HIGH INTENSITY PLASMA GLASS MELTER PROJECT
FINAL DOE REPORT

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Recipient: Plasmelt Glass Technologies, LLC
2845 29th Street
Boulder, CO 80301

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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)
Tim Ramsey (Project Engineer)

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EXECUTIVE SUMMARY

1. How the research adds to the understanding of the area investigated.

Our research adds to the body of existing plasma technology knowledge in two ways:

a. Most past work using plasma melting has been focused on the melting of non-glassy materials systems. Westinghouse, PEC and other companies have emphasized the use of plasma melting for metals and scrap/waste in which the material was highly conductive. Plasmas in these systems were generally a non-transferred type in which the plasma torch was used as a cathode and the molten material was used as an anode. This approach did not focus on the production of high quality glass as a final objective. The Plasmelt project did focus on high-quality non-conductive glass as a primary goal.

b. In the 1990's, JM and the British Glass Technology both actively investigated glass melting using plasmas. However, JM did not emphasize the assessment of glass quality and the relationship between the plasma melting process and glass quality. The JM efforts were largely targeted at discontinuous fibrous glass applications at high throughputs of 1200 #/hr or greater. These high throughputs were never achieved so the program was abandoned.

The British Glass project emphasized a static crucible melting technique that was not a continuous process. It was later adapted to be a continuous refractory box melter that was not able to take maximum advantage of the high rates of heat transfer from the plasma torches. The JM and British Glass efforts ended without any commercial applications.

Our present research has focused on developing a process aimed at high quality glass applications that have commercial applications. We have successfully developed a plasma melting process capable of producing glass with sufficiently high quality to allow it to be fiberized into a small (>10 microns) diameter. This fiberizing test is a tough test that cannot be passed by glass of poor homogeneity/quality. At the completion of the DOE project, Plasmelt is aggressively marketing the plasma technology platform for implementation into specialized niches within the glass industry.

As the first attempt to fiberize plasma-melted glass, this project was successful. To our knowledge, no other company in the world has successfully made continuous glass fibers from plasma-melted glass. The absence of batch stones, moly, or devitrification or any other defects in this plasma-melted glass is very encouraging. Finally, the tensile testing results of glassfibers, comparing the plasma-melted glass and the glass melted in standard production operations, are not statistically different between the two populations.

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.

2. The technical effectiveness and economic feasibility of the methods or techniques investigated or demonstrated.

Past plasma melting efforts have highlighted several technical barriers that must successfully be resolved before plasma melting can take its place as a viable commercial process:

- short torch lives
- instability in the process
- poor glass quality
- metals contamination from process hardware
- low maximum throughput of the melter
- energy efficiency

a. This work has shown that torch lives can be significantly improved toward the goal of 100 hours. We have already demonstrated >30 hours on an un-optimized process. Our design innovations and proprietary process adaptations have allowed this improvement.

b. Process stability can be achieved with careful control of torch placement, batch feeding, and exit orifice design.

c. Quality of glass can be sufficiently high to fiberize into 9 to 13 micron fibers.

d. Metals contamination by moly is manageable through proprietary process setup and operation of the torches. Failure to understand and implement these innovations will render a typical plasma-melting glass operation highly contaminated with “black glass” from the moly used in the glass contact areas of the furnace.

e. Process throughput and efficiency are largely controlled by the type of glasses melted and the melting behavior of these. Attention to detail of process operation including torch locations, proximity to the glass and to each other, kilowatts delivered from the power supply, all play a role in determining the ultimate capacity limitation.

f. Energy efficiency is directly proportional to throughput. Our moderate success in demonstrating efficiency was in part limited by our equipment’s age, not by the fundamental physics and chemistry of our system. Without a high risk of failure, we were not able to push the power supply to its maximum rating of 1.5 megawatts due to its age. We never exceeded 0.75 megawatts during any run. This power limitation did not allow the higher 500 or greater throughputs. With a new power supply in the future, we continue to believe that >500 #/hr is achievable. This work will be pursued under our commercial contract after the DOE project is completed.

3. How the project is otherwise of benefit to the public.
   a) Plasma melting of glass and other materials has been shown to be possible using this low cost very flexible melter that can be started and stopped easily, unlike large existing commercial melters. Flexible melters can be used for one-shift/day operations or sporadic schedules. It is only possible to shut down large melters by first draining glass, then cooling according a show cool-down schedule over many days. Plasma melter can be shutdown and re-started in minutes. Energy savings are possible if these melters are only operated upon demand, as opposed to banking or curtailing large melters and continuing to use energy even though production has ceased.
   b) Low cost plasma-melting modules can be added to existing furnaces that are melting glasses or non-glassy materials as a means of adding incremental capacity without significantly changing the existing footprint of a commercial operation.
   c) Certain mineral compositions, which cannot be melted any other way, can be melted with high temperature plasma melters.
   d) Many small low cost plasma-melting units can be installed in multiple distributed locations to melt glass, materials, or scrap—as opposed to one large regional location. Individual distributed small units close to the end users may help minimize long-distance freight of raw materials or end products.

4. Summary Conclusions & Recommendations:
   a) This project has shown the feasibility of melting glass using a furnace fired with dc remotely coupled transferred arc plasmas.
   b) The rotating furnace design used for this project has demonstrated excellent flexibility via rapid startup and shutdown. Glass flow can be achieved within 15 minutes for many glass compositions; glass flow can be ceased within 5 minutes.
   c) Energy efficiency is a strong function of the type of glass melted and the throughput.
   d) Glass throughputs up to 350 #/hr were achieved with this melter design and plasma firing system. At this throughput, the energy efficiency was approximately 1.0 kwh/# or glass vs. a goal of 0.6. The aged condition of the power supply, which was contributed by cost share partner JM, was the rate-limiting factor. This limit is not a fundamental limit of this furnace design, but simply a practical limit imposed by the used equipment utilized in this project. A state of the art power supply that is capable of generating 1.0 MW should give an excellent change of achieving the goal of 500 #/hr using this same melter design.
   e) Poor glass quality can result if short dwell time glass is allowed to escape the melter orifice prematurely.
   f) Torch design and operation have been shown to allow drastically improved torch lives. Actual lives achieved were in excess of 30 hours.

g) Glass quality was highly variable and was a strong function of the glass composition and furnace operating conditions. Good quality glass that was suitable for fiberizing was demonstrated during this project. The fiberizing performance is an excellent method of assessing the quality of glass produced.
h) The plasma torches can heat glass to very high temperatures in excess of 3400^{o}F. Measuring the actual temperature distribution within the 3-dimensional plasma was a challenge. The spectrometric method used to estimate this distribution, showed temperatures in excess of 15,000^{o}K.
i) High seed levels in the glass are a function of the very short dwell times achieved by this furnace design. To use a rapid plasma melter for a low-seed glass application, a secondary method of refining must be also be used.
j) Our summary recommendations from the project are:
    - Implement this plasma system of melting glasses in commercial operations in which a high level of flexibility is required in order to avoid long periods of banked operations and deliver a more energy efficient operation.
    - Further studies should be done with a state of the art power supply system that can generate the maximum power needed to melt the 500 to 1000 #/hr significantly improve the energy efficiency of this system.
    - Further studies should be done with orifice designs that can stop short-circuiting and allow significantly improved dwell times as a means of lowering seed content and improving the quality of the glass.

COMPARISON OF ACTUAL ACCOMPLISHMENTS WITH GOALS AND OBJECTIVES OF THE PROJECT

- **Project Goal**: Develop an efficient 500 lb/hr transferred arc plasma melting process that can produce high quality glass suitable for processing into a commercial article.
- **Project Objective:** The objective of Phase I is to determine the design, process, and control requirements to produce 500 lb/hr high quality glass without the need for more costly add-on refining and conditioning technology. The very high temperatures and interactions between the plasma and the molten glass allow a high degree of mixing which may be sufficient to produce a high quality product without the need for conventional refining.
- **Project Background:** The purpose of this project was 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 utilized a full-scale test melter system. The system is similar to the one that

was originally constructed by Johns Manville, but Plasmelt added significant improvements to the torch design and melter system. The original JM design was 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 ended 7/27/06.

- **Project Accomplishments:**

a) Within 4 months of the initiation of the project, a building was leased and all lab infrastructure was designed / 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 to allow the routine melting of glass using a plasma system.
b) During the project, more than 50 torch designs were evaluated. A standard 5/8 torch was designed that was routinely used and allowed the process to run continuously in a stable hands-off mode for > 6 hours.
c) Torch lives 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 >30 hours and in a stable operation, its life is expected to be 2 or 3X of the 30 hours.
d) A process has been demonstrated that is capable of continuously melting glass in the 200 to 250 pounds per hour for several hours. We anticipate this same configuration would run for days, but this was not a goal of the project.
e) The standard 5/8 inch torch has been used to operate briefly the process at pull rates of ~ 350 #/hr.
f) 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 design, a more stable power supply, and upgraded infrastructure is required.
g) Preliminary chemical analyses of plasma-melted glasses show that overall, the analyzed glass samples were essentially on-composition, with somewhat higher losses of volatile species, such as boron and fluorine. These glasses were slightly more reduced than their counterparts melted via conventional gas-fired electric boosted melters.
h) Petrographic assessments were made of several hundred E-Glass patties produced during trials. These generally show a good quality of glass with a very high seed count, minimal cord, and only very rare (or no) un-melted batch stones.
i) Initially, contamination from moly was a serious problem. We were able to understand and define successfully the process boundary limits to circumvent the production of black/streaked glass. This accomplishment was a major step forward.
j) The best energy consumption values achieved in the project were 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 due to our emphasis on high glass quality. We have not yet reached the maximum potential of the plasma melter system to deliver better energy

efficiencies. This work is on going beyond the DOE project and is funded by private commercial efforts.

k) A market study was completed. Candidate early adopters were identified and discussions were held with many of these companies.
l) Melting trials have shown that the system is capable of easily melting 200 #/hr of S-2 Glass. The probability is high that 2X this level is possible with only minor improvements in the batch feed system.
m) We developed a preliminary understanding of the process settings and how these relate to a stable melting operation.
n) The design, construction, and operation were completed for a refractory glass delivery channel that will transport the glass from the melter exit orifice to the processing area.
o) A patty-making machine was installed and rendered operational in the Boulder Lab.
p) Several preliminary methods for glass flow control were identified.
q) One exploratory glass melting trial was completed on a frit composition that is commercially produced by a US glass company.
r) Approximately 400 # of good quality glass nuggets were produced from a two-day period when the melting operation was very stable. These nuggets were shipped to AGY for fiberizing trials.
s) Fiberizing trials were 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.
t) Exploratory runs were made on lighting glasses melted in the plasma melter.
u) Exploratory runs were completed on a broad range of glass compositions including E-glass fiber scrap, C-glass, S-glass, AR-glass, Low DK glass, B-glass, and two mineral composition glasses.
v) Several designs of orifices were trialed during the project. None allowed the successful modulation of throughput during glass melting. Further trial work outside the DOE project is planned to develop and refine the orifice design, which is critical to controlling glass flow from the melter.

PROJECT SUMMARY

This project was proposed under the DOE solicitation for “Glass Melting of the Future.” The original premise was to build upon the substantial foundation that has already been laid by JM on the plasma melting of glass. Our optimism was based on the active involvement by Mike Weinstein in this JM project as well as his being an active participant of this Plasmelt initiative. The high temperatures of the plasma melting system were expected to provide much better melting and mixing than lower temperatures found in more conventional melters. In addition,

JM had experience with certain glass compositions being capable of melting at >1000 #/hr in this very small plasma melter. Since both of our cost share partners were fiber companies, we elected to emphasize E-glass as the glass of choice for much of the program. Our goal was to demonstrate that high quality E-glass could be produced at ~500#/hr rates that would be energy efficient and with low emissions.

The approach used was to acquire (as a cost share contribution) much of the same equipment used by JM in their earlier program, and re-construct the melting facility in our leased building in Boulder, CO. Several important missing pieces of equipment were purchased on the outside. This setup was completed quickly and melting began within 4 months of the project kickoff.

Early experience with the new melting system on E-glass showed many problems with very short torch lives and poor glass quality due to short circuiting of the partially reacted glass. The early days of the project was plagued by torch failures after only minutes of operation. The first months of the project were focused on iterating torch designs and torch fabrication workmanship to gain run-time. These efforts succeeded and within six to eight months of the project initiation, torch lives were no longer the weak link and allowed many hours of operation without failures.

Glass quality was quickly shown to be extremely poor at the higher throughputs where short-circuiting was at its worst. The short-circuiting was aggravated by the JM orifice design concept in which there was no mechanical or thermal valve available to modulate flow in order to improve dwell time and minimize short-circuiting. Other designs were conceived and tested, but it became obvious that modifying the JM design on a rotating melter would be a major effort. Thus, after consulting with our cost share partners, we elected to reduce throughputs to minimize short-circuiting, continue with the JM-type orifice designs, and focus the project on achieving good glass quality at lower throughputs. This approach later proved successful by allowing us to produce glass nuggets that were of a good enough quality to fiberize successfully in 9 to 13-micron fiber bushings. Radically different orifice designs were outside the scope of this DOE project. Different orifice designs are currently being pursued outside the DOE work with private funding.

One of the goals of the project was to demonstrate to the glass industry that the plasma technology platform is broadly applicable to glass melting. We therefore scheduled a series of reconnaissance trials on a wide variety of glass compositions to conduct one or two days of melting experimentation on each. The long list of trialed compositions included chemically resistant (to acids) glass; alkali resistant glass, E-glass without boron or fluorine; a high-boron low-dielectric glass; a microfiber composition known as B-glass; lighting glass; frits; minerals melts in the feldspar family; high silica glass waste; zircon (zirconium silicate) minerals melts; kaolin (alumino-silicates) mineral melts; and scrap fibers

from E-glass. Glass was produced from all of these experiments. The quality varied widely. However, all show promise and with additional optimization efforts, most of these glasses are candidates for an efficient melting operation using plasma technology. Broad applicability of the plasma melting platform to a wide variety of glasses has been demonstrated during the project.

The impact of choosing to emphasize glass quality at lower throughputs has adversely affected our ability to demonstrate high energy efficiencies in the project. The work that was done has clearly shown the power consumption at low throughputs is highly inefficient. It has also shown the leverage in making throughput increases. To achieve a goal of ~4.1 MM BTU/ton (equivalent to ~0.6 kwh/pound of glass), it will be necessary to achieve the 500#/hr target glass melting rates. The best runs demonstrated during the project were limited to ~350 #/hr. These throughputs were fundamentally limited by the age and risk that our JM-donated power supply could no longer deliver its rating of 1.5 megawatts. Serious overheating of the power supply and small component failures at the higher wattage settings during some of our high-throughput runs caused us to back off. The risk of burning out the power supply was high and would have likely caused the program to halt due to the time and expense in replacing the unit. So, we elected to get as much out of the program as possible at the lower throughput settings and demonstrate that high glass quality was possible. A new power supply and a larger design torch will overcome these limits on throughput. We are fully pursuing this approach beyond the DOE project with private funding. The best energy consumption numbers achieved were ~ 6.7 MM BTU/ ton (or ~ 1.0 KWH/# of glass). Although this efficiency was lower than our goal, it is still remarkable that a small unit melter that is only one meter in diameter can achieve efficiency similar to other larger commercial conventional gas-fired melters that are 20 times the square foot area of this small plasma melter. This efficiency will allow some niche glass manufacturers to achieve better efficiencies with a much smaller flexible melter at a much lower capital investment—an attractive option!

Further details are included under the “Detailed Technical Discussion Section.”

PRODUCTS DEVELOPED

a) A small flexible rotating furnace design (See Figure 1)

Figure 1. Solidworks® Drawing of Plasma Arc Melter

b) A process definition for this melter including startup, routine operation, and shutdown procedures to demonstrate a highly flexible melting operation
c) Torch designs that have significantly longer lives than the initial designs commonly in use before this project began
d) Methods of performing rapid and low-cost assessments of glass quality
e) A process understanding that links the operation of the torches and batch feeder to the quality of the glass produced, to allow a high-quality glass-melting process to be defined
f) Although no patents were produced from this work, a significant body of trade secrets was assembled into a “plasma melting technology platform”

TECHNOLOGY TRANSFER ACTIVITIES

a) An existing commercially operational plasma melter in Boulder, CO that can, upon demand, perform contract melting of new glasses or materials for other companies
b) After the completion of the DOE funded project, a private contract was signed to commercially develop a plasma-melter as a pilot fiberglass

melter, which allows Plasmelt to bring other companies to view this melter at the ultimate production site

c) US DOE graphic was developed for publication by Energetics
d) Multiple workshops have been conducted by GMIC over the past 3 years to notify the glass industry of the plasma-melter project and highlight project results
e) An invited paper was presented in Dresden, Germany at the Advances in the Fusion of Glass Conference
f) An article was published in the Glass Researcher journal of the American Ceramic Society
g) Plasmelt continues to aggressively market this technology platform beyond the end of the DOE project

DETAILED TECHNICAL DISCUSSION SECTION

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

a) Torch life and stability
b) Glass Quality
c) Maximum throughput of the melter system
d) Energy efficiency

a. 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:

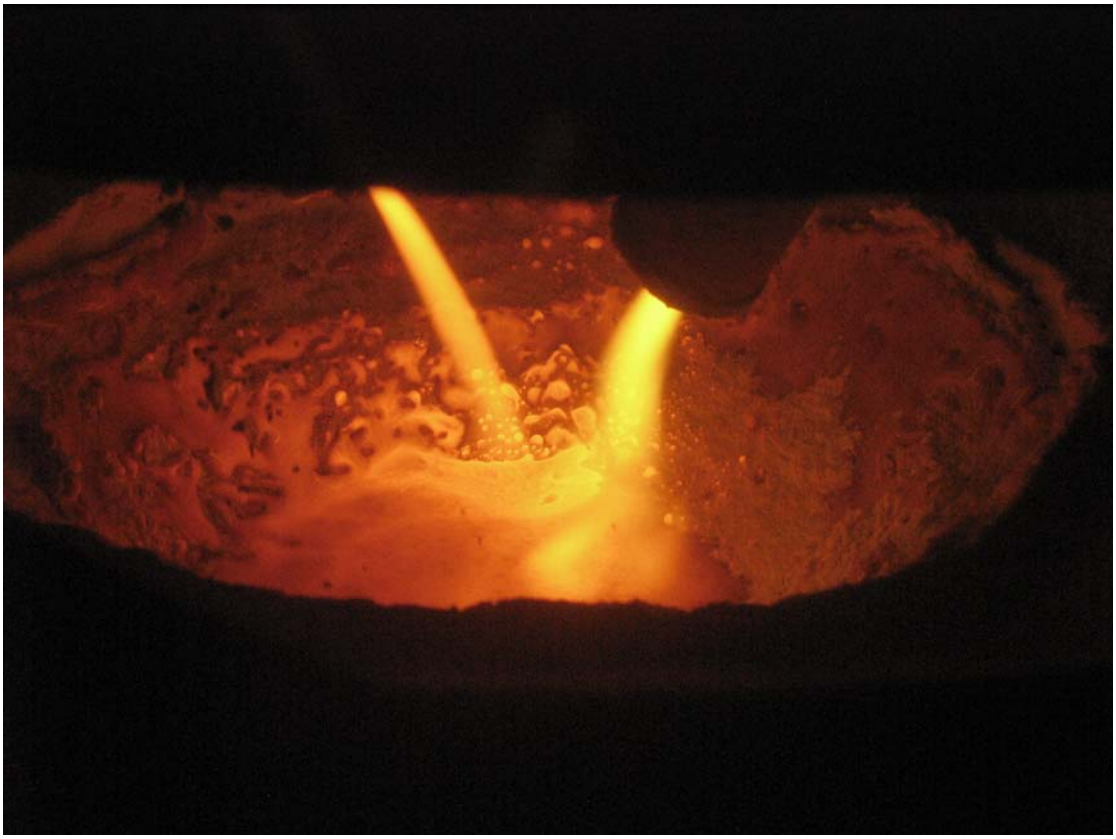


Figure 2. Plasma Torches in S-Glass Melting Operation

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 30 + 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 workmanship--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.

b. Glass Quality

Certainly, one of the most important technical challenges of this program was 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 was beyond the scope of this project.) Although there was always a finite probability that a separate refining process step would be required for plasma-melted glass to achieve the highest quality of glass, the goal of this program was to make this determination based on glass quality data and to quantify how much refining is actually accomplished within the plasma melter itself. Final results indicated that the plasma melting process will yield a high seed level of several hundred or a few thousands of seeds per ounce of glass, but seed level is a strong function of the glass composition. At least one composition, a high boron low dielectric glass used for fiberglass applications, was melted with very low seed levels. This confirms that some glass compositions are less susceptible to high seed levels than others. Low seed glass requirements cannot likely be met without an add-on refiner downstream of the plasma melter.

The temperatures involved in plasma melting are too high to effectively measure and we are left to postulate on the thermal history of the glass itself. Attempts to measure the actual temperatures continue to be a high priority task in the project. Dr. Scott Parker is working with us as a consultant to attempt to characterize spectrally the temperature distribution and the 3-D volume occupied by the plasmas. The approach being used is plasma spectroscopy in the range of 300-900nm. Ratios of intensities of the argon species are used to determine the temperature of the plasma. Abel inversion can be used to obtain the approximate temperature profiles.

During the second quarter of 2005, we 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 Huntingdon, PA facility for subsequent fiberizing trials.

AGY Fiberizing Results

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.

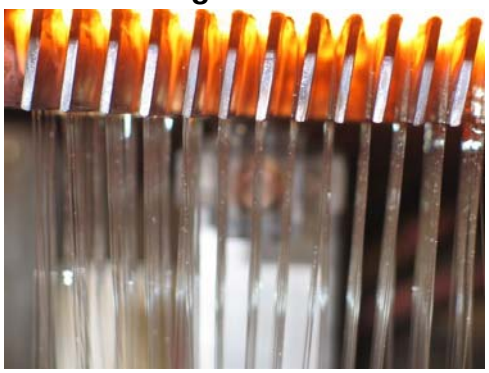
Since the two cost share partners for the High Intensity Plasma Glass Melter are both fiberglass companies, we initially have elected to use this method of characterizing the quality of the glass. One of the cost share partners, AGY, agreed to conduct these trials in their commercial facility. Their 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 lower-cost-marble substitute to conduct these trials.

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.

Figure 3. Nuggets Produced in Boulder Lab

Figure 4. 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.

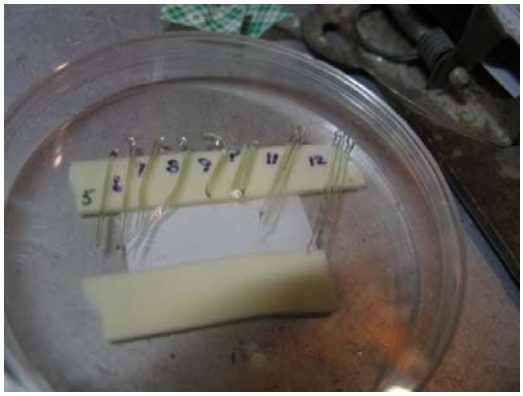


Fig. 5 Glass Beads with Defects Collected During Fiberizing Trials

Summary of 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. No stones were detected.
- Tensile strength tests of fibers showed no statistical difference between plasma melted and standard E-glass

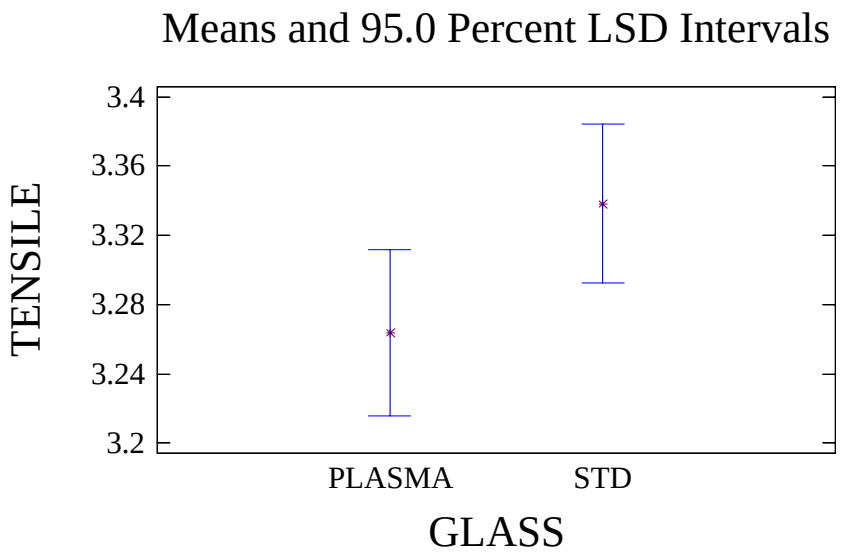


Figure 6. Tensile Strength Testing Showed No Statistically Significant Differences Between Plasma-Melted Glass And Standard Glass

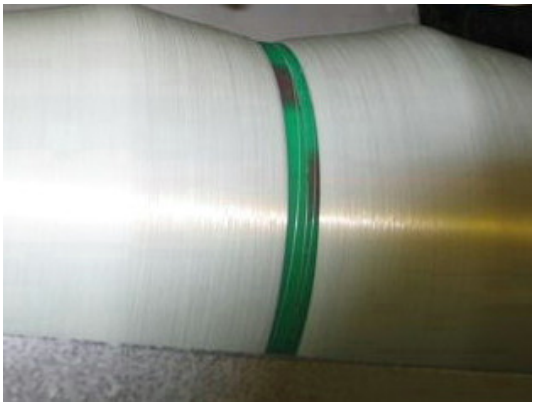
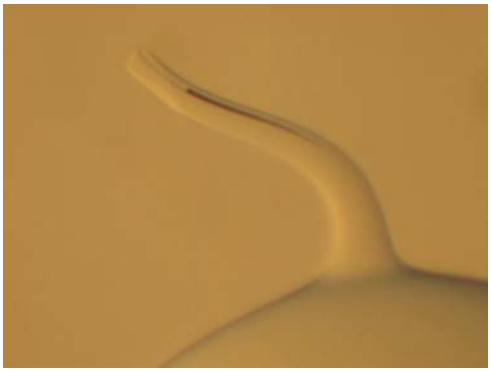
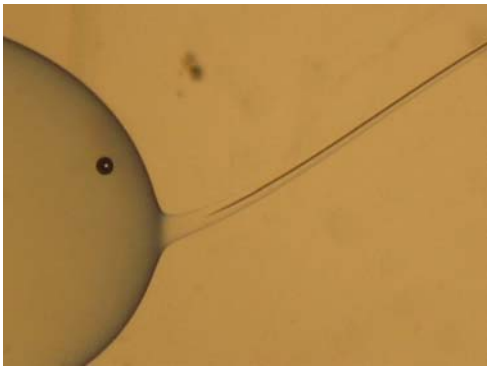


Figure 7. Fiberglass Yarns Wound Onto Forming Packages Used To Test Tensile Strength Of Plasma-Melted Glassfibers





Figures 8a & 8b. Dark Lines In Fiber Tips Are Hollow Filaments (seeds/bubbles) That Likely Caused The Fiber to Break Out

- 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.

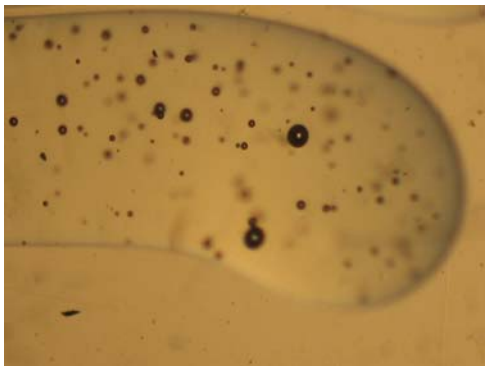
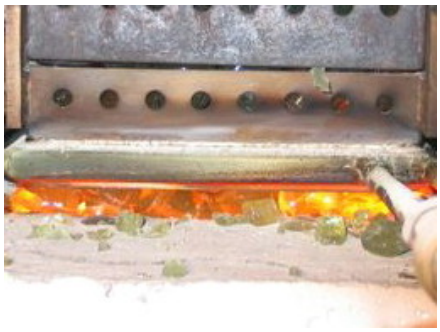


Figure 9. High Seed Levels Of Typical E-Glass Beads

- 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.

Figure 10. Unannealed Nuggets Produced On 4/11 Showing Tendency To Explode Upon Heatup

Implications of AGY Fiberizing Trial Results:

a) 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.

b) 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.

c) The major barrier to glass quality during this trial was high seeds. Thus, the need to conduct a refining project, as proposed to DOE by Plasmelt-

AGY-GAF is now conclusively supported with trial data. (Note: This Plasmelt proposal was not selected by DOE for funding and no further seed reduction work was done.)

d) The absence of batch stones, moly, or devitrification or any other defects in this plasma-melted glass is very encouraging.
e) The tensile testing results, comparing the plasma-melted glass and the glass melted in standard production operations, are not statistically different between the two populations.

Chemical Analysis Of Glasses Used for Fiberizing

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 Figure 11. 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 %.

Figure 11. Chemical Analyses of Plasma Melted E-glass

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.

In addition to the E-glass trials, further melting work was conducted using S-glass—a magnesium alumino-silicate high strength fiberglass composition. 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. Several trials were performed to help understand and circumvent this melt segregation problem. Alternate species and forms of raw materials were explored as a means to avoid unwanted silica scum formation. Significant progress was made in reducing this melt segregation via several proprietary methods, which will not be discussed here.

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 our orifice was not possible. We drastically increased the size of the orifice and 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 concluded that such a high viscosity glass, although it melts, cannot flow from our current design and it is not suitable for melting in this melter.

Exploratory Glass Melting Trials

A broad range of glass compositions was melted in the plasma melter. The purpose of these trials was to demonstrate broad applicability of plasma melting to a wide variety of glass compositions and to understand the limitations. 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.
- Scrap fiberglass made from E-glass chopped strand.

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.

Chemical Analysis of Glasses Melted in 4th Quarter, 2005

	Final Glass Chemistry	Starting Glass Chemistry	CALCULATED RETENTIONS	Final Glass Chemistry	Starting Glass Chemistry	RETENTIONS	Final Glass Chemistry	Starting Glass Chemistry	CALCULATED 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	0.0003			0.0012						CuO

Figure 12. Chemical analyses of Exploratory Glasses. Note: chemical analyses were contributed by JM.

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.

Figure 13. 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.

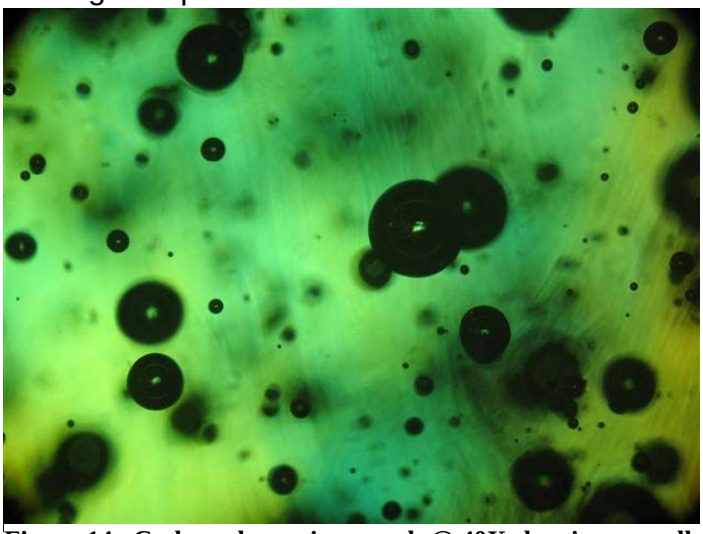


Figure 14. C-glass photomicrograph @ 40X showing overall good quality with low levels of cord, zero batch stones, and abundant seeds

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.

Figure 15. 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.

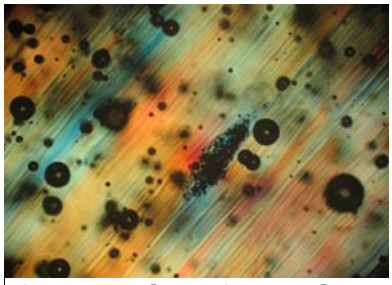


Figure 16. Photomicrograph @ 40X showing multiple cords, seeds, and unmelted batch stones

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 achieved 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

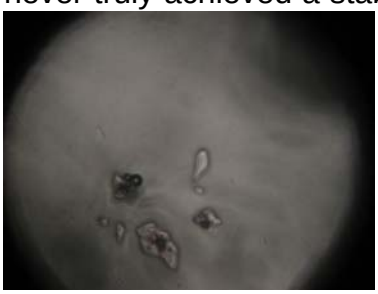


Figure 17. Low Flux E-glass showing clusters of unmelted batch silica grains (cristobalite)

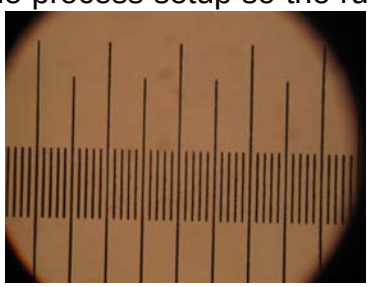


Figure 18. Reference scale with each division = 0.01mm

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 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.

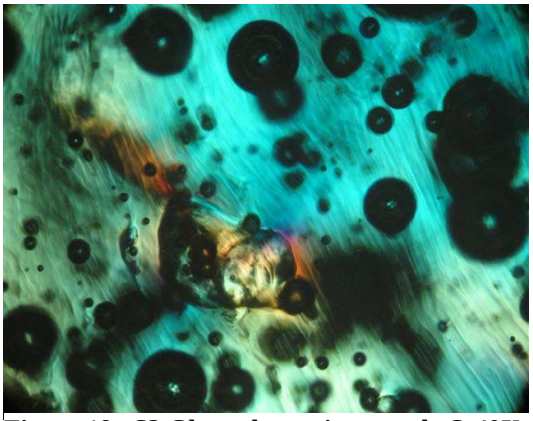


Figure 19. S2 Glass photomicrograph @ 40X showing cristobalite (silica) scum

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.

Figure 20. 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.

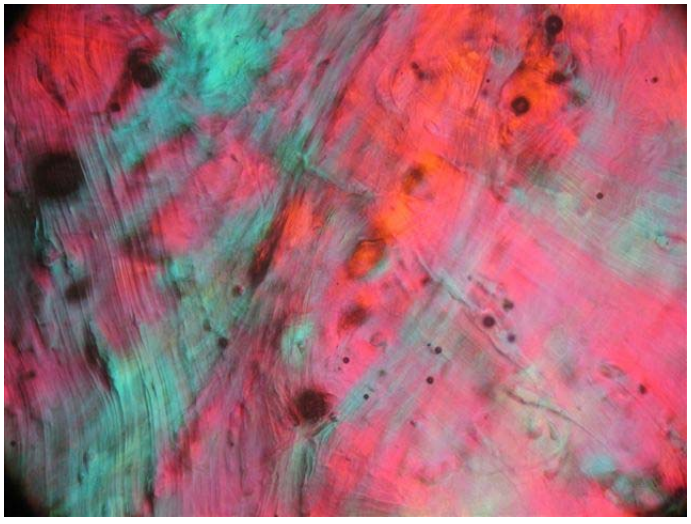


Figure 21. Low DK Glass photomicrograph @ 40X with crossed nicols

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.

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.

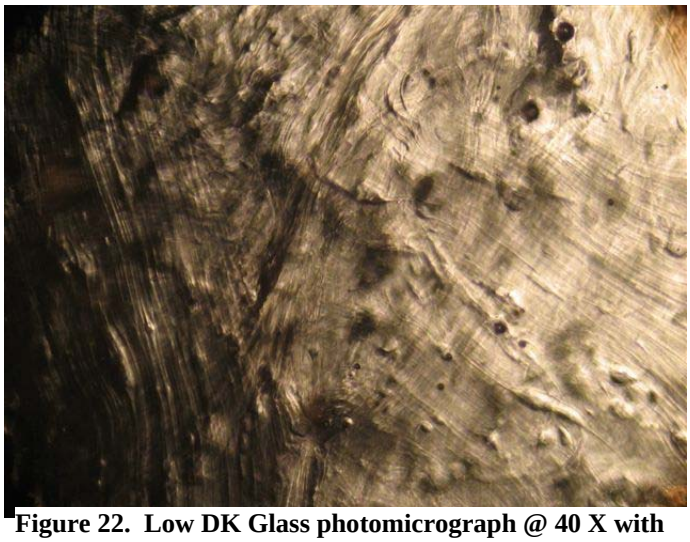


Figure 22. Low DK Glass photomicrograph @ 40 X with plane polarized light

This photomicrograph (Fig. 21) 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 temperature 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.

Maximum Throughput Of The Plasma Melter

All of the initial E-glass melting trials were conducted in the 50-350 #/hr range. The goal of 500 #/hr was not achieved. The method used for establishing throughput was 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^{o}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.

During the project, a “hands-off” process was 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 were also successfully completed. Automatic data logging equipment was used routinely to log all process conditions during glass melting trials. Temperature monitoring was 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.

Factors contributing to the lack of achieving the 500 #/hr goal includes:

- old age and instability (at high power levels) of the dc power supply contributed to the project as in-kind by JM
- small diameter and limited ability of torches to deliver the higher kwh required by 500 #/hr
- lack of stable batch feeder system
- lack of exhaust ductwork to handle the higher heat loads required by the higher power consumption
- the team (Plasmelt & cost share partner) decision to emphasize glass quality over high throughputs

Plasmelt’s future plans beyond the DOE project are to pursue the 500#/hr goal with private funding as a commercial R&D objective. This work is actively being pursued.

Energy Efficiency

The stated goal of the program is to achieve a melt rate of 4.1 MBTU/hr melting efficiency, which is 0.6 kwh/# of glass. That number was selected as a stretch goal over the previously demonstrated work completed at Manville. The following graph illustrates the measured energy efficiency for actual runs made during the program:

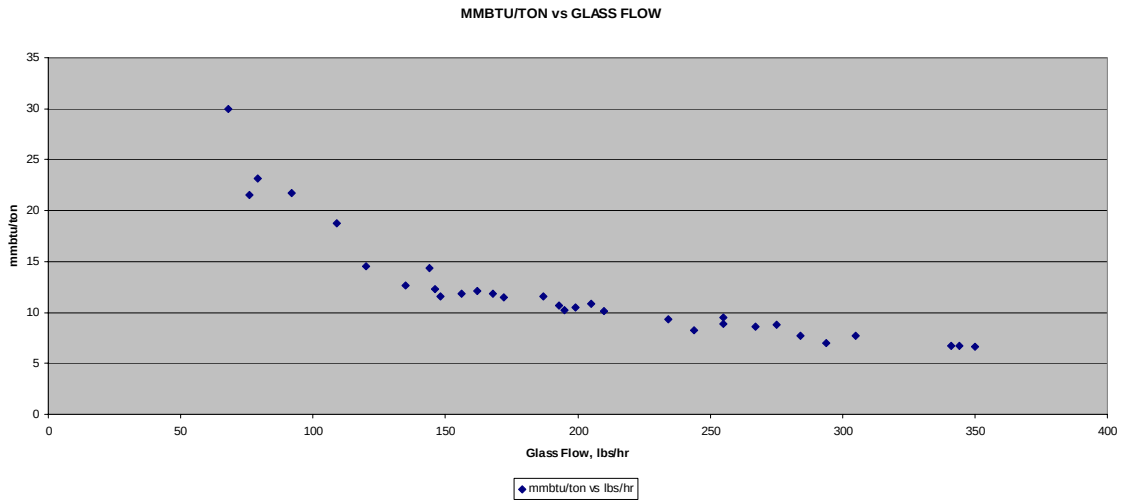


Figure 23. Energy Consumption vs. Glass Throughput

As the graph illustrates, the plasma melting process may be able to meet the goal of 4.1 MBTU/hr with increased production throughput.

Most of the glass melting runs made during the program were made at the lower throughput range (75 to 350 #/hr) to emphasize glass quality and process stability. Early in the program, it became obvious that the high throughputs gave significantly worse unmelted batch and cristobalite (silica) stoning. In addition, it also became obvious that the infra-structure would not easily handle large quantities of hot glass. 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.

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

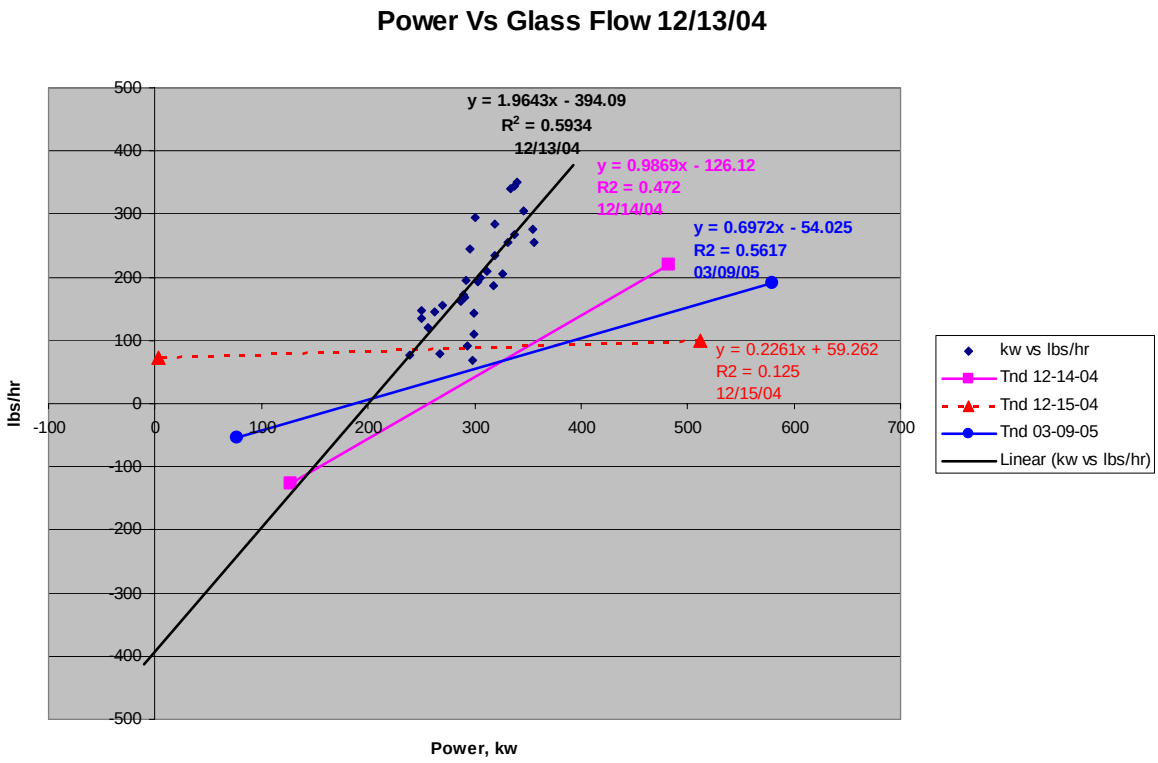


Figure 24. Data points for energy consumption vs. throughput

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 of 500 #/hr or greater.

The glass composition also plays a great deal of importance to the efficiency of the process. The majority of the work for this program was directed towards Eglass. Other glasses have proved much harder to melt and other are easier. When other commercial applications are investigated, we will generate another set of data.

Energy Balance

Based on this 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 efficiency at this throughput is still very poor. The losses of energy at various points in the process includes the torches, hood, exhaust, and miscellaneous losses, which total about 78% of the input energy. This extremely poor energy balance is due to the glass throughput still being too low. Since these losses are more or less constant, a significantly higher glass throughput will not cause significantly more losses and therefore, is delivered to the glass itself. The table below summarizes these losses.

DC Power	300	kW			
	Flow Rate		Delta T	Energy (kw)	
Torch and power supply water loss	55	GPM	4	30.7	10%
Hood water losses	10	GPM	50	69.7	23%
Exhaust losses	1200	ACFM	175	62.6	21%
Misc losses				71.0	24%
Glass Energy	350	PPH	2600	65.8	22%
				299.8	

The practical throughput limit of the system installed in Boulder is the age and condition of the JM contributed power supply (p.s.), which is about 18 years old. The higher throughputs require pushing the p.s. to high power settings that have caused overheating and damage to the SCR's. Due the very high cost of a new power supply and the unavailability of parts for this p.s. unit, we made a decision with the cost share partners not to push the p.s. to its limits. Damage to the p.s. unit beyond repair would have prematurely ended the project since the budget did not contain sufficient funding to purchase a new unit. Compromises were made to focus the project on the highest practical throughput and emphasize process R&D in order to achieve a glass quality that had practical utility. Using this approach, we were successful in achieving fiberizable quality glass so, in hindsight, this decision was prudent. A commercial contract has been given to Plasmelt to pursue this high throughput goal with private funding. This private work in now on going.

Market Study

In 2004, a Market Study was commissioned by Plasmelt and conducted by Gabe Tincher. The scope of work for this Study included the identification of glass industry segments and companies that will find economic advantage by using the assumed attributes of the plasma melting system. In addition to the Market Study, a technical and economic analysis (TEA) program was developed that allows one to compare the projected operating and maintenance costs using the plasma melting system to the costs of the current systems used by the cost share partners. This TEA was built upon several assumptions that addressed by later work in the research program. This study has served as the foundation for the development of the Plasmelt business plan in which our goal is broad implementation of plasma technology within the glass industry. The Study did help identify the likely early adopters of this technology, on which we focused our initial efforts.

Of the 15 to 20 companies / organizations / individuals contacted for this market study, several important conclusions were drawn. These conclusions, which are shown in the graphic below, highlighted the importance of the low capital cost of installation and the rapid changeover capabilities of the plasma melting system.

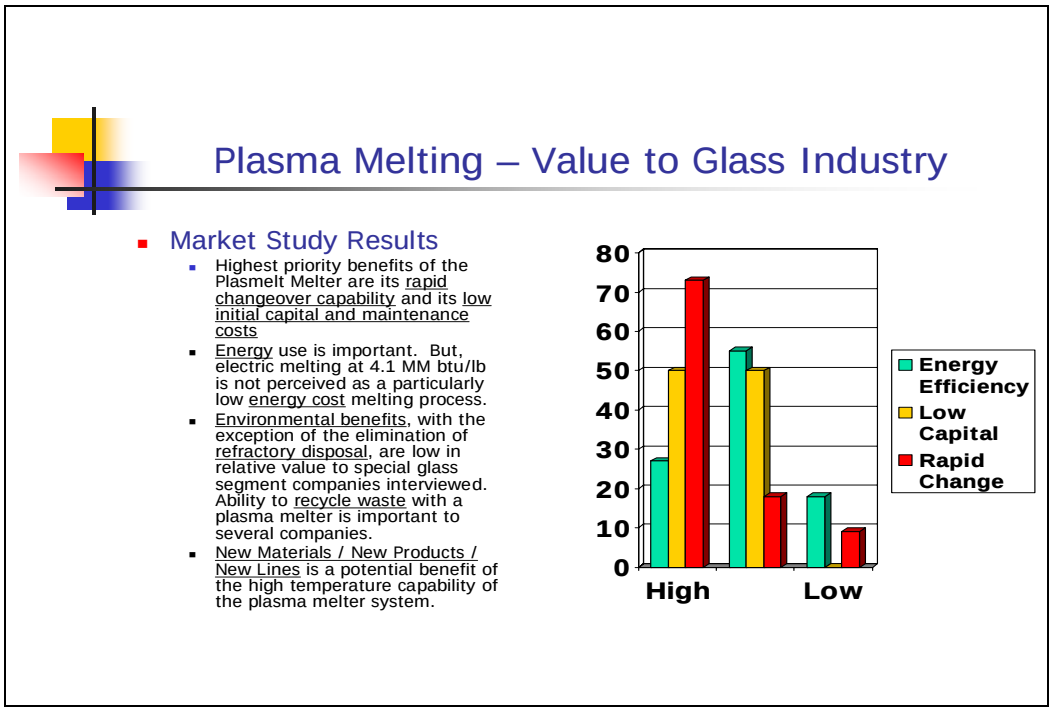


Figure 25. Survey Results of Plasma Marketing Study

Environmental Screening Test

The proposed environmental testing of the plasma melter was based on the assumption that a stable 500#/hr process would be defined form which the environmental impacts would need to be characterized. These conditions were never achieved during the program. The significant cost of an environmental test was not justified, nor would the results be meaningful without a set of stable baseline conditions.

However, in order to do a crude reconnaissance test for particulate, we developed a simple testing apparatus and method for determining the particulate emissions from the Plasma Melter. Typical testing means were deemed not applicable for the current operation. Considering the high exhaust temperatures, relatively small CFM exhaust stream and the potentially extremely fine particulates, we developed a custom means of determining the particulate loading in the exhaust stream. This apparatus pulls over 5% of the exhaust stream through a 1-micron filter. The temperatures of the sample were less than 200 deg F, thus all particulates should have been in the solid phase for the exhaust stream. The preliminary readings from the exhaust stream taken during the melting of JM's fiberglass scrap indicate that a particulate loading of ~1.641 grams per 200 # of glass pulled. This number equates to 0.001 # of particulate per pound of glass pulled. This number is in the range of acceptable environmental numbers that are allowed in our cost share partner's facility. Further testing is planned whenever the true baseline conditions are stabilized.

BUDGET / FINANCIAL

As of March 31, 2006, the project funds were exhausted.

Budget Data (as of 07/27/06): Actual spending for the project period is shown below.

Project Spending							
	From Project Startup	**To Project Completion**	**Estimated Federal Share of Outlays**	**Actual Federal Share of Outlays**	**Estimated Recipient Share of Outlays**	**Actual Recipient Share of Outlays**	**Cumulative**
Totals	07/28/03	07/27/06	$1,312,356	$1,312,356.00	$563,000	$563,849.25	**$1,876,205.25**

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 2/28/06) minus AGY cash contributions plus Mar-July, 2006 expenditures

Total Cost Share Contributions of $563,849.25 = AGY Cash Contributions of $181,572.84 plus AGY non-cash in-kind of $139,427.16 plus JM non-cash in-kind of $242,037.02 plus Plasmelt cash of $812.23.

MILESTONE SUMMARY TABLE: This is a complete list of milestones for the project.

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	7/27/06	350 #/hr on E-glass 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.

ID Number	Task / Milestone Description	Planned Completion	Actual Completion	Comments
M 6.1	Optimization: Process refinement, energy balance updates [GO/NO GO DECISION]	6/30/05	7/27/06	Optimization was an on-going priority. Final glass melting work was focused on demonstrating the broad glass compositional capability of plasma melting.
M 6.2	Final Reporting to DOE	Before end of 3rd Quarter, 2006.	10/27/06	Final report filed 10/27/06

OVERALL PROJECT CONCLUSIONS

- This project has shown the feasibility of melting glass using a furnace fired with dc remotely coupled transferred arc plasmas.
- The rotating furnace design used for this project has demonstrated excellent flexibility via rapid startup and shutdown. Glass flow can be achieved within 15 minutes for many glass compositions; glass flow can be ceased within 5 minutes.
- Energy efficiency is a strong function of the type of glass melted and the throughput.
- Glass throughputs up to 350 #/hr were achieved with this melter design and plasma firing system. At this throughput, the energy efficiency was approximately 1.0 kwh/# or glass vs. a goal of 0.6. The aged condition of the power supply, which was contributed by cost share partner JM, was the rate-limiting factor. This limit is not a fundamental limit of this furnace design, but simply a practical limit imposed by the used equipment utilized in this project. A state of the art power supply that is capable of generating 1.0 MW should give an excellent change of achieving the goal of 500 #/hr using this same melter design.
- Poor glass quality can result if short dwell time glass is allowed to escape the melter orifice prematurely.
- Torch design and operation have been shown to allow drastically improved torch lives. Actual lives achieved were in excess of 30 hours.
- Glass quality was highly variable and was a strong function of the glass composition and furnace operating conditions. Good quality glass that was suitable for fiberizing was demonstrated during this project. The fiberizing performance is an excellent method of assessing the quality of glass produced.
- The plasma torches can heat glass to very high temperatures in excess of 3400^{o}F. Measuring the actual temperature distribution within the 3-

dimensional plasma was a challenge. The spectrometric method used to estimate this distribution, showed temperatures in excess of 15,000^{o}K.

- High seed levels in the glass are a function of the very short dwell times achieved by this furnace design. To use a rapid plasma melter for a low-seed glass application, a secondary method of refining must be also be used.

OVERALL PROJECT RECOMMENDATIONS

1. Implement this plasma system of melting glasses in commercial operations in which a high level of flexibility is required in order to avoid long periods of banked operations and deliver a more energy efficient operation.
2. Further studies should be done with a state of the art power supply system that can generate the maximum power needed to melt the 500 to 1000 #/hr significantly improve the energy efficiency of this system.
3. Further studies should be done with orifice designs that can stop short circuiting and allow significantly improved dwell times as a means of lowering seed content and improving the quality of the glass.