of the melter, separated by recirculation zones. Figure 6 shows the fluid deceleration and re-acceleration (again, on a quasi-steady average basis) as the bubbles reach the free surface and break free of the melt. Figure 7 shows the relative uniformity of the predicted equilibrium wall temperature.

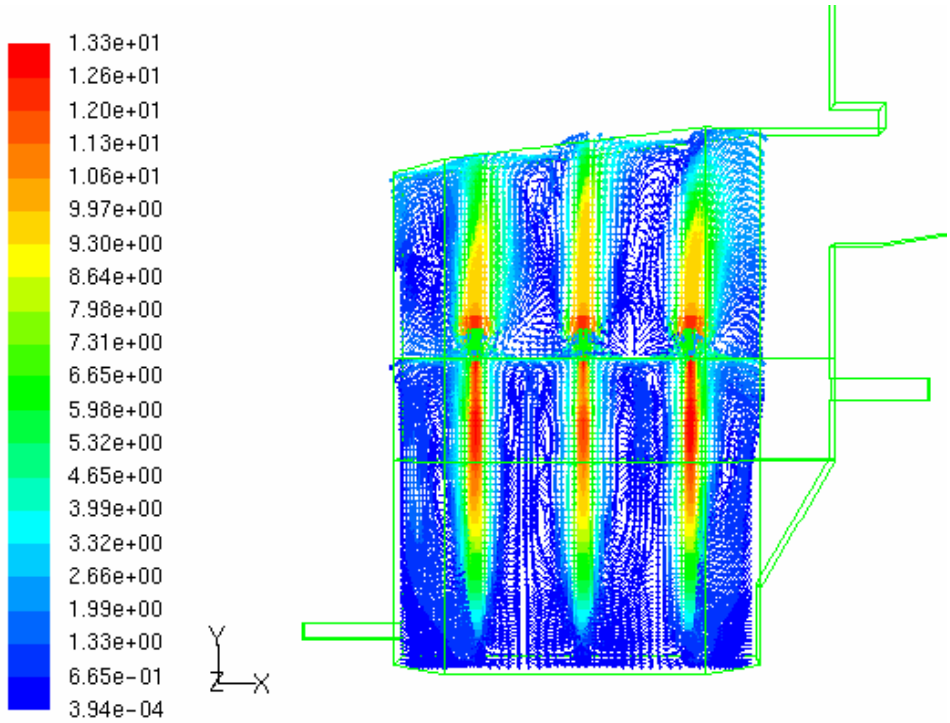


Figure 5. Fluid velocity vectors in vertical plane of burners (m/s)

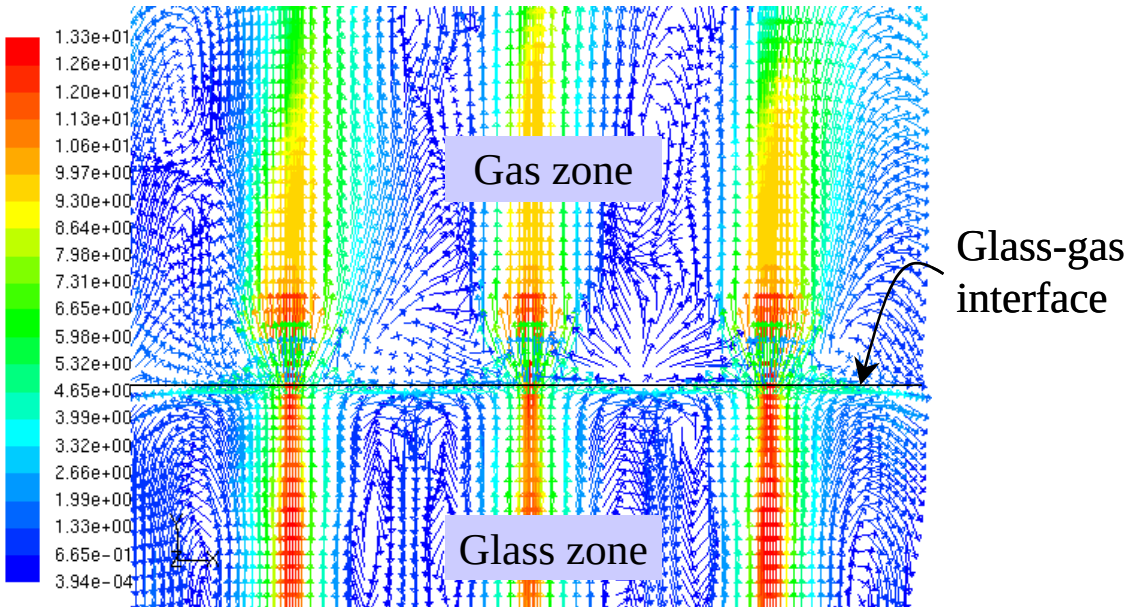


Figure 6. Close-up view of velocity vectors near melt surface (m/s)

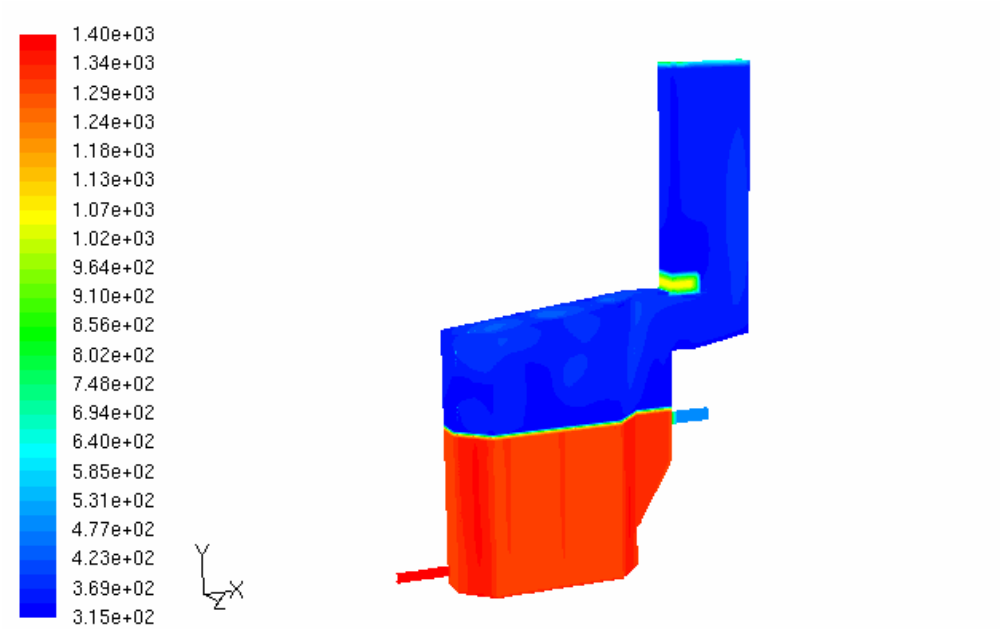


Figure 7. Fluid temperatures at melter inner walls (K)

The predicted wall temperature range of 1225-1334 K adjacent to the melt may not yet be realistic, given that the model is intended to explicitly represent the so-called frozen layer of slow-moving molten glass at the refractory wall. The results do not yet exhibit the expected velocity and thermal boundary layers at the walls. This issue, which may involve refining the mesh and/or the wall thermal boundary condition, remains under investigation.

Project Management

The CFD Committee met by teleconference on May 9 and in person prior to the June team meeting at GTI. The team meeting at GTI on June 21 was supported by Raj Venuturumilli. He and Jaydeep Kulkarni also made site visits to Corning and Owens-Corning in June at which the GTI project and melter model were summarized for a broad audience of glass company engineers.

The cumulative Fluent efforts on this project as of the end of the quarter are summarized in Table 1 in terms of labor hours. The average Fluent level of effort this quarter was about 23% full-time equivalent (FTE), primarily provided by Raj Venuturumilli. 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 pending extension in the period of performance (1-May-04 through 31-Jan-07), the Fluent sub-project was 79% complete by schedule at the end of this reporting period.

Table 1. Fluent task status as of 6/30/06

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	AT, RV	150	249
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, RV	50	100
A.3a	Support FLUENT use by team members	AT, RV	100	134
A.3b	Administrative support: contracting, provide FLUENT licenses, etc.	ERF	0	6
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	70
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	56
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, JAK, RV	100	251
C.2	Quarterly technical reports, final report, and technical paper contributions	ERF, AD, RLC	200	109
	TOTALS		**3670**	**3927**

Issues and Resolution

Table 2 summarizes the remaining important issues and our plans to resolve them.

Table 2. Summary of outstanding CFD issues and resolution plans

Issue	Proposed resolution
1. Step 2 results do not show expected momentum and thermal and boundary layer	Perform an audit of effective wall boundary conditions, fluid properties, and mesh resolution, and make adjustments as required.
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 in Step 3, involving a combination of DPM and an equivalent liquid-phase reaction to simulate melting effects.
4. GTI computer resources may be suboptimal for many runs of the time-intensive Step 1 calculations.	GTI considering procurement of Linux cluster for project use. Also, after several iterations with Step 2, a reasonably invariant Step 1 solution may exist.

Mathematical Modeling for the Pilot-Scale SCM

Efforts on CFD modeling this quarter focused on mathematical modeling and optimization of heat loss and heat balances of submerged combustion melters. The estimates of maximum expected thermal efficiency of glass melters, the related minimum expected heat loss, and the optimum firing rate distributions have been analyzed.

The “minimum heat loss value” means that it cannot be less than some minimal level determined by the requirements to frozen glass layer thickness.

Since any glass melter can be roughly divided into two zones – the zone of glass batch melting and the zone of glass melt homogenization – it was assumed that maximum thermal efficiency requires maximum available heat input (the firing rate) in the first melting zone and minimum necessary heat input in the zone of homogenization. VOF (Volume of Fraction) method of multiphase system SFD modeling has been applied in all considered cases.

All results presented in this report have been obtained based on the same simplifications and assumptions. The similarity of the main simplifications and assumptions provides the results with necessary compatibility and allows making conclusions valuable for optimal design of submerged combustion melters.

- The melters to be modeled have been divided into several sections. Each section has been provided with its own slot shaped charge and discharge located close to glass melt free surface and to floor respectively and spread over the full width of corresponding front and back walls.
- Glass melt has been considered as a continuous flow of liquid without solid particles and bubbles. Chemical transformations have not been taken into account.

- Radiation heat transfer in the glass melt and gaseous medium has not been modeled directly. An effective thermal conductivity temperature curve with radiative component has been used instead.
- The viscosity temperature curve for E-glass has been used for CFD modeling.

Thermal efficiency optimization for rectangular melter with the production rate of 1 t/h

According to simplifications listed above the whole melter has been considered as a system of three rectangular sections (Figure 8).

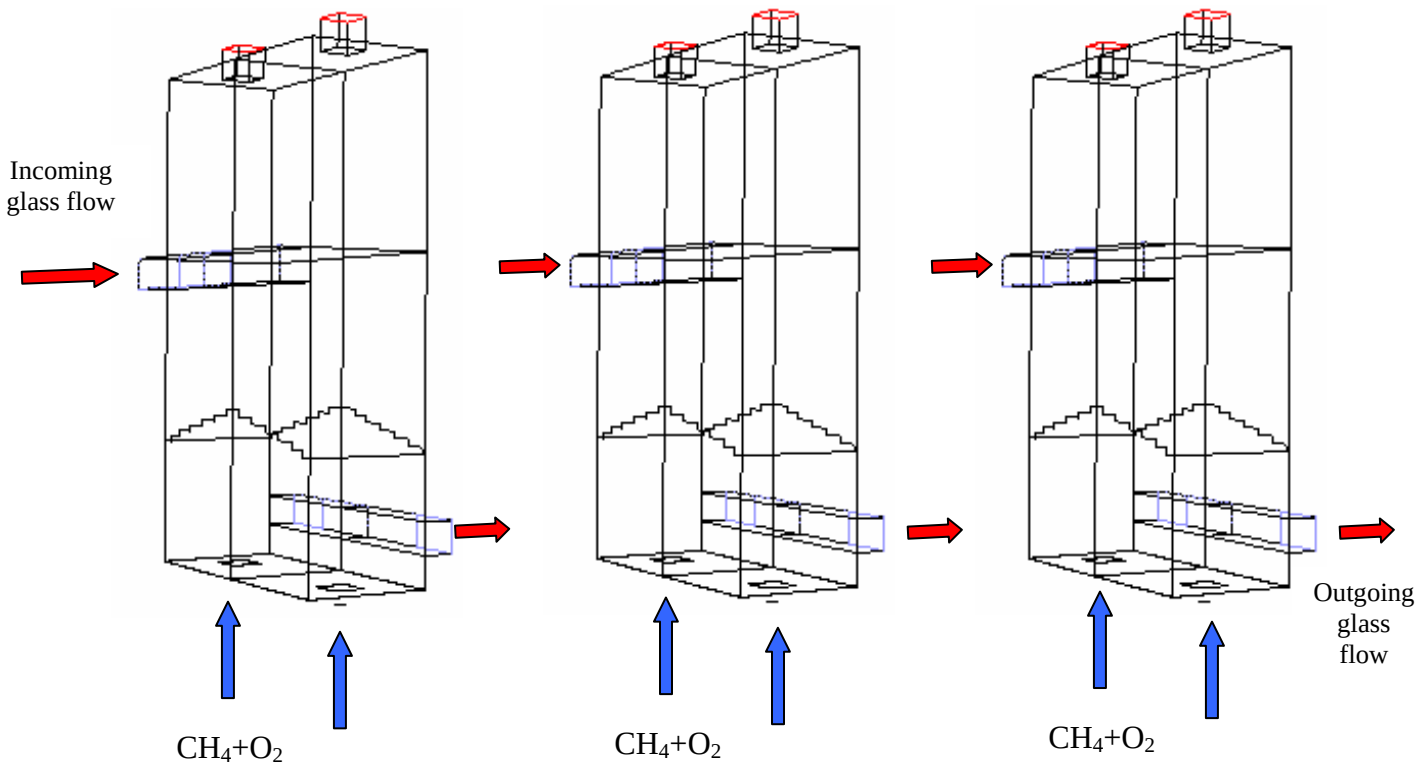


Figure 8. Simplified schematic of pilot melter

Each section has its own slot shaped charge and discharge near the glass melt free surface and near the floor respectively and spread over whole width of corresponding front and back walls. The dimensions of each section have been assumed to be 0.4 m x 0.9 m x 1.5m. The nominal glass melt level is 1.0 m (3 ft).

Optimization of heat balance components has been carried out by variations of firing rate values in each row of burners, and variations of wall boundary conditions.

The numerical experiments have showed that the optimal total firing rate of the melter is approximately 6.4 MMBtu/h. The resultant optimal firing rate distribution along the sections or rows of burners is shown in Table 3.

The obtained optimal firing rate distribution results in a glass melt temperature distribution along the furnace which is close to the intuitively best one – the first zone has a

maximum available firing rate and a maximum available heating rate, and the last zone has approximately constant glass melt temperature along it (the zone is approximately isothermal) (Figure 9).

Table 3. Optimal Firing Rate Distribution

Characteristics	1st row of the burners	2nd row of the burners	3rd row of the burners
Firing rate per burner: MMBtu/h % of nominal	 1.4[1] 100%	 0.8 55%	 1.0 70%
Firing rate per row: MBbtu/h % of nominal	 2.8 100%	 1.6 55%	 2.0 70%
% of total firing rate	44%	25%	31%

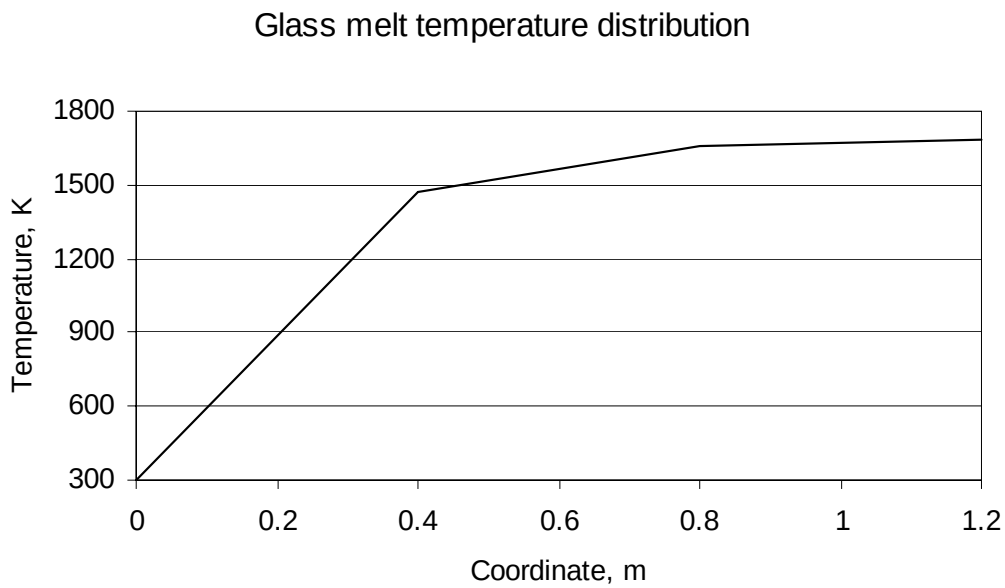


Figure 9. Optimum Glass Melt Temperature Profile Along the Furnace

A correlation between heat input (firing rate) distribution and thermal efficiency of groups of sections is illustrated by histogram in Figure 10.

[1] The burner's actual firing rate appeared to be smaller than the nominal one because of computational inaccuracy in gas jets approximation

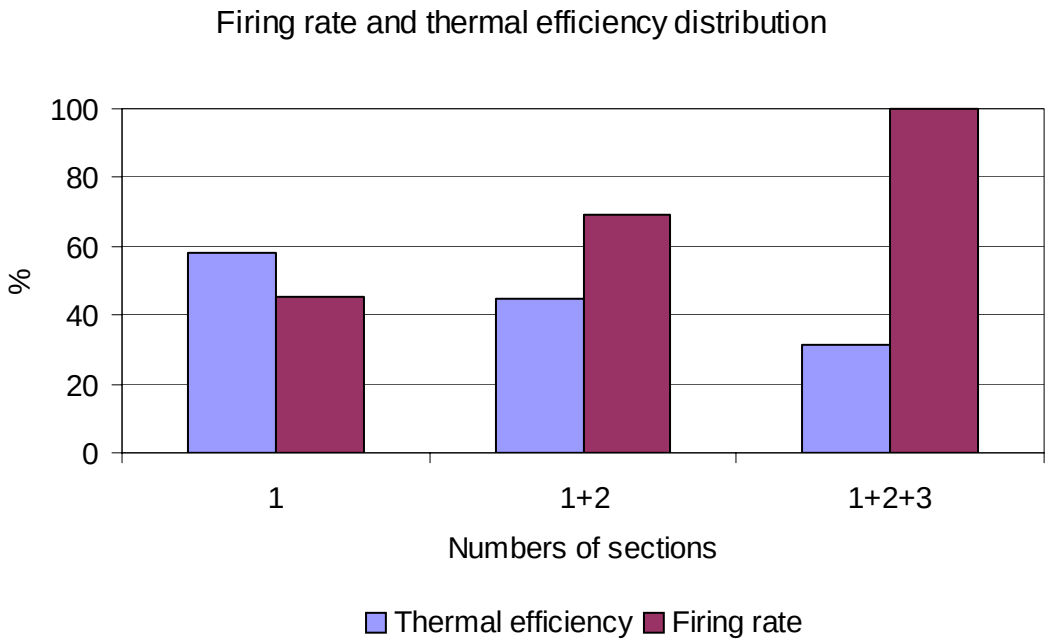


Figure 10. Firing Rate and Thermal Efficiency Distribution Along the Melter

The histogram reflects a correlation between each section's contribution into the overall heat input and its influence on the thermal efficiency of the furnace.

The flow of cold incoming raw material determines the relatively low average temperature in the first section. The low average temperature of molten glass in the section and high temperature of gas jets leads to a high value of average temperature gradient and to high thermal efficiency of the first section. Ideally, the temperature of the glass flow at the exit of the first section should be equal to the required glass melt final temperature. All later sections serve mostly for homogenization and needed additional residence time for silica dissolution and their heat consumption has to compensate for the heat loss through cooled walls only. Ideally, sections after the first section should not contribute to final glass melt temperature.

For this case with the given assumptions and restrictions, the obtained optimal heat balance is shown in Table 4.

Table 4. Estimate of Optimal Heat Balance for the Pilot Melter with Nominal Production Rate

Input			Output							Overall thermal efficiency, %
Glass	Gas	Total, kW	Glass		Gas		Heat loss		Total, kW	
Q, kW	Q, kW		kW	%	kW	%	kW	%		
11.3	1835.9	1847.2	590.0	33	613.9	34	579.9	33	1783.8	32

Since the total wall area of the melter including floor and roof is 7.11 m^2, the minimal average specific heat loss is estimated at 82.3 kW/m^2.

Thermal Efficiency Optimization for Rectangular Melter with a Production of 1.5 t/h

Increased production rate in the same sized melter is one of the obvious ways to increase thermal efficiency of submerged combustion melters. This is possible because the heat input can be increased easily. The limitation on higher pull rate will be based on residence time required for complete melting (with no stones) and full homogenization.

Numerical experiments show that the optimal total firing rate for the melter in 1.5 ton/h case is approximately 7.2 MMBtu/h versus 6.4 MMBtu/h for the case of a nominal 1 ton/h production rate. The total firing rate has increased 12.5% though the production rate has been increased by 50%. The resultant optimal firing rate distribution along the sections or rows of burners is shown in Table 5.

Table 5. Optimal Firing Rate Distribution

Characteristics	1st row of the burners	2nd row of the burners	3rd row of the burners
Firing rate per burner: MMBtu/h % of nominal	 1.4 100%	 1.0 70%	 1.0 70%
Firing rate per row: MBbtu/h % of nominal	 2.8 100%	 2.0 70%	 2.0 70%
% of total firing rate	42%	29%	29%

The obtained optimal firing rate distribution results in glass melt temperature distribution along the furnace similar to the case of the nominal firing rate (see Table 3). The temperature distribution is also similar but it is impossible to heat up the glass to required final temperature in the first zone due to lack of available firing rate. As a result, a part of the second zone is also occupied by relatively cold glass melt (compare Figures 9 and 11).

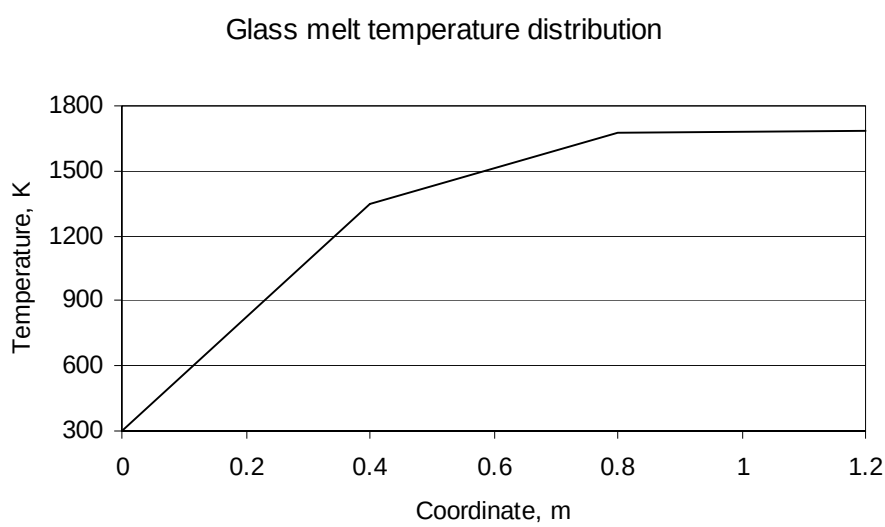


Figure 11. Optimum Glass Melt Temperature Profile Along the Furnace

A correlation between heat input (firing rate) distribution and thermal efficiency of groups of sections is illustrated by the histogram in Figure 12.

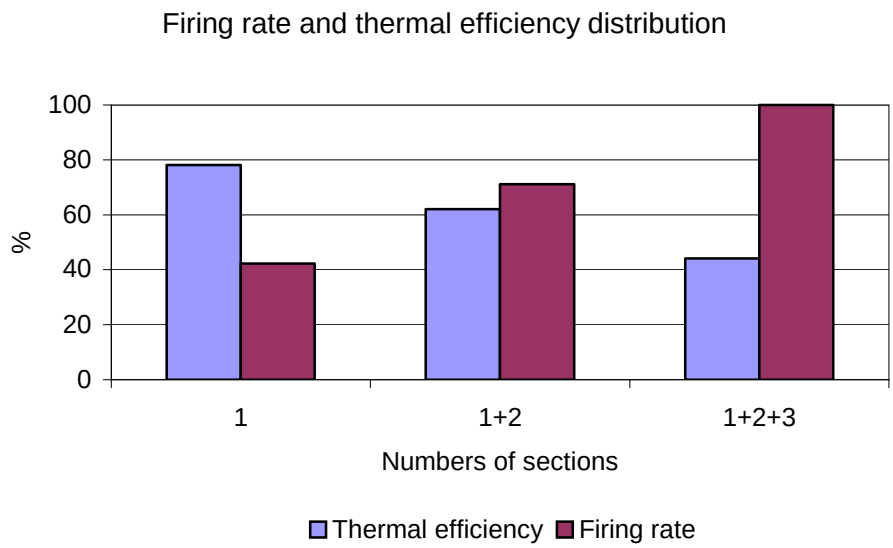


Figure 12. Firing Rate and Thermal Efficiency Distribution Along the Melter

The histogram reflects a correlation between each section's contribution into the overall heat input and its influence on the thermal efficiency of the furnace.

The demonstrated results illustrate the importance of heat input concentration in the cold zone. In other words, the first section should provide the maximum possible firing rate. The firing rates in the next sections should be minimized to the level that just allows to compensate for the heat loss. The obtained optimal heat balance for the whole melter is shown in Table 6.

Table 6. Estimated optimal heat balance for the pilot melter with increased production rate

Input			Output							Overall thermal efficiency, %
Glass	Gas	Total, kW	Glass		Gas		Heat loss		Total, kW	
Q, kW	Q, kW		kW	%	kW	%	kW	%		
17.0	1964.5	1981.5	886.6	44.9	556.4	28.2	530.0	26.9	1972.9	44

Since the total wall area of the melter including floor and roof is 7.11 m^2, the minimal average specific heat loss is estimated at 75 kW/m^2.

The estimates of thermal efficiency values at 1 t/h and 1.5 t/h of production rate allow depicting the correlation in Figure 13. Linear regression gives rough prognosis of accessible thermal efficiency.

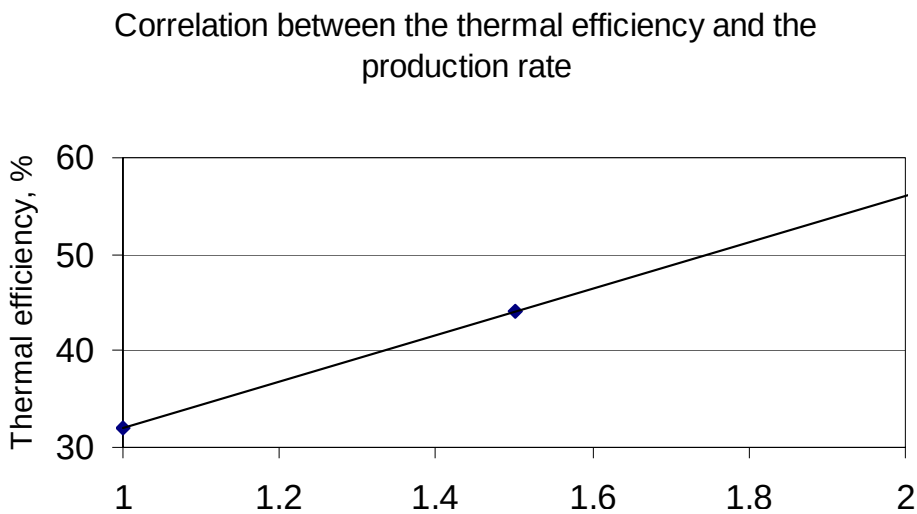


Figure 13. Production Rate – Thermal Efficiency Correlation

Analysis of Cooled Refractory Parameters

Results of CFD modeling of hydrodynamics and heat transfer allow estimation of the maximum possible wall temperature at which the frozen glass layer exists and to have the minimal necessary thickness. Those temperature values are assumed to be constant for certain parts of the walls, floors, and roof of the furnace.

The problem of cooled refractory parameters optimization requires additional assumptions and models. For the purpose of analysis of cooled refractory design parameters, it has been considered as a system consisting of water-cooled steel flat walls with cylindrical steel studs covered by the layer of some refractory material. The second section of the rectangular melter with the nominal pull rate of 1 t/h has been chosen as subject for analysis.

The following properties and parameters of the cooling system and cooled refractory have been assumed for further analysis:

- The cooling water temperature is T_0 = 300 K, the heat transfer coefficient from the steel wall to cooling water is h_0 = 5000 W/m^{2}K. Some rough estimate of average heat transfer coefficient in a flat channel of 1” of width with average water flow velocity gave h_0 = 3500 W/m^{2}K. Since more precise information is not available at this point and overestimated heat transfer coefficient leads to greater than necessary thermal resistance of cooled refractory, the heat transfer coefficient of h_0 = 5000 W/m^{2}K has been assumed for the analysis.
- The density of studs (the ratio of the studs cross section area to the wall area) has been chosen in the middle of the range $f_S \approx 0.12 - 0.18$.

- The steel wall thermal resistance is assumed to be negligible. The thermal conductivity of studs and refractory have been assumed to be λ_S = 50 W/m·K and λ_R = 2 W/m·K respectively.

The assumptions of given hot surface temperature of refractory requires a special thermal resistance distribution along the walls, the floor, and the roof. Since it is not convenient to work with distributions along the whole surfaces, several particular straight lines have been chosen for that purpose. Those lines along with XYZ coordinate system are depicted in Figure 14.

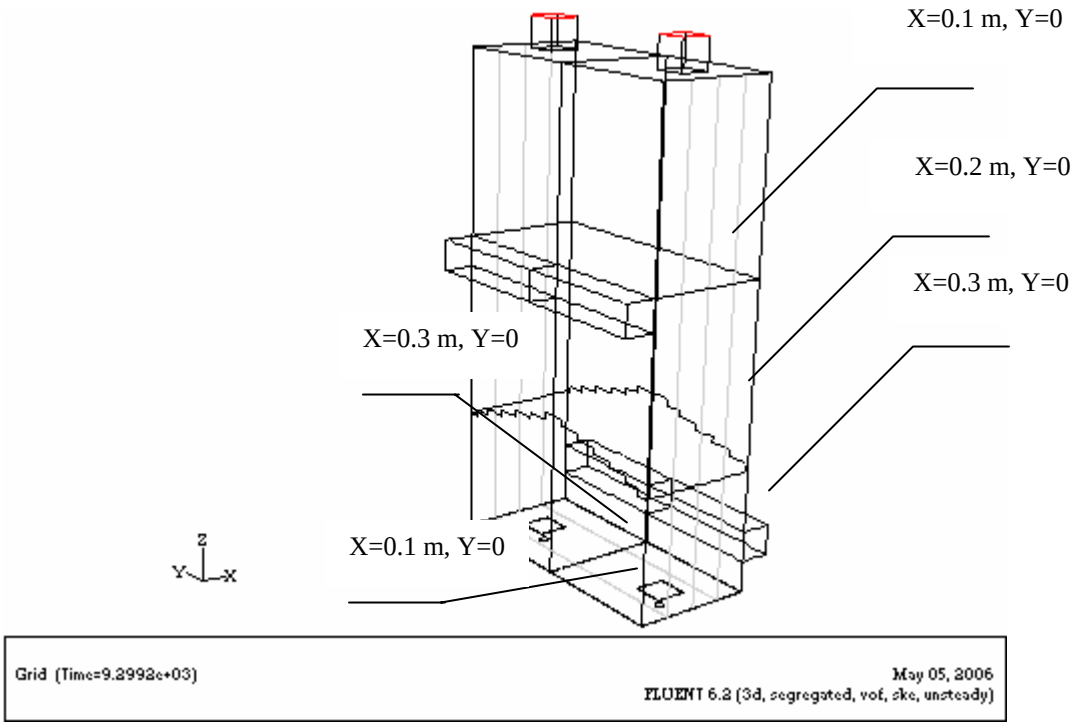


Figure 14. System of Characteristic Lines

The heat flux distributions at the sidewall are showed in Figures 15 and 16.

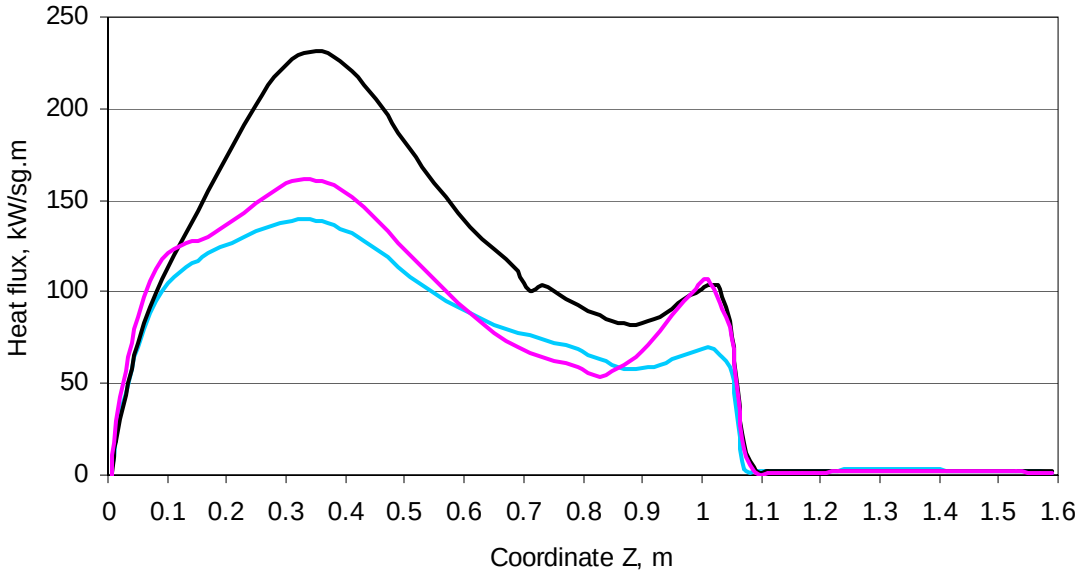


Figure 15. Heat Flux Distribution at the Sidewall

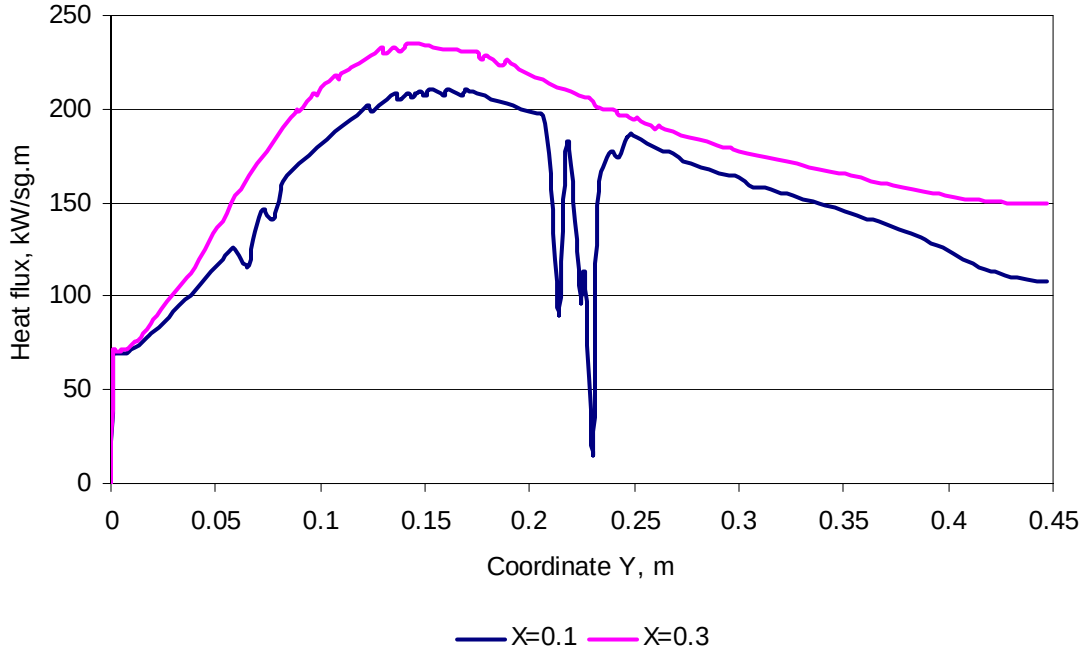


Figure 16. Heat Flux Distribution at the Floor

The effective refractory thermal resistance distributions for the sidewall central line X=0.2m and for the floor line X=0.2m are shown in Figures 17 and 18.

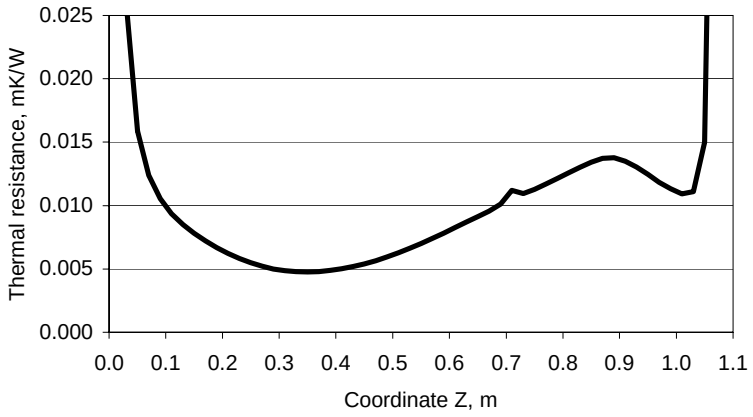


Figure 17. Maximal Equilibrium Refractory Thermal Resistance Along the Sidewall Below the Glass Melt Level

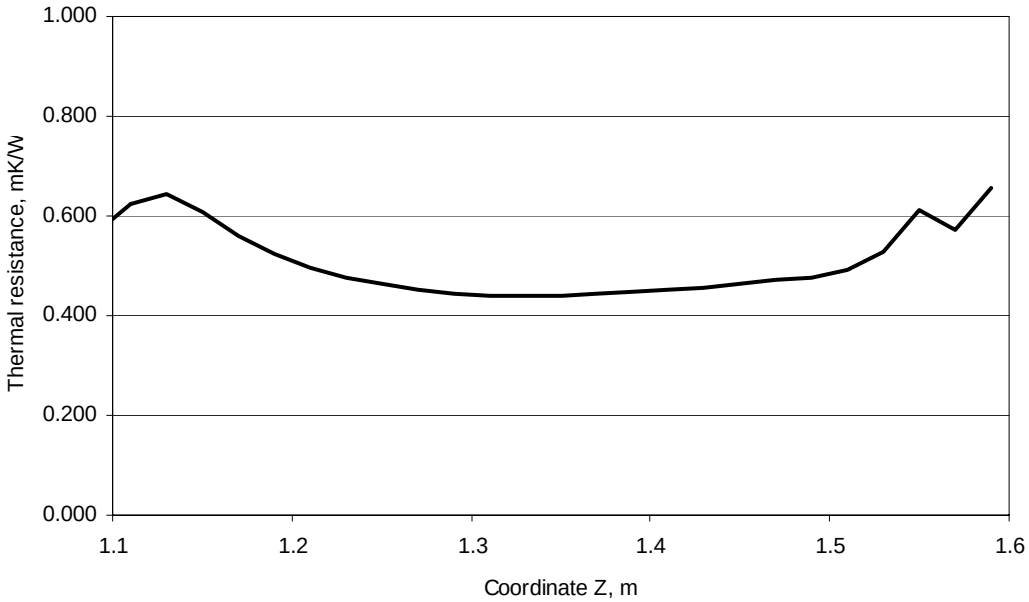


Figure 18. Maximal Equilibrium Refractory Thermal Resistance Along the Sidewall Above the Glass Melt Level

A peak of the thermal resistance at the bottom of the sidewall (at the corner between the sidewall and the floor) is determined by low heat flux values at that area.

The maximal equilibrium thermal resistance values at the sidewall above the glass melt level appeared to be several orders of magnitude greater than that below the glass melt level due to a large difference in heat flux values in those areas.

Generally, the less the heat fluxes at the wall, the greater the maximal equilibrium thermal resistance of cooled refractory.

The last conclusion does not mean that the effective thermal resistance of cooled refractory on different areas of the walls (and floor) should have such non-uniform distribution. It only means that if initially the cooled refractory has a large enough thermal resistance it will decrease in time to its maximal equilibrium value. If its initial thermal resistance is less than that, it will be covered by a frozen glass layer, which prevents it from destruction, but the heat loss value will be greater than tje minimal possible value.

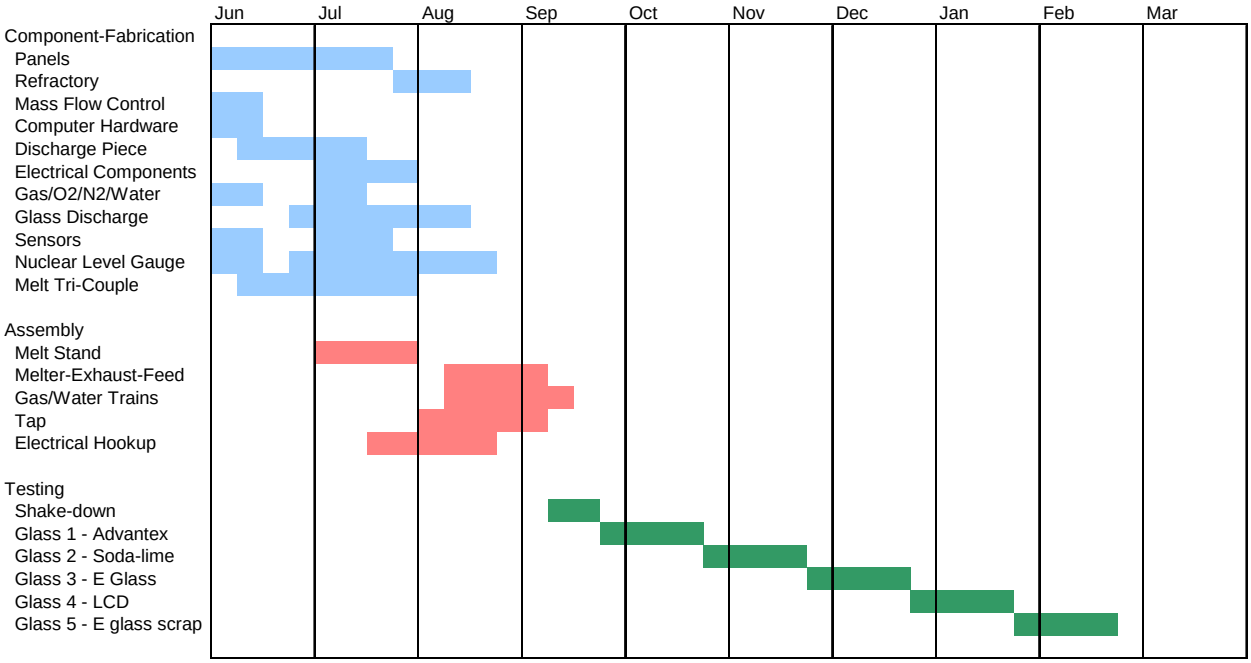
Pilot-Scale Melter Fabrication and Assembly

No melting tests were conducted this quarter. Instead, all efforts were focused on preparing for installation and operation of the pilot-scale melter later this year. The project team has agreed to focus all pilot-scale melt tests on three glass types and four compositions:

- Soda-lime glass (flat glass composition provided in batch by PPG)
- E glass
    - borosilicate glass batch provided by Johns Manville
    - Non-boron Advantex batch provided by Owens Corning
- LCD glass (no alkali glass batch provided by Corning)

A project consortium team meeting was held this quarter (early June, 2006) at GTI in Des Plaines, IL. At that time, all project team members had the opportunity to review the pilot-scale melter design and instrumentation package. Melt test planning was initiated, and assignments were made to acquire needed glass batch and to schedule glass company engineers to attend tests and participate in operations and sampling. The schedule for assembly and testing with the pilot-scale melter is presented below.

Table 6. Pilot-Scale 1 ton/h SCM Assembly and Testing Schedule



Pilot Melter Design and Assembly

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 and the last two quarters 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 last 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 last 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 a 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 devitrifidcation 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 uniform 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, how 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 used 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 med level.
- Burner firing rate up to 9 MMBtu/h divided among 6 burners - with the tank bottom designed to be removal 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 digital 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

Pilot-Scale Melter Fabrication

The new melter will be built from a number of water-cooled panels joined together. Once assembled, a 1.5 in. layer of high alumina castable refractory will be applied in a monolithic layer on all surfaces. Work was begun last quarter on the panel assembly, and the quote has been received for the refractory work to be conducted when all panels are fabricated and assembled.

The lab-scale melter was removed from the test cell last quarter. A new floor drain was installed, and underground piping laid for removal of higher volumes of discharge water. The team considered using a chiller instead of once-through water, but consideration of the number and length of tests vs. cost led to the decision to go with once-through water. Work also began this water on designing the flow control systems for gas, oxygen, and nitrogen to six burners instead of two. The water flow system was also designed. All of the components needed for metering, flow, valving, piping, and instrumentation were ordered this quarter. All data will be collected through Labview data acquisition modules. These modules have now been ordered, and the software modifications were initiated this quarter.

Several special systems must be properly designed and built for a melter producing up to 1 ton of glass per hour. These include the six burners (fabricated this quarter), a new platinum discharge pipe (under fabrication at Corning), an in-bed thermocouple (to be fabricated at Corning next quarter) to directly read melt temperature, and a safe, practical melt collection system. A design for the melt removal conveyor was completed this quarter, and the unit was ordered with delivery planned for late next quarter in time for use with the first melt tests.

Glass companies consider the platinum discharge pipes they use to be proprietary. Therefore, the pipe designed for the lab-scale SCM was intentionally designed to not conflict with known, proprietary designs. The pipe consisted 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 operation, a new pipe was designed for flows up to 1500 lb/h when used with the new pilot-scale SCM unit. This new pipe will be straight instead of having a 90 degree bend. The pipe diameter will be increased to 60 mm. Carsten Weinhold of Schott is again designing this piece, and the Corning metal shop will again fabricated the platinum pipe. Owens

Corning is providing the power pack and transformer to operate the platinum pipe. This work was underway this quarter and will be completed next quarter.

Collecting up to 2000 lb per hour of molten glass requires careful operation to avoid unsafe situations. The team considered a number of methods to handle this rate of glass flow and spent considerable time looking at water channels with belts and chains. These systems are used industrially and would work well. However, they are large and costly and were considered to be excessive for the pilot-scale melter tests. The final design was simple and robust for testing and met with the available budget and timing. The WHM Co. of Cincinnati is building the discharge unit.

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 lab-scale SCM unit before the last melt tests. 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 last quarter and sent out for fabrication bids. This second burner modification was sent out for fabrication this quarter and will be tested next quarter.

The six burners for the pilot-scale melter will be based on the stable, proven burner already used in the lab-scale SCM. If the new burner design proves superior, future burners will incorporate some of those design features. One modification explored this quarter for the burners is the concept of applying a plasm-deposited zirconia coating on the top face of the burner. This should improve burner life and reduce potential for metal contamination of the glass. Talks with Sulzer-Metco engineers revealed this is possible, and a shop has been found to do this work. The burner tops will be zirconia coated next quarter in preparation for testing.

Figures 19, 20, and 21 show an end view, a side view, and a top view of the plilot-scale SCM final design.

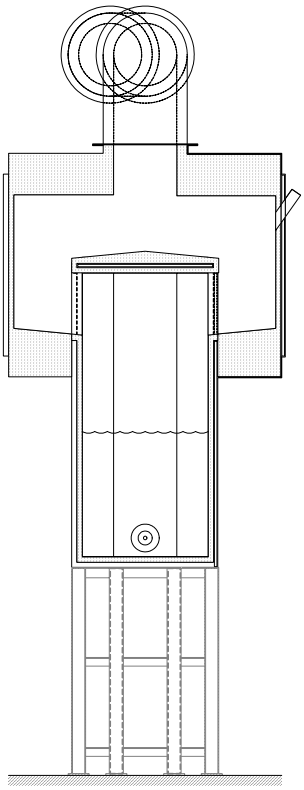


Figure 19. End-View of the Pilot-Scale SCM Unit

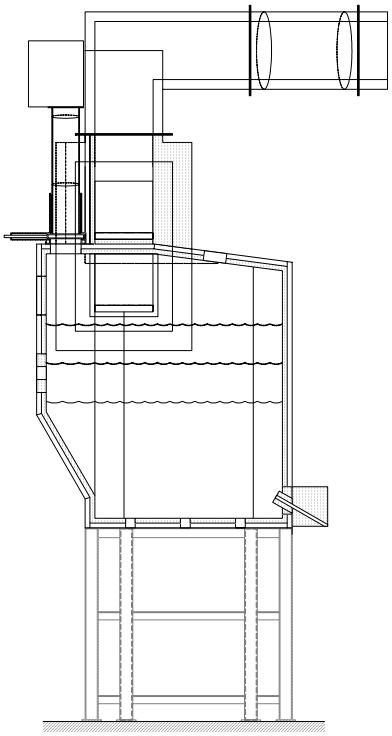


Figure 20. Side View of the Pilot-Scale SCM Unit

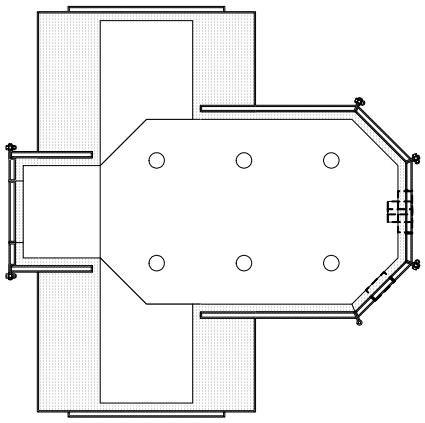


Figure 21. Top View of the Pilot-Scale SCM Unit

Oxygen Transport Membrane (OTM)

Engineers from Praxair and GTI met in December, 2005 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. Upon further analysis, Praxair engineers now feel that the OTM technology may offer some important advantages for the NGMS process. They are now tasked with this analysis and providing a full report over the next two quarters. The report from Praxair is expected by the end of Augusts, 2006 and will be submitted to both DOE and NYSERDA.

Industrial Bandwidth Analysis

GTI, with support from consultant Warren Wolf, completed a report titled, "Industrial Glass Bandwidth Analysis" this quarter. The full report will be made available next month through both DOE and GMIC.

This Industrial Glass Bandwidth Analysis has been prepared as a guide to determining places in the glass-making process where energy can be saved and means by which energy can be saved. This has been accomplished by reviewing available literature, discussions with industry experts, and several rounds of questionnaires sent to industry experts. The glass industry is often reluctant to reveal detailed energy data for proprietary reasons. For this reason, public data has been used as much as possible and affiliations of industry experts have been left out of the references. The authors trust that this approach has improved the quality of the reported information without detracting from the credibility of the sources. Energy use data is often not collected directly but is embedded in the price of materials, utilities, or oxygen. Other times, energy data is available but only for the combination of several process steps. Efforts have been made to examine energy use alone in this report.

The objective of the Bandwidth Analysis is to provide a current benchmarking of glass industry energy use. When benchmarking energy use in the glass industry, each of the major

glass segments must be considered separately in order to reach useful energy use profiles. Also, to provide guidance on where the largest energy savings are possible, the energy use in each glass industry segment has been presented two ways: 1) by process step, and 2) in current average, state of the art, practical minimum, and theoretical minimum. Details of the project approach are presented in the appendix of the Final Report for reference.

Plans for Next Quarter

Work will be carried out next quarter on a number of project activities. The primary focus will be on installations of pilot-scale melter components and on continued CFD modeling.

Modeling. Model refinement activities will continue next quarter as the time of the first pilot tests approaches. 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 Step 2 and iterate back to Step 1. In addition, the research to define the Step 3 method will be performed. The FLUENT development work will target those enhancements that can aid the chosen simulation approach. Commercial release of FLUENT 6.3 (the beta version of which is being used by the project team) is targeted for September.

Stage 3 method development	Jul-Aug
Validation using pilot test data	Sep
Simulation of other glass types & design variations	Oct
Melter scale-up analysis	Nov
Model documentation and deployment	Dec

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:

- Solution of combustion kinetics and incorporation of these results into the overall SCM model
- Work with FLUENT to complete a working model of the full SCM unit that incorporates hydrodynamics, combustion, heat transfer, radiation heat transfer, and turbulence.
- Preparations to use the CFD model to compare calculations with experimental results in the fourth quarter when pilot-scale tests are planned with multiple glass compositions.

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 supporting components for the pilot melter system. This system was adapted to work originally with the smaller lab-scale SCM unit. The larger 1 ton/h melter design concept work was has been completed and all CAD fabrication drawings were completed this quarter. This quarter components have been ordered and pilot melter panel fabrication continued. Pilot-scale SCM erection is planned for next quarter. This will include

- Assembling the melter
- Installing a 1.5 inch layer of high-alumina castable refractory
- Installing the burners and combustion control system
- Installing all oxygen, natural gas, nitrogen, and water lines and flow control systems
- Installing all sensors and data acquistion equipment
- Completing the electrical hookups for the full unit
- Finishing fabrication of an improved platinum discharge pipe at Corning followed by installation and shakedown at GTI
- Rebuilding the tri-plex platinum thermocouple at Corning and installation through the melter floor up into the melt chamber
- Construction of the water trough conveyor system to collect and remove product glass for storage and disposal.

Shake-down testing of the complete pilot-scale SCM unit is scheduled for the end of next quarter, and pilot-scale SCM tests are planned for the following two quarters.

The platinum discharge pipe and the triplex melt thermocouple were tested on the lab-scale melter. The tap worked well but must be redesigned and re-built for higher pilot-scale SCM flow rates. The triplex thermocouple will be replaced with a new triplex platinum sheathed thermocouple coming up from the floor. The peripheral units (batch hopper, feeder, baghouse, melt removal, sample collection, etc.) were installed last year and have been 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 Labeiew data collection are now installed and operational. These systems are being expanded for the pilot-scale melter.

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 in 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 was removed from the test cell. No testing is planned for the next quarter as the pilot-scale melter is assembled. Tests will be made in the next two quarters with the new pilot-scale melter and new tap piece. Glass compositions will include soda-lime, LCD, E glass (containing boron and boron-free), scrap continuous fiber, and scrap

matt glasses. All data will be collected via Labview software. Samples of product glasses will be analyzed by GTI and several glass company partners (Corning, Owens Corning, Johns Manville).

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 7th 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. 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 were made last quarter to the management and senior technical staffs of three of the five glass consortium member companies as well as to project managers at NYSERDA. Presentations to the other two glass company partners (Johns Manville and Schott) were made this quarter. These presentations were 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.

A report titled, "Industrial Glass Bandwidth Analysis", was completed this quarter and will be made publicly available through DOE and GMIC next quarter. This document is based on extensive review of published data and discussions with many glass industry professionals regarding energy use in the U.S. glass industry.

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 last quarter
3	Procure equipment for pilot scale melter	Sept. 2004		Continued this quarter
4	Fabricate pilot scale melter	March 2005		Continuing next quarter for larger pilot melter
5	Prepare test plan	March 2005	March 2006	Completed last quarter
6	Complete pilot scale melting tests and collect samples	July 2005	Nov. 2005	Completed
7	Complete all sample analyses	Sept. 2005	Dec. 2005	Completed last quarter
8	Modify melter as needed	Dec. 2005		Complete next quarter
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		
13	Complete Bandwidth Report	Feb. 2006	June 2006	Completed this quarter

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.

			Approved Spending, $K			**Actual Spending, $K**		
Phase / Budget Period			**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**	**922**	**2**	**924**
Total			**3983**	**1450**	**5433**	**3490**	**817**	**4307**

References

1. Rose, J.W., and Cooper, J.R., eds. (1977), *Technical Data on Fuels*, New York: Wiley, 7th Edition.
2. 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
06-30-06

Project Title: High-Intensity Plasma Glass Melter

Covering Period: 4/1/06 to 6/30/06

Date of Report: July 29, 2006

Recipient: Plasmelt Glass Technologies, LLC
2845 29th 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
Michael A. Weinstein, 303-530-2727, 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 and ends 7/27/06.

EXECUTIVE SUMMARY

During the Second Quarter, there has been no activity since the funds are now exhausted. We are now focusing our efforts on getting organized to write the final report and to give presentations to as many companies as possible in order to get the message out among the glass industry. We continue to solicit and work with private companies to try to take this technology to the glass industry and locate those customers that can take advantage of the strengths of plasma melting technology in their production operations. We are committed to implementing the technology within the glass industry as rapidly as possible. Two presentations were given in the Second Quarter—the Glass and Optical Materials Division in Greenville, SC and the Advances in the Fusion of Glass in Dresden, Germany. Since our request for additional DOE funding was not approved, Plasmelt paid for these trips from its own coffers since we continue to believe it is very important to try to implement this work to assist the glass industry to save energy.

A final DOE report will be written in the Third Quarter, 2006.

<End of Executive Summary>

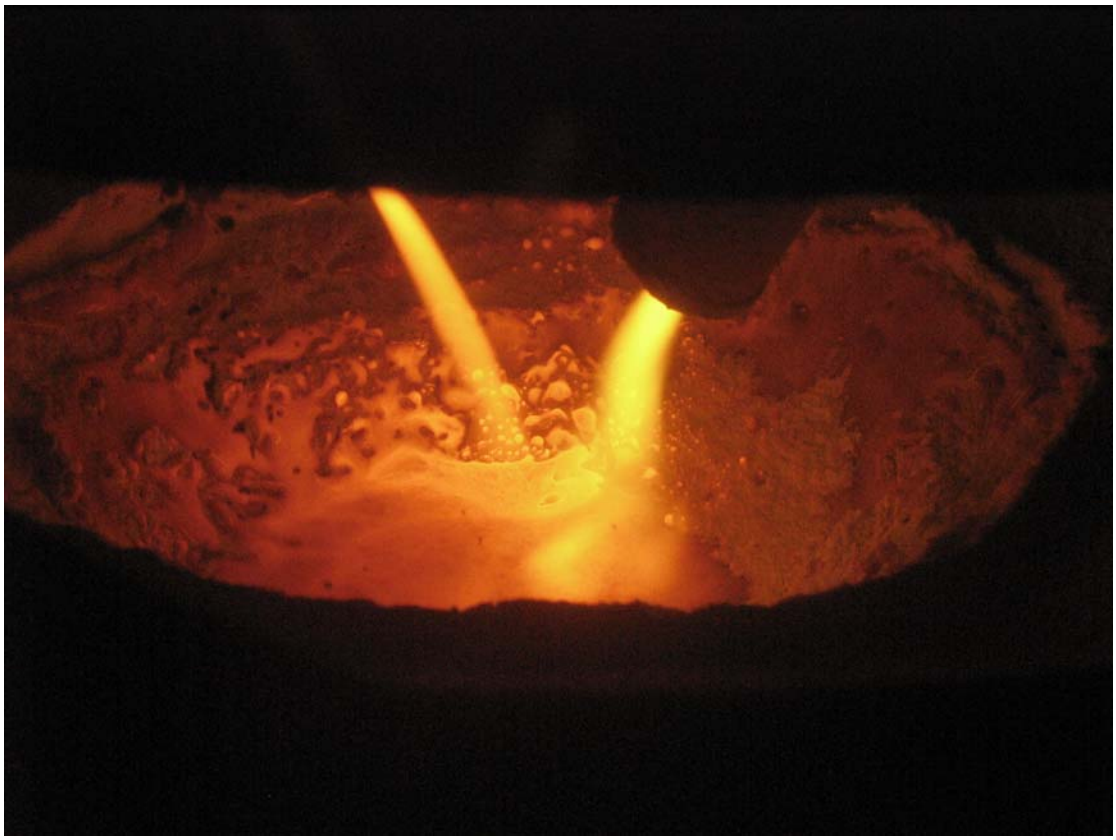
TECHNICAL CHALLENGES

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

4th 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.

DETAILS OF THE EXPLORATORY MELTING TRIALS

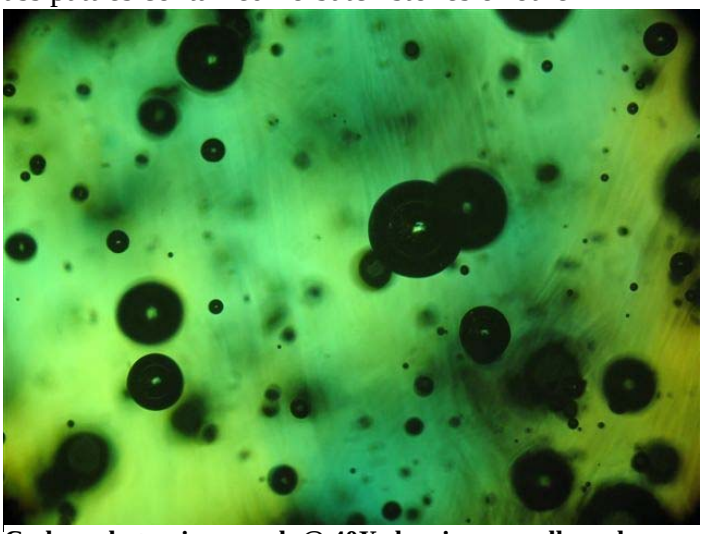
Chemical Analysis of Glasses Melted in 4th Quarter, 2005

	Final Glass Chemistry	Starting Glass Chemistry	RETENTIONS	Final Glass Chemistry	Starting Glass Chemistry	RETENTIONS	Final Glass Chemistry	Starting Glass Chemistry	RETENTIONS	
Oxide	C-glass			Low Flux E-glass			AR-glass			
SiO2	66.5	**66.39**	100.2%	58.7	**59.49**	98.7%	60.8	59.37	102.4%	SiO2
Al2O3	6.52	**6.44**	101.3%	13.6	**13.23**	102.8%	0.23	0.19	123.0%	Al2O3
Fe2O3	0.37	**0.39**	94.5%	0.425	**0.39**	108.9%	0.02	0.03	59.3%	Fe2O3
TiO2	0.01			0.07			0.044	0.04	99.6%	TiO2
B2O3	0.01			0			0			B2O3
Na2O	13.2	**13.21**	99.9%	1.35	**1.12**	120.8%	18.4	19.34	95.1%	Na2O
K2O	0.009			0.036			0			K2O
Li2O	0			0.001			0			Li2O
CaO	9.26	**9.41**	98.4%	22.6	**22.66**	99.7%	0.07			CaO
MgO	4.13	**4.16**	99.2%	3.19	**3.11**	102.4%	0.02			MgO
SrO	0.004			0			0.001			SrO
BaO	0.002			0.003			0.001			BaO
ZnO	0.003			0.009			0.002			ZnO
SO3	0.008			0			0.029			SO3
ZrO2	0.003			0.007			20.3	21.03	96.5%	ZrO2
MoO3	0.004						0.005			MoO3
CuO										CuO

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.

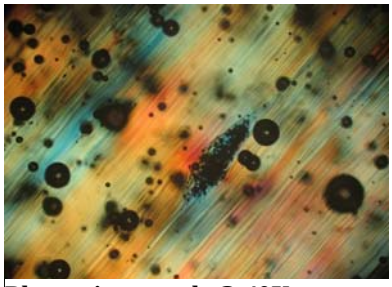
During the first of two runs, considerable difficulty was encountered with the torch operations. Two outages of the torches were traced to unstable purge gas flow through an error in the construction of the torch orifices. After correcting the problem, the torches

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 MoO3 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

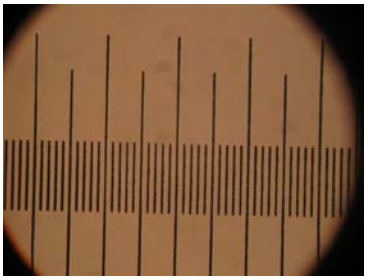
Glass quality was poor throughout the run. Numerous examples of incompletely melted batch were in evidence in most glass samples. The fine streaks of cordy glass typically contained abundant unmelted zircon grains. (Zircon is a batch ingredient used to supply zirconia to the AR Glass formulation.) The 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. 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

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

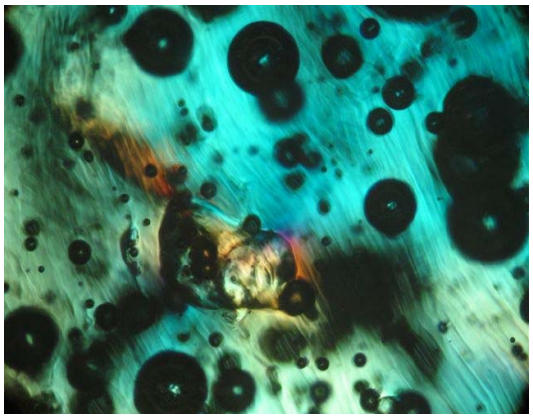


Reference scale with each division = 0.01mm

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% B2O3) 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.

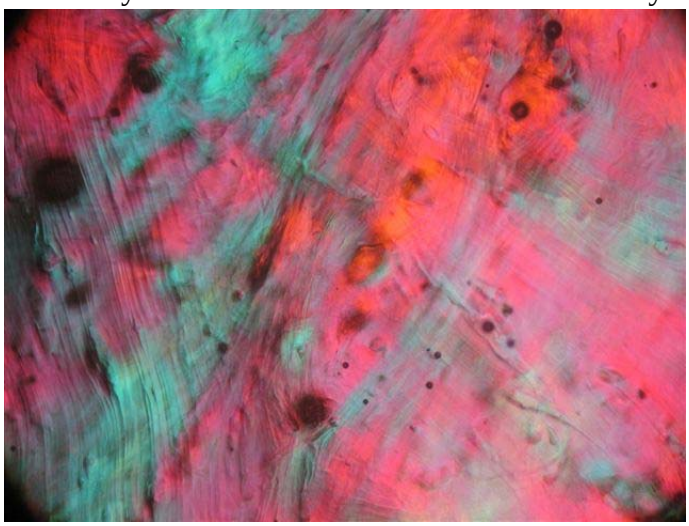
The glass melted and began draining in 6 minutes from start up. It became immediately apparent that the corrosion rate with the molybdenum orifice was very high, resulting in substantial quantities of black or streaked glass. High effluent was in evidence from the melter as the boron escaped as both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

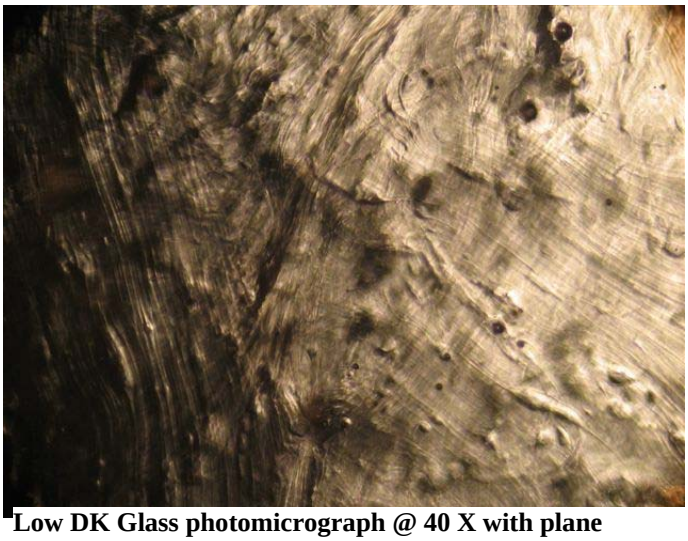
Petrographic analyses were performed on all glass patties. The glass was the lowest quality of any glass ever melted in the plasma melter. Abundant unmelted batch, scum, and heavy cord were much in evidence. The only redeeming attribute of this glass was its near zero seed level. This glass was, by far,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



Low DK Glass photomicrograph @ 40X with crossed nicols

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%

Na2O). 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.

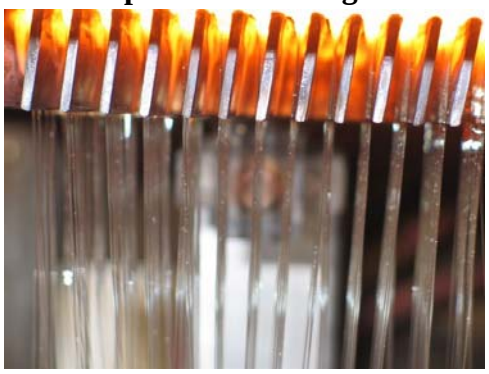
FIBERIZING TRIAL RESULTS

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.

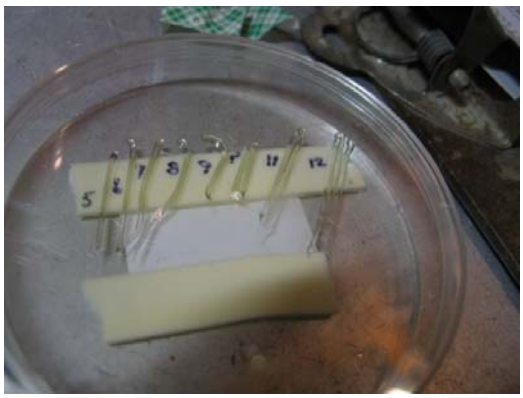
Nuggets were fed to a marble re-melt bushing for more than 15 hours. Fiberizing was continuously conducted.

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.

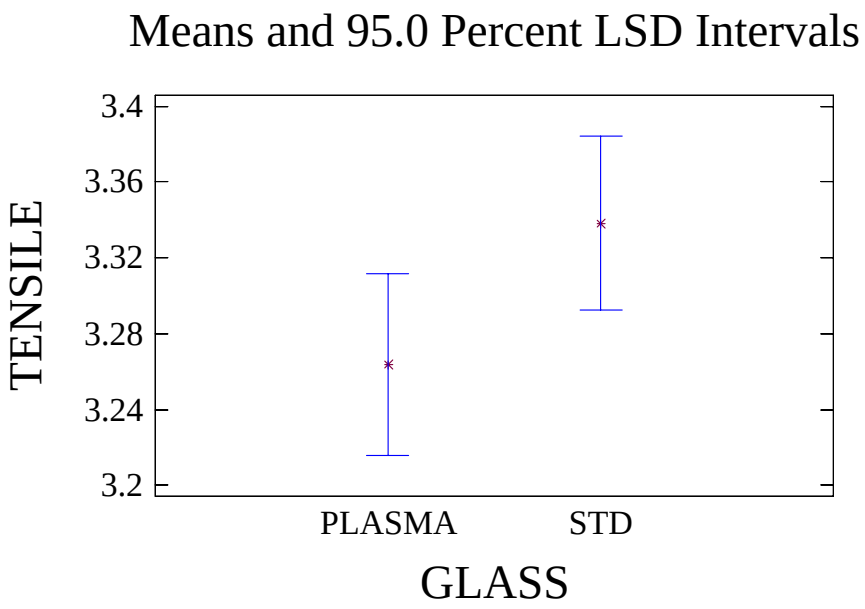


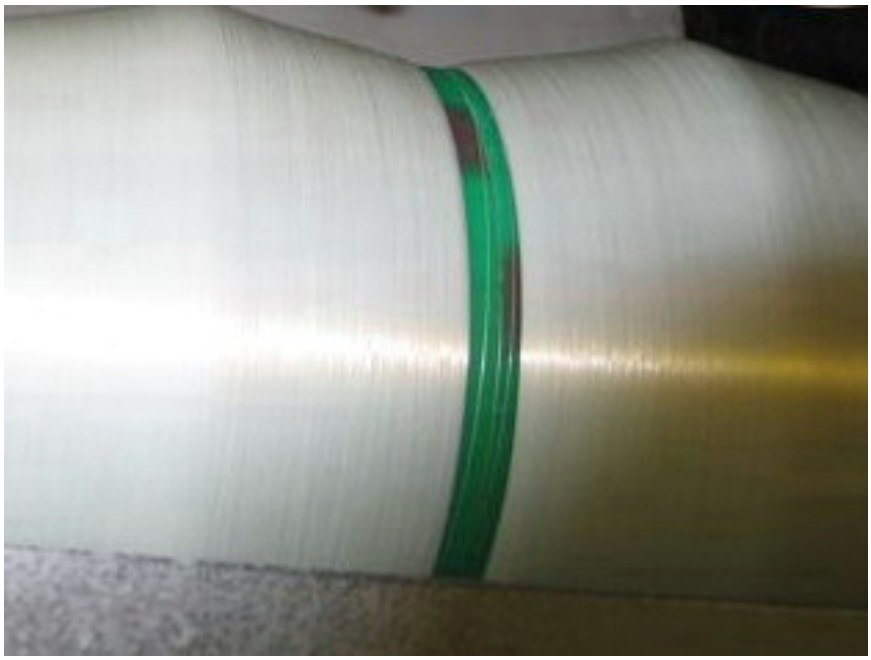
Glass Beads with Defects Collected During Fiberizing Trials

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.

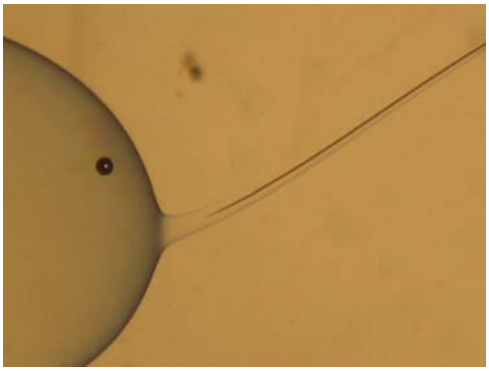
TENSILE STRENGTH TESTING SHOWED NO STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN PLASMA-MELTED GLASS AND STANDARD GLASS

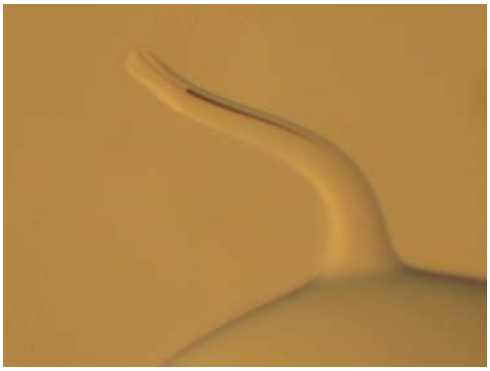




FIBERGLASS YARNS WOUND ONTO FORMING PACKAGES USED TO TEST TENSILE STRENGTH OF PLASMA-MELTED GLASSFIBERS

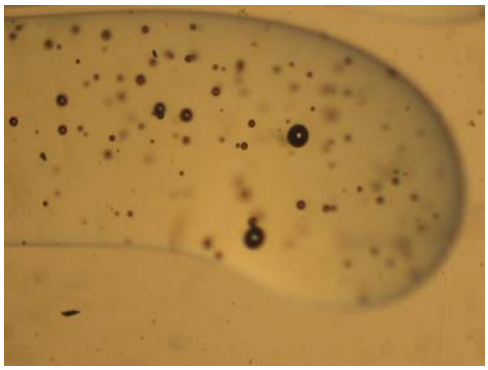
TYPICAL SEED BREAKS AS STUDIED BY MICROSCOPIC ANALYSIS
(100x magnification)





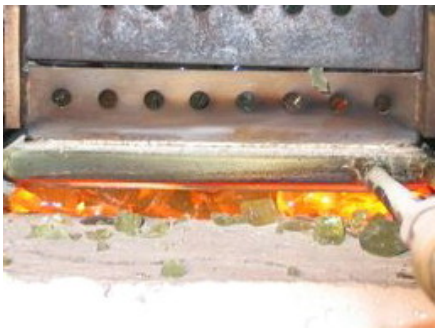
DARK LINES IN FIBER TIPS ARE HOLLOW FILAMENTS (seeds/bubbles)
THAT LIKELY CAUSED THE FIBER BREAKOUT

- 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.

	Plasma-Melted E-glass Produced in Boulder, CO Lab					"STANDARD" E-glass
Time of Production	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	
SiO2	54.39	--	54.32	--	54.27	**53.55**
Fe2O3	0.279	--	0.279	--	0.278	**0.26**
FeO	0.133	--	0.133	--	0.127	**0.09**
TiO2	0.57	--	0.57	--	0.57	**0.58**
Al2O3	15.06	--	15.01	--	15.00	**14.78**
Cr2O3	0.01	--	0.01	--	0.01	
CaO	23.05	--	22.91	--	23.07	**22.35**
SrO	0.167	--	0.166	--	0.165	
MgO	0.52	--	0.52	--	0.51	**0.52**
Na2O	0.33	--	0.37	--	0.37	**0.64**
K2O	0.03	--	0.04	--	0.03	
Fluorine	0.21	0.25	0.27	0.29	0.30	**0.45**
B2O3	5.42	5.56	5.57	5.66	5.67	**6.94**
MoO3	0.0054	0.0079	0.0049	0.0043	0.0082	
CuO	0.004	0.005	0.005	0.004	0.004	

SO3	<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 MoO3 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_2) 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 Na2O, K2O, and B2O3. 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 2nd 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:

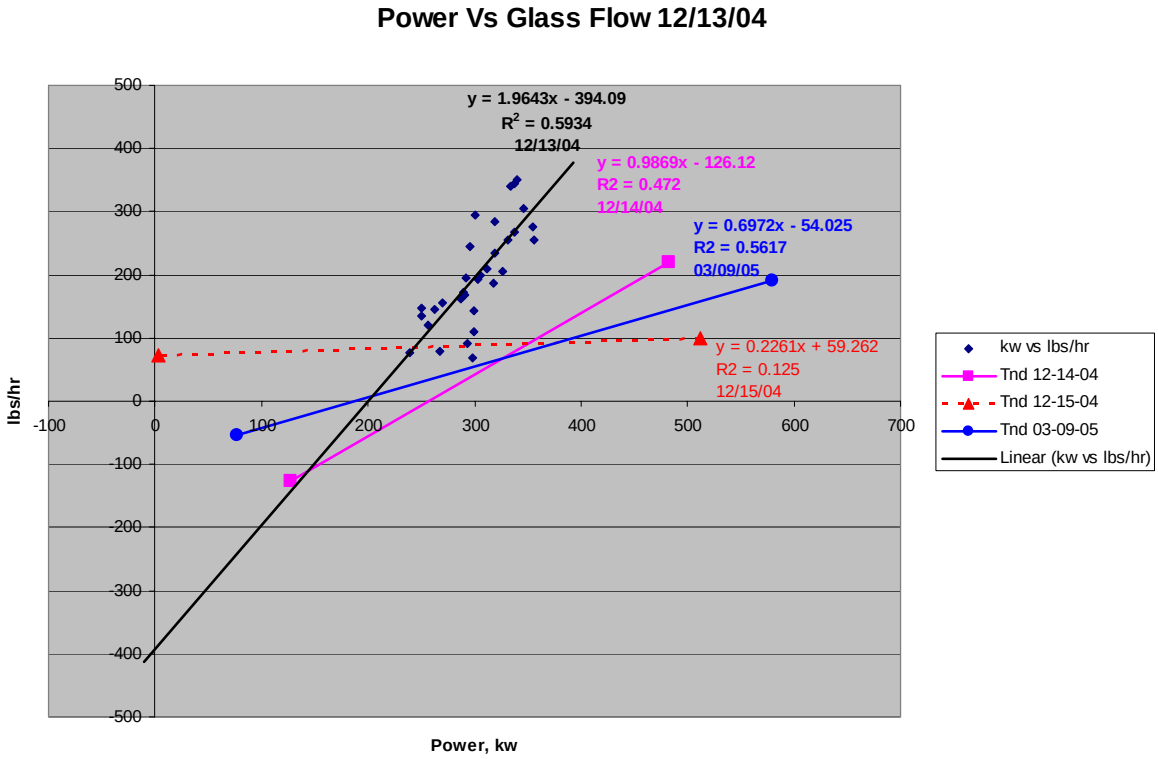
$$Power = Volts \times Amps = 415v \times 712a = 295kW$$

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

$$1kW = 3412.4BTU/hr$$

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

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 March 31, 2006, the project funds are exhausted. However, the final report will be written before the end of 3rd Quarter, 2006.

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

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	3/31/06	Note 1	$1,312,356	Note 1	$564,361.51	**$1,876,717.51**
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.							
Totals				$1,312,356		$564,361.51	**$1,876,717.51**

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 12/31/05) minus AGY cash contributions plus 1st Quarter, 2006 expenditures
i.e. $1,312,356=$1,876,717.51 (Total Project Expenses) minus $564,361.51 (Total Cost Share Contributions)
Total Cost Share Contributions of $564,361.51 = AGY Cash Contributions of $181,572.84 plus AGY in-kind of $139,427.16 plus JM in-kind of $242,037.02 plus Plasmelt cash of $1324.49.

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.
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:

The project officially closes on 7/27/06. We plan to write the final report in 3rd Quarter, 2006.

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 3rd Quarter, 2006.		On-going

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: April 1, 2006 through June 30, 2006

Date of Report: August 4, 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[1] 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,

[1] 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:

No costs were incurred this quarter as work was temporarily suspended.

Plans for Next Quarter:

The in-plant shakedown and testing of the improved system will be scheduled following successful testing of the system in ERCo's LIBS laboratory.

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):

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	6/30/05	Note 1	1,179,178.00	Note 1	1,605,006.00	2,784,184.00
3Q05	7/1/05	9/30/05	Note 2	1,179,178.00	Note 2	1,605,006.00	2,784,184.00
4Q05	10/1/05	12/31/05		1,179178.00		1,605,006.00	2,784,184.00
1Q06	1/1/06	3/31/06		1,278,375.01		1,605,006.00	2,883,381.01
2Q06	4/1/06	6/30/06		1,278,375.01		1,605,006.00	2,883,381.01
3Q06	7/1/06	9/30/06					
4Q06	10/1/06	12/31/06					
1Q07	1/1/07	3/31/07					
Etc.							
Totals				1,278,375.01		1,605,006.00	2,883,318.01

* 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).
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.

DOE Laboratory Spending Table (if applicable):

DOE Laboratory Partner Spending and Estimate of Future Spending					
Quarter	**From**	**To**	**Estimated DOE Lab Amount***	**Actual DOE Lab Amount**	**Total**
	Start	6/30/05	Note 1	155,000.00	155,000.00
3Q05	7/1/05	9/30/05	Note 2	0	0
4Q05	10/1/05	12/31/05		0	0
1Q06	1/1/06	3/31/06		0	0
2Q06	4/1/06	6/30/06		0	0
3Q06	7/1/06	9/30/06			
4Q06	10/1/06	12/31/06			
1Q07	1/1/07	3/31/07			
Etc.					
Totals				155,000.00	155,000.00

* Update quarterly

Index of Award CID Numbers

Index of Award CID Numbers

Agr id:04895 1
GO13092 2
GO13093 3
ID14030 4