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ABSTRACT

The need for a Combustion and Melting Research Facility focused on the solution of glass manufacturing problems common to all segments of the glass industry was given high priority in the earliest version of the Glass Industry Technology Roadmap (Eisenhauer et al., 1997). Visteon Glass Systems and, later, PPG Industries proposed to meet this requirement, in partnership with the DOE/OIT Glass Program and Sandia National Laboratories, by designing and building a research furnace equipped with state-

of-the-art diagnostics in the DOE Combustion Research Facility located at the Sandia site in Livermore, CA. Input on the configuration and objectives of the facility was sought from the entire industry by a variety of routes: (1) through a survey distributed to industry leaders by GMIC, (2) by conducting an open workshop following the OIT Glass Industry Project Review in September 1999, (3) from discussions with numerous glass engineers, scientists, and executives, and (4) during visits to glass manufacturing plants and research centers.

The recommendations from industry were that the melting tank be made large enough to reproduce the essential processes and features of industrial furnaces yet flexible enough to be operated in as many as possible of the configurations found in industry as well as in ways never before attempted in practice. Realization of these objectives, while still providing access to the glass bath and combustion space for optical diagnostics and measurements using conventional probes, was the principal challenge in the development of the tank furnace design. The present report describes a facility having the requirements identified as important by members of the glass industry and equipped to do the work that the industry recommended should be the focus of research. The intent is that the laboratory would be available to U.S. glass manufacturers for collaboration with Sandia scientists and engineers on both precompetitive basic research and the solution of proprietary glass production problems.

As a consequence of the substantial increase in scale and scope of the initial furnace concept in response to industry recommendations, constraints on funding of industrial programs by DOE, and reorientation of the Department's priorities, the OIT Glass Program is unable to provide the support for construction of such a facility. However, it is the present investigators' hope that a group of industry partners will emerge to carry the project forward, taking advantage of the detailed furnace design presented in this report. The engineering, including complete construction drawings, bill of materials, and equipment specifications, is complete. The project is ready to begin construction as soon as the quotations are updated.

The design of the research melter closely follows the most advanced industrial practice, firing by natural gas with oxygen. The melting area is 13 ft x 6 ft, with a glass depth of 3 ft and an average height in the combustion space of 3 ft. The maximum pull rate is 25 tons/day, ranging from 100% batch to 100% cullet, continuously fed, with variable batch composition, particle size distribution, and raft configuration. The tank is equipped with bubblers to control glass circulation. The furnace can be fired in three modes: (1) using a single large burner mounted on the front wall, (2) by six burners in a staggered/opposed arrangement, three in each breast wall, and (3) by down-fired burners mounted in the crown in any combination with the front wall or breast-wall-mounted burners. Horizontal slots are provided between the tank blocks and tuck stones and between the breast wall and skewback blocks, running the entire length of the furnace on both sides, to permit access to the combustion space and the surface of the glass for optical measurements and sampling probes. Vertical slots in the breast walls provide additional access for measurements and sampling. The furnace and tank are to be fully instrumented with standard measuring equipment, such as flow meters, thermocouples,

continuous gas composition analyzers, optical pyrometers, and a video camera. The output from the instruments is to be continuously recorded and simultaneously made available to other researchers via the Internet.

A unique aspect of the research facility would be its access to the expertise in optical measurements in flames and high temperature reacting flows residing in the Sandia Combustion Research Facility. Development of new techniques for monitoring and control of glass melting would be a major focus of the work. The lab would be equipped with conventional and laser light sources and detectors for optical measurements of gas temperature, velocity, and gaseous species and, using new techniques to be developed in the Research Facility itself, glass temperature and glass composition. The object is a partnership of Sandia combustion and materials scientists with industry, combining advanced measurement techniques with industrial melting to achieve new levels of productivity, yield, and energy efficiency in glass production.

The work envisaged for the Melting Research Facility includes all of the following:

- Fundamental studies of chemistry, heat transfer, mass transfer, melting, mixing, gas evolution, fining, and foam dissipation.

- Collection of detailed data sets for model validation.

- Specific tests, e.g. of burners, sensors, and batch formulations.

- Adaptation of optical measurement techniques to melting tank furnaces.

- Development of new sensors and instrumentation for industrial application.

- Examination of transient behavior and refinement of model-based control.

- Exploration of radical departures from accepted practice and a test bed for new ideas to improve product uniformity, increase output, decrease waste, extend furnace life, and control emissions from glass production.

- Develop refined models for melting, fining, flow, combustion, and heat transfer for incorporation in full furnace simulations.

The proposed focus of the first measurement campaign is on radiative exchange among all the major emitters and absorbers in the furnace: flames, combustion products, crown, superstructure, openings, batch, foam, and clear glass. Both conventional and optical methods could be applied to measurement of temperature, composition, and radiative properties of these media. However, the actual research agenda and direction would be determined by the needs and interests of the industrial partners.

Researchers affiliated with the Melting Facility would also be engaged in work in other areas important to glass research and development, such as fundamental investigations in spectroscopy and coating of glass.

Judging by the interest in the facility among glass manufacturers, and the research priorities specified in the latest version of the Glass Industry Technology Roadmap

(Jamison et al., 2002), new approaches to monitoring and control of glass production and the design of melting furnaces are seen as essential to increasing the productivity and efficiency of glass manufacturing. The Melting Research Facility would be at the center of that activity, helping to put the U.S. at the forefront of new developments in glass production.

ACKNOWLEDGMENTS

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1. INTRODUCTION

Background

       At the Glass Technology Roadmap Workshop held in Alexandria, VA, in April 1997, experts from the glass industry and related organizations selected research priorities and outlined the strategy to achieve the goals specified in the Industry Vision Statement, *Glass: A Clear Vision for a Bright Future* (U.S. DOE, 1966). At the summary session of the Roadmap Workshop, a set of glass industry research needs was identified that had emerged as important in all of the Work Groups and were common to all segments of the industry [see Exhibit 7-1 of the report from the workshop (Eisenhauer et al., 1997, p. 54)]. In the exhibit, under the heading, "Fundamental Understanding/Models," and opposite the category, "Melting/Glass Furnace," is the following recommendation: "*Establish a central research facility for combustion and furnace testing and model validation.*"

       Visteon's Glass Systems Division and Sandia National Laboratories responded to the recommendation by proposing to the DOE Office of Industrial Technologies the establishment of a Glass Industry User Facility at Sandia's Combustion Research Facility in Livermore, California. The proposed User Facility is a pilot-scale natural-gas-fired glass melting tank located in high-bay laboratories in the Phase-II addition to the Combustion Research Facility completed in November 1999. The User Facility will serve as a combustion and melting research center where engineers and scientists from industry, universities, and other national laboratories can collaborate on the solution of problems connected with the design, construction, operation, and control of glass melting tank furnaces.

       The Visteon/Sandia proposal was among those chosen for support by the DOE Office of Industrial Technologies' Glass Program in combination with in-kind support from Visteon. During Phase I, the glass industry's needs and interest in participation and support of the facility were assessed. With active involvement of members of the glass industry, a consensus was reached on the problems to be investigated and the features to be incorporated in the melting tank. Following the reorganization of Visteon in 1998/99, the OIT Glass Program asked PPG Industries to take Visteon's place as industry lead, and PPG assumed that role in December 2000.

       A team of scientists and engineers from PPG, Sandia, and contractors specializing in glass manufacturing equipment was fully engaged in the design and engineering of the research facility from February 2001 to July 2002. The project participants resolved, as a group, the principal technical questions regarding furnace design, batch preparation, batch charging, burner design and placement, refractory selection, glass circulation, and access to the furnace for measurements and sampling. Resolution of these problems was

accomplished while keeping in mind the scientific objectives of the facility as well as the need to properly represent industrial glass production conditions and practice. Such a facility is an essential resource for the discovery of scientific and engineering fundamentals that will provide the foundation for progress in melting technology in the years ahead.

The *Glass Industry Technology Roadmap* was revised in April 2002 (Jamison et al., 2002) to incorporate the new thinking and refined strategy for glass manufacturing that resulted from continuing collaboration among members of the industry, its suppliers, the OIT Glass Program, independent consultants, and others working on glass technology at universities and National Laboratories. The revised roadmap makes an even stronger case for a Melting Research Facility than the original roadmap and vision statement, reiterating the research needs and benefits to be gained, as in this excerpt (p. 18):

> "The glass industry has historically lacked a common facility for testing new production technologies and products, as capital costs in the industry are very high. In particular, this is important for improved combustion and furnace efficiency. Applications that may be tested if a facility was available include sensors, instrumentation, refractories, and burners."

Many of the specific problems given high priority in the Vision Statement, *Glass: A Clear Vision for a Bright Future*, in the report from the Roadmap Workshop, and in the latest version of the Roadmap itself are ideal subjects for investigation using nonintrusive optical diagnostic techniques, which are a specialty of the staff at the Combustion Research Facility at Sandia National Laboratories.

The Sandia Combustion Research Facility

The Combustion Research Facility is the Department of Energy's designated laboratory for research on the fundamentals of flame processes and development of innovative solutions to practical problems in systems utilizing combustion. As consequences of their focus on flame chemistry, fluid dynamics, and heat transfer over the past 25 years, researchers at the Combustion Research Facility are among the nation's leaders in measurements and modeling of high temperature reacting flows. With a full time staff of over 100 focused on the study of these processes, the Sandia Combustion Research Facility is the only place in the U.S. where expertise in all aspects of combustion is combined in a single organization. It is also a User Facility where, each year, over 100 visiting scientists from other organizations stay for periods of 2 weeks or longer working with members of the permanent staff. There is also close cooperation at the Sandia/California site among the various research groups performing measurements, modeling, and simulation applicable to industrial furnaces. The value of work done in the Combustion Research Facility is leveraged by support for the Facility's infrastructure by the DOE Office of Basic Energy Sciences, Division of Chemical Sciences.

2. SCALING CONSIDERATIONS: PULL RATE, MELTING AREA, GLASS DEPTH, AND CIRCULATION

The starting point for the proposed melting furnace design was the selection of a glass pull rate high enough to provide realistic tank conditions, but not so high that materials handling, rather than research, would become the major focus of the work. To get advice from the glass industry on this and other questions, a survey prepared by Sandia and Visteon was distributed to members of the industry by the Glass Manufacturing Industry Council (GMIC). The survey and its results are in Appendix A to this report. Pull rates suggested by the respondents to the survey (Appendix A, p. A2) ranged from 2 to 200 tons/day. The highest rates, 30 to 200 tons/day, are thought to result from misinterpretation of the question, i.e. they represent respondents' suggestions regarding the size of tank to be simulated, not the size of the research tank itself. Those experienced in glass manufacturing and the operation of pilot-scale melters indicated that a pull rate in the range of 1000 to 2000 lb/h would provide realistic flow patterns and furnace environments. A pull rate of 25 tons/day was chosen as the target capacity and the starting point for the design. However, the batch feed and glass withdrawal systems will be sized to accommodate the lower pull rates to be maintained between experiments.

An area of melter per unit of pull rate equal to 3 ft^2/ton/day was then chosen as a value at the lower end of the range of specific pull rates for production tank furnaces (Trier, 1987, p. 184). To satisfy the two conditions, output of 25 tons/day and area/output of 3 ft^2/ton/day, requires a melter having an area of 75 ft^2. For geometric similarity to large industrial melters, the ratio of length to width should be between approximately 2 (container and float glass) and 3 (fiber glass). However, in small production tank furnaces the length-to-width ratio approaches 1 (Hufen, 1965), because, as the width of the combustion space in a cross-fired furnace is decreased, flame impingement on the walls and incomplete combustion become more likely. On the other hand, if a tank is too short, undissolved sand grains and poorly mixed glass appear in the product. To balance these considerations inside dimensions of 6 ft × 13 ft were chosen, giving a length-to-width ratio slightly greater than 2 and an area of 78 ft^2. To achieve a realistic mean residence time of glass in the tank, about 1 day, requires a glass depth of 3 ft, close to the average of the depths suggested by the respondents to the survey (Appendix A, p. A2). This depth was then tested for its ability to satisfy another requirement, the need for good glass circulation.

Sufficient circulation of the glass should be present to reproduce the mixing and homogenization processes found in large tanks. The requirement for proper circulation is considered so important that geometric similarity (same ratios of length, width, and depth as in industrial tanks) may be compromised to achieve it. The criteria for circulation were determined from the equations governing flow and heat transfer in the glass bath and evaluation of the dimensionless groups obtained from those equations.

The description of the glass flow was restricted to two dimensions by considering a thin vertical slice along the long axis of a rectangular tank in which the glass properties are assumed to be uniform in the lateral direction. The variables x and y represent positions on the longitudinal and vertical axes, respectively, and u and v are the corresponding components of the glass velocity. The governing equations for unsteady flow of a viscous, incompressible fluid, neglecting viscous dissipation of heat, and assuming a constant coefficient of thermal expansion and constant specific heat are given below in dimensional form (Schlichting, 1979, pp. 265-285). Following Noble et al. (1972), Wright and Rawson (1973), and Leyens (1974a), the influence of the inertia of the glass flow through the tank was neglected. Definitions of the symbols may be found in the list of Symbols and Abbreviations, Section 9; the primes denote dimensional variables.

Continuity:

$$\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} = 0 \tag{1}$$

Momentum:

$$\rho_{ref}\left(\frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'}\right) = 2\frac{\partial}{\partial x'}\left(\mu'\frac{\partial u'}{\partial x'}\right) + \frac{\partial}{\partial y'}\left(\mu'\frac{\partial u'}{\partial y'}\right) + \frac{\partial}{\partial y'}\left(\mu'\frac{\partial v'}{\partial x'}\right) \tag{2}$$

$$\rho_{ref}\left(\frac{\partial v'}{\partial t'} + u'\frac{\partial v'}{\partial x'} + v'\frac{\partial v'}{\partial y'}\right)$$

$$\tag{3}$$

$$= \frac{\partial}{\partial x'}\left(\mu'\frac{\partial v'}{\partial x'}\right) + 2\frac{\partial}{\partial y'}\left(\mu'\frac{\partial v'}{\partial y'}\right) + \frac{\partial}{\partial x'}\left(\mu'\frac{\partial u'}{\partial y'}\right) + \rho_{ref}\, g\, \beta(T' - T_0)$$

Energy:

$$\rho_{ref}\, c\left(\frac{\partial T'}{\partial t'} + u'\frac{\partial T'}{\partial x'} + v'\frac{\partial T'}{\partial y'}\right) = \frac{\partial}{\partial x'}\left(k'_{eff}\frac{\partial T'}{\partial x'}\right) + \frac{\partial}{\partial y'}\left(k'_{eff}\frac{\partial T'}{\partial y'}\right) \tag{4}$$

Variable viscosity:

$$\mu' = \mu'(T') \tag{5}$$

Variable effective thermal conductivity, including heat transfer by both conduction and radiation:

$$k'_{eff} = k'_{eff}(T') \tag{6}$$

The non-dimensionalization of Equations (2) and (3) was discussed by Noble et al. (1972), Wright and Rawson (1973), and Leyens (1974a). These authors wrote the momentum balance in the form of a vorticity transport equation (Schlichting, 1979, pp. 73-75; Goldstein, 1938, pp. 90-100), in contrast to its expression in terms of velocity components, as above, but the groups of parameters obtained from the non-dimensionalization are identical.

The characteristic length scale for the system is defined by the depth of the glass. Because the net flow through the system was neglected, there is no characteristic velocity that could be used for the non-dimensionalization of velocity and time. Time scaling can be based on either of the transport properties: kinematic viscosity or thermal diffusivity (Wright and Rawson, 1973). Possible dimensionless variables and their definitions are listed in Table 2-1. Noble et al. (1972) and Wright and Rawson (1973) defined the time scale using the thermal diffusivity.   Following these authors and introducing the corresponding dimensionless variables, Equations (2), (3), and (4), become:

$$\frac{1}{\text{Pr}}\left(\frac{\partial u_\alpha}{\partial t_\alpha} + u_\alpha\frac{\partial u_\alpha}{\partial x} + v_\alpha\frac{\partial u_\alpha}{\partial y}\right) = 2\frac{\partial}{\partial x}\left(\mu\frac{\partial u_\alpha}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u_\alpha}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial v_\alpha}{\partial x}\right) \qquad (7)$$

$$\frac{1}{\text{Pr}}\left(\frac{\partial v_\alpha}{\partial t_\alpha} + u_\alpha\frac{\partial v_\alpha}{\partial x} + v_\alpha\frac{\partial v_\alpha}{\partial y}\right) = \frac{\partial}{\partial x}\left(\mu\frac{\partial v_\alpha}{\partial x}\right) + 2\frac{\partial}{\partial y}\left(\mu\frac{\partial v_\alpha}{\partial y}\right) + \frac{\partial}{\partial x}\left(\mu\frac{\partial u_\alpha}{\partial y}\right) + \text{Ra}\,\theta \quad (8)$$

$$\frac{\partial \theta}{\partial t_\alpha} + u_\alpha\frac{\partial \theta}{\partial x} + v_\alpha\frac{\partial \theta}{\partial y} = \frac{\partial}{\partial x}\left(k_{\text{eff}}\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{\text{eff}}\frac{\partial \theta}{\partial y}\right) \qquad\qquad (9)$$

Values for the physical properties of glass, the system characteristics, and the dimensionless groups are given in Table 2-2. Noble et al. (1972) noted that for values of the Prandtl number, Pr >> 1, which is the case in glass tanks, Equations (7) and (8) imply that the inertial forces in the flow are negligible compared with the buoyant and viscous forces, and that the solution is therefore not a function of the Prandtl number. This was confirmed by Wright and Rawson (1973), who found that solutions for the streamlines and temperature distribution in their two-dimensional model were independent of Prandtl number over the range of values of practical interest. According to Equations (7), (8), and (9), similarity between the research tank and industrial tanks can be achieved by requiring that the Rayleigh number, Ra, and the vertical distributions of viscosity and thermal conductivity be the same in both tanks. These conditions can be met, in turn, by requiring that the depth of the glass, the average glass temperature, and the temperature difference between the top and bottom of the tank be the same in the research tank as in practice.

The alternative to scaling time using the thermal diffusivity is to scale it using the kinematic viscosity. When this is done, Equations (2), (3), and (4) become:

Table 2-1. Definitions of the dimensionless variables.

| Variable | ------------- Symbol ------------- | | Relationship |
	Dimensional	Dimensionless	
Length	x	x	$x = x'/H$
Length	y	y	$y = y'/H$
Time	t	t_α	$t_\alpha = t'\alpha/H^2$
Velocity	u	u_α	$u_\alpha = u'H/\alpha$
Velocity	v	v_α	$v_\alpha = v'H/\alpha$
Time	t	t_ν	$t_\nu = t'\nu/H^2$
Velocity	u	u_ν	$u_\nu = u'H/\nu$
Velocity	v	v_ν	$v_\nu = v'H/\nu$
Time	t	t_u	$t_u = t'u_{ref}/H$
Velocity	u	u_u	$u_u = u'/u_{ref}$
Velocity	v	v_u	$v_u = v'/u_{ref}$
Temperature	T	θ	$\theta = \dfrac{T' - T_0}{T_H - T_0}$
Effective thermal conductivity	k'_{eff}	k_{eff}	$k_{eff} = k'_{eff}/k_{ref}$
Viscosity	μ	μ	$\mu = \mu'/\mu_{ref}$

Table 2-2. Tank dimensions, physical properties of soda-lime-silica glass, and
comparison of the Reynolds, Prandtl, Grashof, and Rayleigh numbers for an industrial tank and the research tank.

Property	Symbol	Value Industrial tank	Research tank	Reference
Acceleration due to gravity	g	9.8 m s^{-2}	same	-
Temperature difference between top and bottom of the melt	$T_H - T_0$	150 °C	same	Trier, 1987, pp. 144-145
Glass pull rate	q_m	4 kg s^{-1} (380 ton/day)	0.26 kg s^{-1} (25 ton/day)	-
Glass depth	H	1.2 m (4 ft)	0.91 m (3 ft)	-
Tank cross section area perpendicular to direction of glass flow	A	9.3 m^2 (25 ft x 4 ft)	1.67 m^2 (6 ft x 3 ft)	-
Density of soda-lime-silica glass at 1500 °C	ρ_{ref}	2259 kg m^{-3}	same	Cable and Martlew, 1984
Average glass velocity (withdrawal current)	$u_{ref} = q_m/(\rho_{ref} A)$	0.0002 m s^{-1}	0.00007 m s^{-1}	-
Thermal expansion coefficient for molten soda-lime-silica glass, in the range 1300 – 1500 °C	$\beta = \dfrac{1}{\rho}\dfrac{\partial \rho}{\partial T}$	5.5 x 10^{-5} °C^{-1}	same	Cable and Martlew, 1984

Table 2-2 (continued)

Property	Symbol	Value Industrial tank	Research tank	Reference
Absolute viscosity of molten soda-lime-silica glass at 1500 ºC	μ_{ref}	6.34 kg m^{-1} s^{-1}	same	Cable and Martlew, 1984
Kinematic viscosity of molten glass at 1500 ºC	$\nu = \mu_{ref}/\rho_{ref}$	0.0028 m^2 s^{-1}	same	Cable and Martlew, 1984
Effective thermal conductivity of clear glass at 1500 ºC, including the contribution from radiation	k_{ref}	20 J m^{-1} s^{-1} K^{-1}	same	Leyens, 1974b
Specific heat of soda-lime-silica glass, 20 – 1500 ºC	c	1274 J kg^{-1} K^{-1}	same	Trier, 1987, p. 80
Thermal diffusivity of molten soda-lime-silica glass at 1500 ºC	$\alpha = k_{ref}/(\rho_{ref}c)$	7 x 10^{-6} m^2 s^{-1}	same	-
Reynolds number	$Re = u_{ref} H/\nu$	0.086	0.023	-
Prandtl number	$Pr = \nu/\alpha$	400	same	-
Grashof number	$Gr = \dfrac{g\,\beta\,(T_H - T_0)\,H^3}{\nu^2}$	18,000	8,000	-
Rayleigh number = Gr·Pr	$Ra = \dfrac{g\,\beta\,(T_H - T_0)\,H^3}{\nu\,\alpha}$	7 x 10^6	3 x 10^6	-

$$\frac{\partial u_v}{\partial t_v} + u_v \frac{\partial u_v}{\partial x} + v_v \frac{\partial u_v}{\partial y} = 2 \frac{\partial}{\partial x}\left(\mu \frac{\partial u_v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u_v}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v_v}{\partial x}\right) \qquad (10)$$

$$\frac{\partial v_v}{\partial t_v} + u_v \frac{\partial v_v}{\partial x} + v_v \frac{\partial v_v}{\partial y} = \frac{\partial}{\partial x}\left(\mu \frac{\partial v_v}{\partial x}\right) + 2 \frac{\partial}{\partial y}\left(\mu \frac{\partial v_v}{\partial y}\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial u_v}{\partial y}\right) + Gr\,\theta \qquad (11)$$

$$Pr\left(\frac{\partial \theta}{\partial t_v} + u_v \frac{\partial \theta}{\partial x} + v_v \frac{\partial \theta}{\partial y}\right) = \frac{\partial}{\partial x}\left(k_{eff} \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{eff} \frac{\partial \theta}{\partial y}\right) \qquad (12)$$

Because the Rayleigh number is equal to the product of the Prandtl and Grashof numbers, the conditions for similarity indicated by Equations (10), (11), and (12) are identical to those arrived at using the alternative scaling of time in Equations (7), (8), and (9).

If the research melting tank is designed so that a desired variation of glass temperature with depth can be achieved by proper combination of flame heat input, pull rate, and bubbling, it will be possible to duplicate the viscosity, effective thermal conductivity, and Prandtl number of the same glass in an industrial tank. From the point of view of circulation, the key parameter is the depth of the glass, which appears in both the Rayleigh and Grashof numbers raised to the third power. If the depth of the research tank were reduced by the same factor as the length and width, which are roughly four times smaller than the length and width of a large container tank, the Rayleigh and Grashof numbers would be reduced by a factor of 64. It is this constraint, more than any other, that prevents simple geometric scaling of industrial tank dimensions to the research melter. The depth of 0.91 m (3 ft), obtained from the melting area and residence time argument above, will provide Grashof and Rayleigh numbers within a factor of 2.25 of those in the deepest industrial tanks.

A temperature gradient is not, by itself, sufficient to drive circulation. In a tank in which temperature increases with increasing height above the tank bottom (typical of flame-heated melters), if the temperature and glass composition were uniform over all horizontal planes, there would be no circulation at all. As pointed out by Wright and Rawson (1973), circulation depends not just on the temperature difference between the top and bottom of the tank, but on the way this temperature difference is distributed around the boundaries of the tank. Wright and Rawson used a cosine function to describe the temperature distribution over the glass surface in their calculations, introducing the temperature at the ends of the tank as a new parameter, in addition to the temperature of the tank bottom and the maximum glass surface temperature at the center. They also introduced a new dimensionless variable, s, to characterize the extent of non-uniformity of the surface temperature:

$$s = \frac{T_H - T_W}{T_H - T_0} \qquad (13)$$

Wright and Rawson (1973) considered a two-dimensional tank under conditions typical of soda-lime-silica glass melting: glass depth of 1 m, Prandtl number of 200, Rayleigh number of 3×10^5, and a 150 °C difference in temperature from the top to the bottom of the tank, $T_H - T_0$. They considered three cases in detail: (1) length of tank equal to four times its depth and s = 0.267 (40 °C difference from the center of the tank to the end walls), (2) same ratio of length to depth, but with s = 1 (150 °C difference from center to walls), and (3) length of tank equal to its depth and s = 0.267. The calculated intensity of circulation, characterized by the maximum value of the stream function, increased seven-fold on going from case 1 to case 2, and decreased by a factor of 2 on going from case 1 to case 3. Circulation is evidently a strong function of the temperature distribution on the surface of the glass (increasing with increasing temperature difference between center and walls) and the length of the tank (increasing with increasing length). These observations support the choice of the length to width ratio near 2, discussed above, in spite of the trend of the data assembled by Hufen (1965) which showed that the length-to-width ratio of small tanks in operation at that time approached 1 as size decreased.

Finally, we consider the equations obtained if the average velocity of glass through the tank (described by Trier as the "withdrawal current") is taken as the characteristic velocity. In this case Equations (2), (3), and (4) become:

$$\text{Re}\left(\frac{\partial u_u}{\partial t_u} + u_u \frac{\partial u_u}{\partial x} + v_u \frac{\partial u_u}{\partial y}\right) = 2\frac{\partial}{\partial x}\left(\mu \frac{\partial u_u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u_u}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v_u}{\partial x}\right) \tag{14}$$

$$\text{Re}\left(\frac{\partial v_u}{\partial t_u} + u_u \frac{\partial v_u}{\partial x} + v_u \frac{\partial v_u}{\partial y}\right) = \frac{\partial}{\partial x}\left(\mu \frac{\partial v_u}{\partial x}\right) + 2\frac{\partial}{\partial y}\left(\mu \frac{\partial v_u}{\partial y}\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial u_u}{\partial y}\right) + \frac{\text{Gr}}{\text{Re}}\theta \tag{15}$$

$$\Pr\text{Re}\left(\frac{\partial \theta}{\partial t_u} + u_u \frac{\partial \theta}{\partial x} + v_u \frac{\partial \theta}{\partial y}\right) = \frac{\partial}{\partial x}\left(k_{\text{eff}} \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{\text{eff}} \frac{\partial \theta}{\partial y}\right) \tag{16}$$

The average velocity of glass through the research tank is a factor of 3 smaller than in the high throughput industrial tank used for comparison. The requirements for realistic glass depth and mean residence time in the relatively short research tank are the factors largely responsible for the lower velocity in the smaller tank. The Reynolds numbers in both tanks are very low (Table 2-2), supporting the conclusion of Noble et al. (1972) that the effect of the through-flow is negligible. Because the Reynolds number in the industrial tank is already so small, the factor of 4 decrease in Reynolds number in the research tank will have minimal impact on the flow field. The interactions of the heat flux distribution, withdrawal current, and convection currents and their importance to glass quality are discussed by Trier (1987, pp. 144–147).

The remaining major dimension to be set is the average height of the combustion space. According to the data assembled by Hufen (1965), the average height of the combustion space in furnaces having an area of 78 ft^2 would be approximately 3 ft. This

height will provide a reasonably long radiation path length perpendicular to the glass surface, realistic heat input per unit of furnace volume, and proper gas residence time.

3. DESIGN OF THE MELTING TANK FURNACE

Furnace Dimensions and Unique Features

The characteristics of the furnace arrived at by the argument outlined in the previous section are a melting area of 13 ft x 6 ft, a glass depth of 3 ft, and an average height in the combustion space, from glass surface to crown, of 3 ft. The maximum pull rate is 25 tons/day, ranging from 100% batch to 100% cullet. The furnace is fired using oxygen and natural gas, has continuous batch feed, and is equipped with bubblers.

The furnace can be fired in three modes: (1) using a single large burner mounted on the front wall, or (2) by six burners in a staggered/opposed arrangement, three in each breast wall, or (3) by a down-fired burner mounted in the crown in any combination with the front wall or breast-wall-mounted burners.

Three-inch-high slots are provided between the tank blocks and tuck stones and between the breast wall and skewback blocks, running the entire length of the furnace on both sides, to provide access to the combustion space and the surface of the glass for optical measurements and sampling probes. Vertical slots in the breast walls provide additional access for measurements and sampling. The furnace and tank are to be fully instrumented with standard measuring devices, such as flow meters, thermocouples, continuous gas composition analyzers, optical pyrometers, and a video camera. The output from the instruments will be continuously recorded and simultaneously made available to other researchers via the Internet.   The lab will be equipped with conventional and laser light sources needed for optical measurements of gas temperature and gaseous species and, using techniques to be developed in the Research Facility itself, glass temperature and composition. The principal features of the tank furnace are summarized in Table 3-1.

An artist's rendering of the research furnace, based upon the engineering drawings, is shown in Figure 3-1. The view in the figure is of the glass discharge end of the furnace with the glass drain bay, front wall, and one sidewall of the furnace visible. The glass surface and the flame from the front wall mounted burner are visible near the center of the figure through the cutaway portion of the front wall. The exhaust and tank block cooling wind ducts can be seen at the top and bottom of the sidewall, respectively. The furnace is to be surrounded by a concrete floor, not shown in Figure 3-1, at a height that will provide convenient access for measurements on both sides of the furnace through the horizontal and vertical slots at the skew lines, the tuck lines, and in the breast walls. The construction features shown in the figure make it evident that the furnace was designed from the industrial glass manufacturer's perspective, while the flexibility in firing mode (burner location and height above the glass surface) and number of probe access slots meet its need to function as a flexible research tool.

Table 3-1. Characteristics of the Glass Melting Research Furnace.

Dimensions: Melting area, 6 ft × 13 ft
                      Glass, 3-ft deep
                      Average height of combustion space, 3 ft

Glass types: Soda-lime-silica
                      Alkali borosilicate, experimental, and proprietary compositions
                           toward end of furnace campaigns

Glass discharge rate: 25 ton/day

Firing: Oxygen/natural gas

Gas flowrates: Gas – 8,600 scfh
                      O_2 – 19,000 scfh

Burners: opposed, staggered, 3 in each breast wall, elevation adjustable
                      single burner in front end wall
                      down-fired burners in crown

Fill doghouse: full tank width
                      gates for control of the configuration of the batch raft

Bubblers: two rows of 4 each
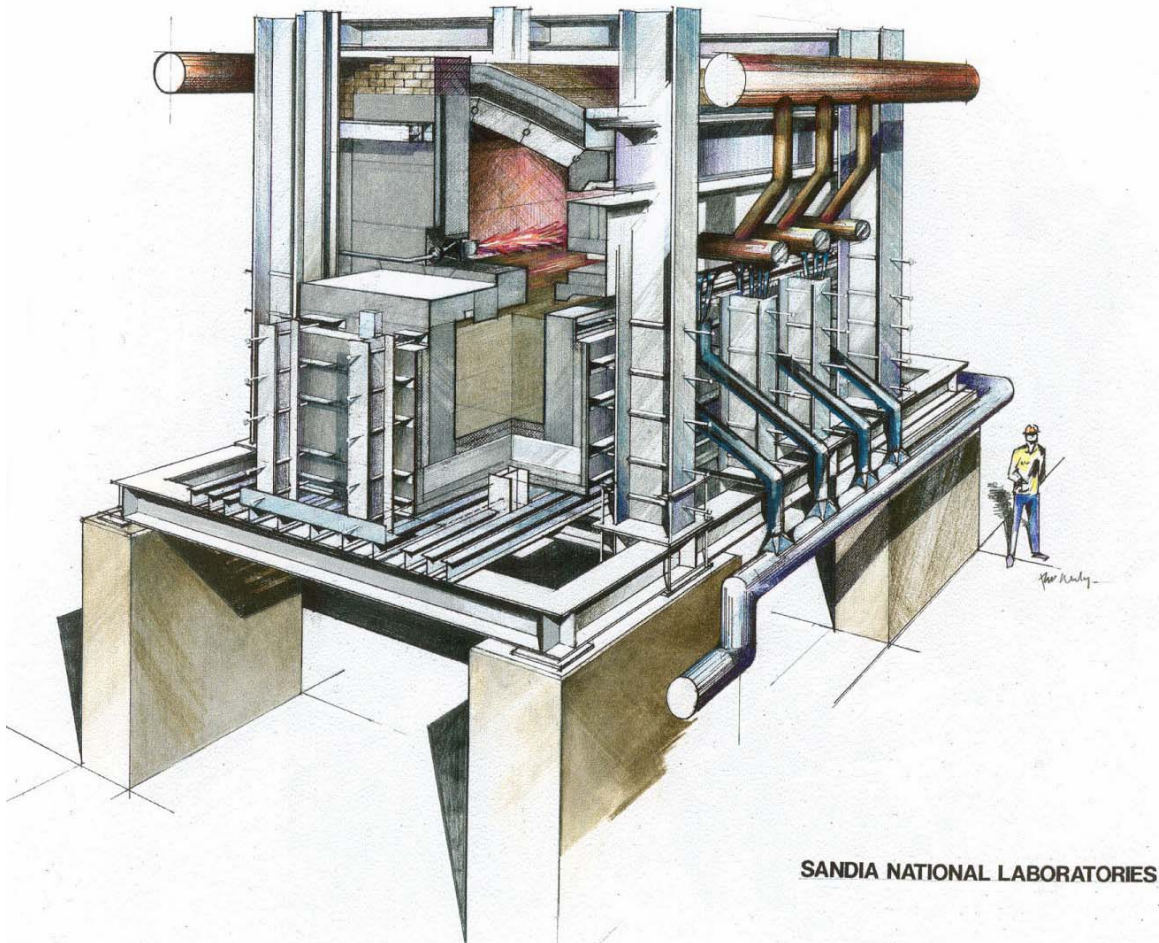
Figure 3-1. Artist's rendition of the tank furnace in the Glass Furnace Combustion and Melting Research Facility. The view is from the glass discharge end, with a cutaway showing the glass surface and flame from the burner mounted in the front wall. Furnace exhaust and cooling wind ducts are shown on the right side on the upper and lower portions of the furnace, respectively. The furnace meets industrial production melter design criteria, with the addition of thorough instrumentation, provision for versatile burner placement, and access to the glass and combustion space for measurements using optical and conventional diagnostic techniques. Artwork by Paul Deely of Fort Worth, TX, for A. C. Leadbetter and Son.

Arrangement of the Laboratory

The plan of the second floor of the melting research laboratory (not shown in Figure 3-1) is specified in Figure 3-2. The melting tank, defined by the tank blocks, is in the center of the figure. The batch elevator and charger are at the top of the figure and the glass drain is at the bottom. One side of the furnace is to be devoted primarily to the instrumentation needed for optical measurements, while the other side is devoted primarily to measurements using water-cooled gas sampling, suction pyrometer, and radiation probes.

The majority of the light sources and other optical equipment will be mounted on the 4 ft x 15 ft table located on the left side of the furnace. When it is required to locate a source on one side of the furnace and a detector or mirror or other optical element on the opposite side, a small optics table (4 ft x 4 ft) will be placed to the right of the furnace for the duration of that experiment.

The probe rack shown on the right side of the furnace is a pair of overhead "I" beams from which a carriage is suspended that supports water-cooled probes. This system, provided by the International Flame Research Foundation of Ijmuiden, The Netherlands, permits the tip of a probe to be moved along the length of the furnace and across the width of the furnace without removing the probe from the carriage. However, because space is limited, this will be possible only when sampling through the slot at the tuck line. At the skew line it will be necessary to remove a probe from the carriage in order to move past the exhaust risers (Figure 3-1).

Burners

The first set of burners to be installed for the first phase of the experimental work are Maxon Corp. (Muncie, IN) OXY-THERM LE concentric tube burners firing natural gas with oxygen. The six burners mounted in the breast walls are Model No. 600 LE, having maximum output of 2.7 million Btu/h, and the single burner mounted in the front wall is Model No. 900 LE, having maximum output of 11 million Btu/h.

Other types of burners will be installed for subsequent test campaigns. Measurements of heat transfer and NO_X emissions associated with different types of flames are expected to be among the most active areas of investigation in the melting research facility.

Furnace Design, Access for Measurements, and Adjustment of Burner Heights

The side elevation of the furnace is shown in Figure 3-3, highlighting some of the features that make the furnace uniquely suited for research. In the orientation shown, the batch charger is on the left and the glass drain on the right. At the tuck line there is a 3-inch high horizontal slot running the entire length of the melting area that provides access to the glass surface and to the combustion space underneath the flames. At the skew line is a similar slot providing access to the combustion space between the flames and crown.
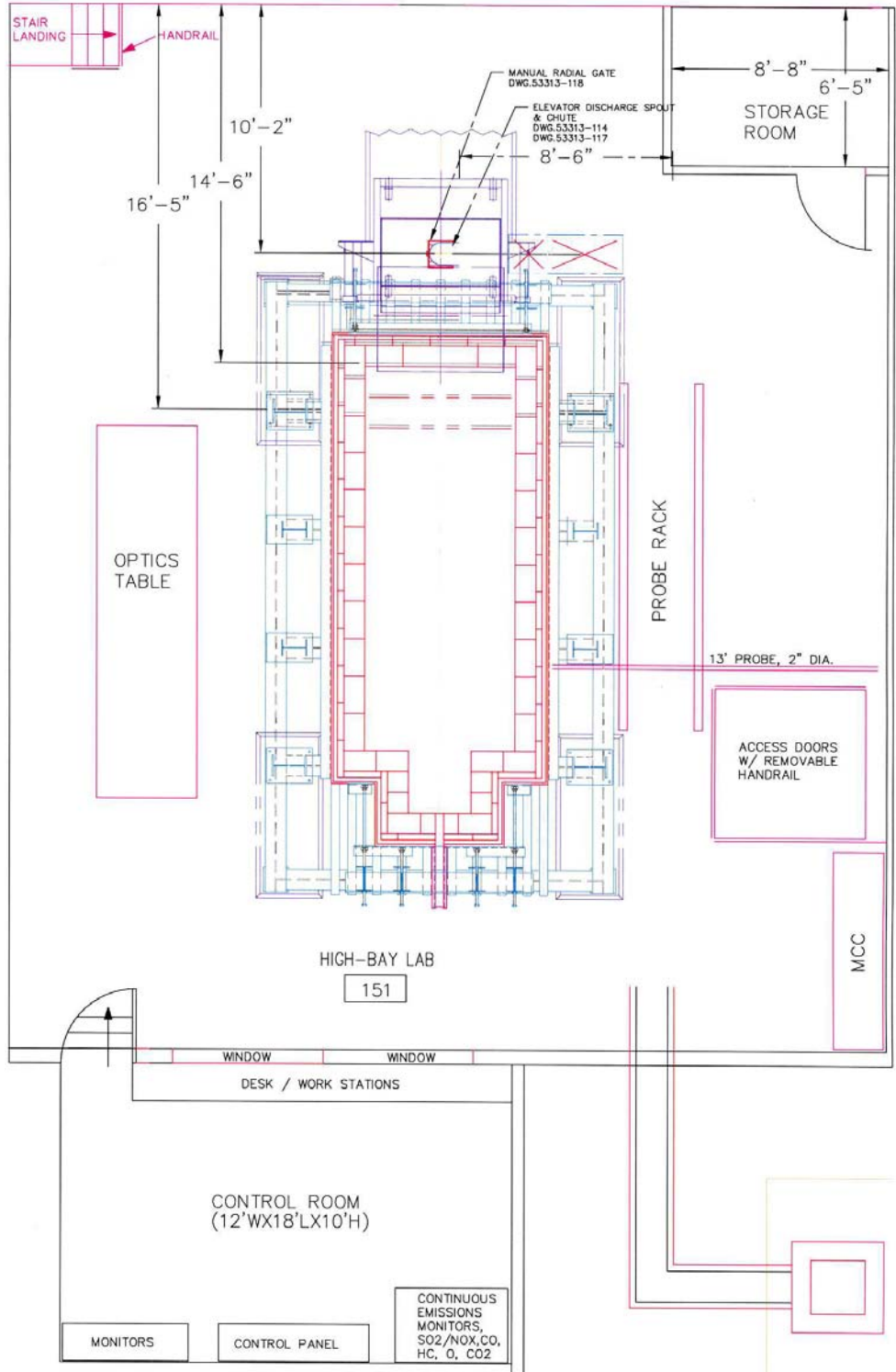
Figure 3-2. Plan of the second floor of the laboratory showing the locations of the melting tank, steel, batch charger and full width doghouse (top), glass drain bay and chute (bottom), control room, optics table for lasers and detectors (to left of melter), and rack for water cooled probes (to right of melter). Drawing by Lilja Corp., Sandia National Laboratories, A. C. Leadbetter and Son, Inc., and Merkle Engineers, Inc.
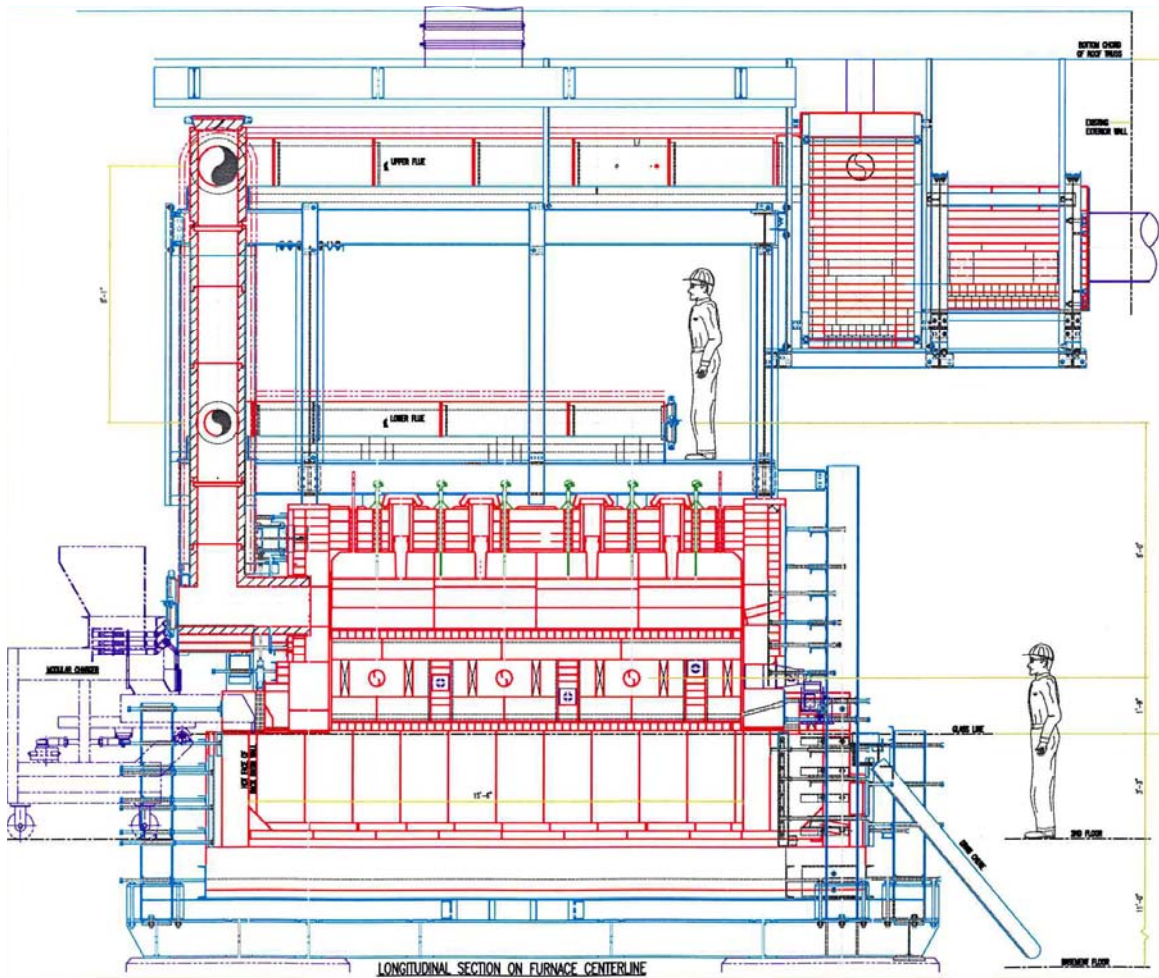
Figure 3-3. Side elevation of the melter showing the tank blocks, charger (left), drain chute (right), flues (upper left and top), drop box (upper right), burners in the breast wall at three elevations, vertical slots in the breast wall for optical and probe access, long horizontal slots (shown plugged with brick) for sampling and optical access at the tuck and skew lines, sampling and burner ports (four) in the crown, and the provision of room for introduction of probes and withdrawal of samples through the crown. Drawing by A. C. Leadbetter and Son, Inc.

These slots are sealed, when not in use, with tapered brick. Typically, only a short section wide enough to admit a probe or laser beam would be opened at a time.

Three breast wall mounted burners are visible in Figure 3-3 and, between them, the exhaust ports serving the three burners on the opposite wall. The cross section of the front wall mounted burner is also visible on the right end wall. Refractory selection (please see the key to refractory composition in Figure 3-6) has been made to provide a tank able to withstand the unusual degree of cycling that will be associated with frequent changes in feed mode, firing mode, and operating conditions. Some examples of the types of refractory chosen for critical areas are: alpha beta alumina for the crown, fused cast AZS (32% ZrO_2) for the skews, fused cast AZS (37% ZrO_2) for the basin wall, and fused cast AZS (32% ZrO_2) for the melter bottom paving.

The end elevation of the furnace, in Figure 3-4, more clearly shows the slots (plugged) provided for optical and probe access at the tuck and skew lines. The close proximity of the slot at the tuck line to the glass surface facilitates sampling and measurement of temperatures, velocities, and heat fluxes at the surfaces of batch, foam, and glass. The glass level can be raised and lowered by adjustment of the discharge gate at the entrance to the drain chute.

An important feature of the furnace design is the provision for varying the elevation of the burners by changing the thickness of the blocks above and below them, as shown in the drawing at the top center in Figure 3-5. A convenient support for the burners was designed by A. C. Leadbetter and Son to facilitate the adjustment of burner height. In the drawings at the upper left in Figure 3-5, the burners are shown in their highest, lowest, and middle positions. The lowest position places the burners directly on the tuck stones, in close proximity to the glass. Although this is a burner location that might not be considered in the design for a production furnace, and would be nearly impossible to implement, even temporarily, in a production furnace, the ability to examine such extreme cases provides valuable data on the dependence of heat and mass transfer processes on the distance between the flames and the glass surface. Examples of these processes are: (1) radiative and convective heat transfer from the flames to batch, foam, and glass, (2) radiative transfer within the glass, and (3) alkali volatilization. Adjustments in burner elevation are not limited to the three positions shown; other heights can be obtained using different sets of brick and by making modifications to the fixture.

Four large sampling ports are provided at the top of the crown, as shown in the crown plan and elevation, on the left in Figure 3-6. The sampling ports are 4 inches in diameter, large enough to withdraw glass samples and large enough to accept burners for firing through the crown. Plugs for the crown sampling ports, visible in Figure 3-6 at the bottom left, and a tool for their installation and removal, have been designed to provide an unbroken surface on the hot face when the ports are not in use, to avoid having cold spots on the crown that would complicate the measurements and computation of radiative exchange with the crown surface.
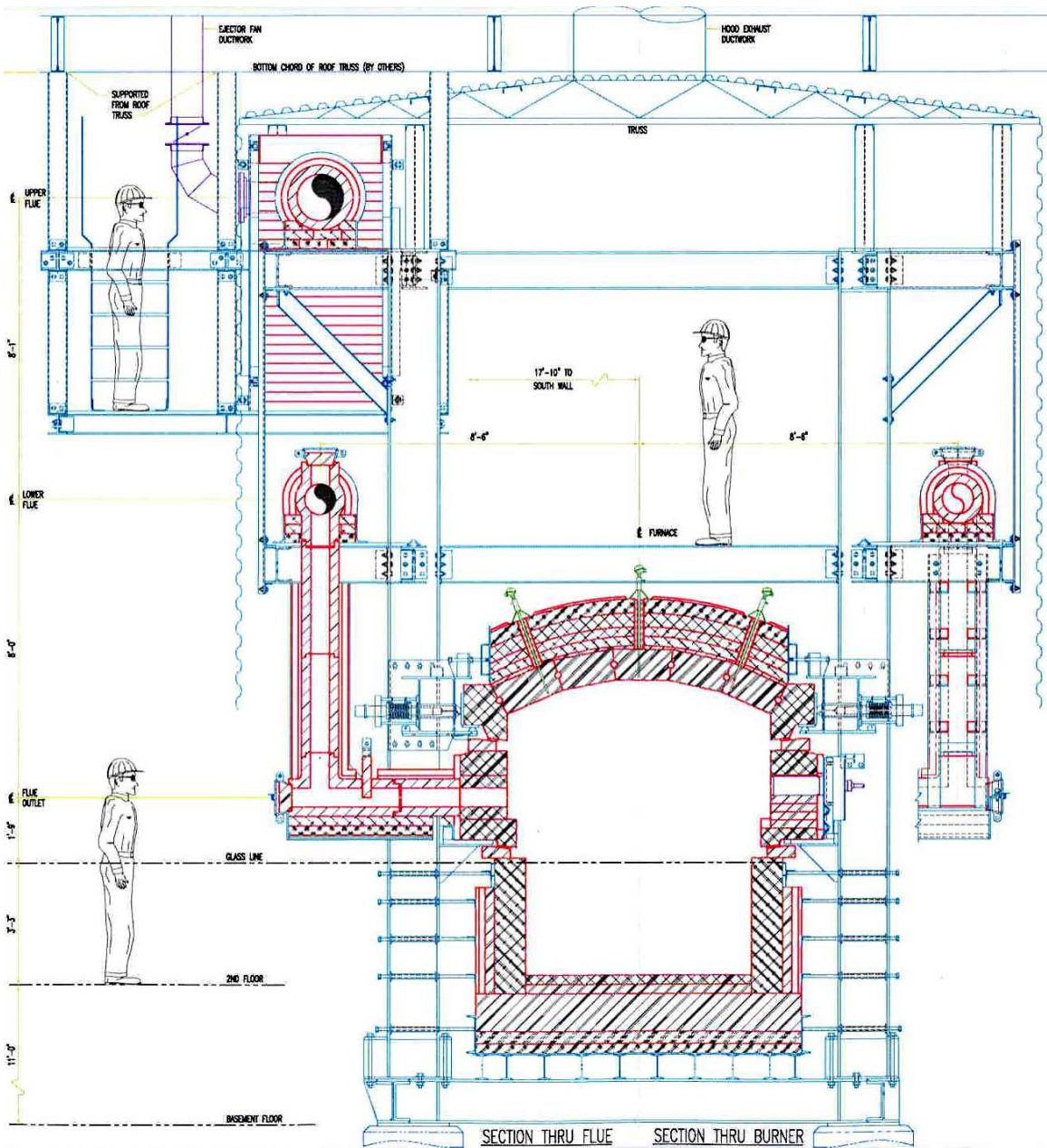
Figure 3-4. End elevation of the melter showing the construction of the tank, superstructure, and crown; buckstays and grillage; arrangement of the burners, flues, and drop box; the slots for optical and probe access at the skew and tuck lines (shown plugged with tapered brick); and the hood to exhaust hot air from the lab (top). Drawing by A. C. Leadbetter and Son, Inc.
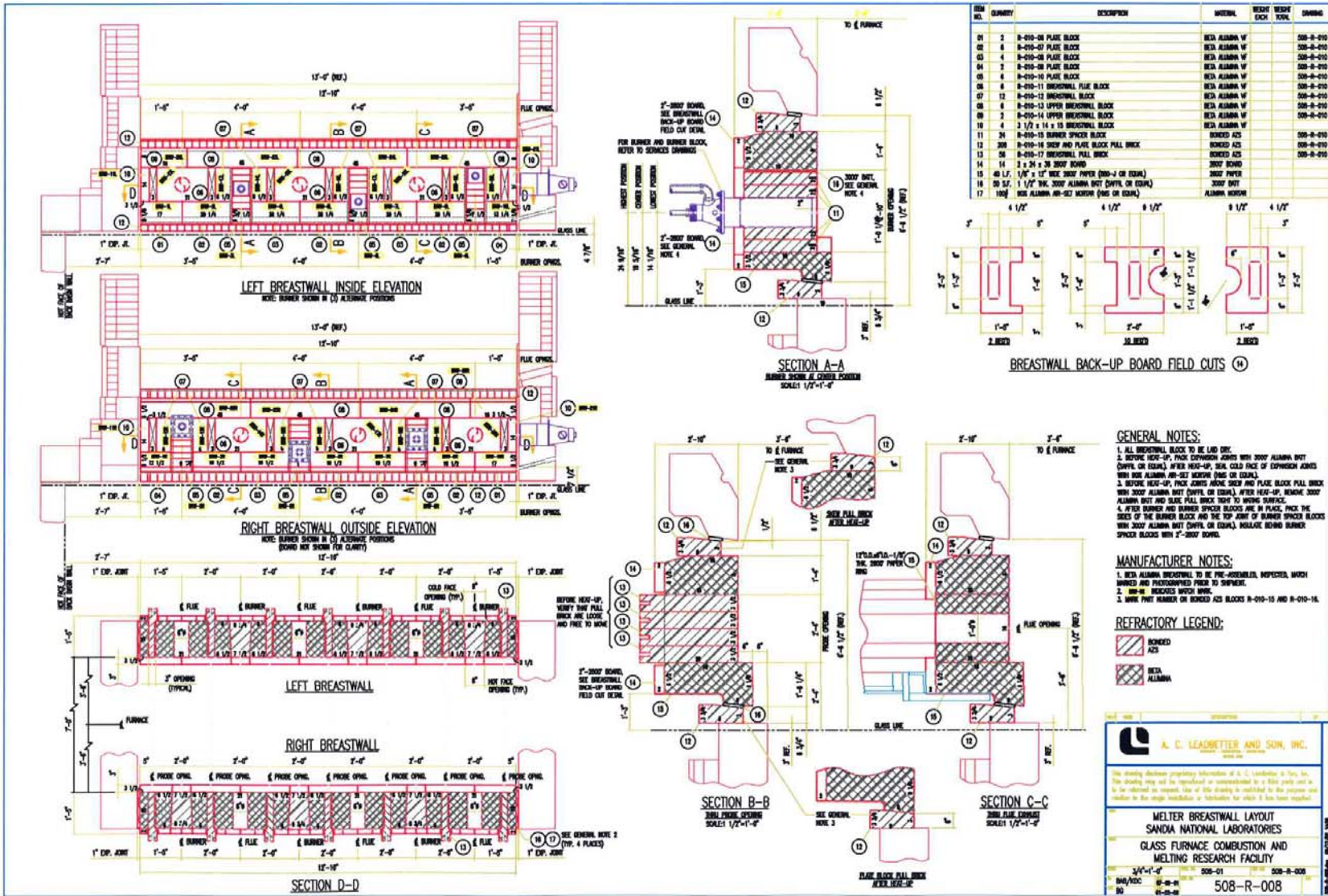
Figure 3-5. Breast wall, burner, and exhaust port detail, showing the front wall burner, breast wall burners at three elevations, and the vertical slots in the breast walls for introduction of optical and conventional probes into the combustion space between the flames from the breast wall burners and across the flame from the front wall burner. Drawing by A. C. Leadbetter and Son, Inc.
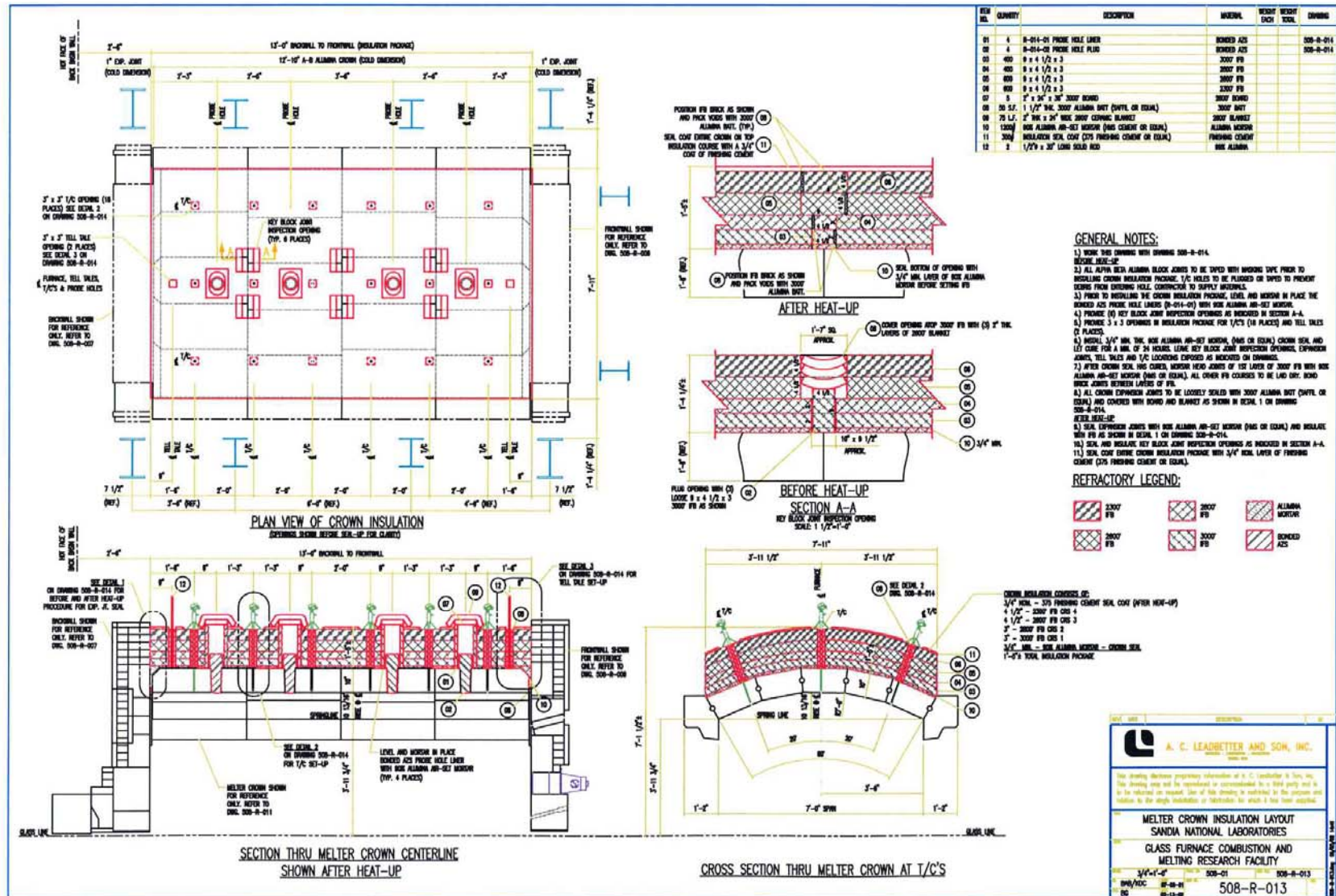
Figure 3-6. Crown detail showing its insulation; ports for burners, probes, and sampling; plugs for the ports when not in use to minimize disturbance to crown radiation and temperature; arrangement of the 18 crown thermocouples; and crown height indicators. Drawing by A. C. Leadbetter and Son, Inc.

Bubblers

Two rows, containing four bubblers each, at the locations shown in Figure 3-6, will be used to control glass circulation. The arrangement of the bubblers was optimized by study of the results of fluid dynamic calculations of the glass flow by David Bivins of PPG Industries. There are two objectives in the placement of the bubblers: (1) to minimize the possibility of devitrification of glass in regions of the tank where heat loss is highest and (2) to provide control over glass circulation for experiments. The heights of the bubblers above the tank floor, and their flow rates, are variable. Provision has been made for oxygen delivery to the bubblers, in addition to air and nitrogen, so the amount of nitrogen into the furnace is under the highest possible degree of control, for studies of NO_X formation.

Temperature Measurements

Temperature is among the most basic and critical properties of the glass, tank, and furnace enclosure. The crown temperature distribution will be defined with a high degree of spatial resolution, as shown in Figure 3-6. A total of 18 thermocouples, each at the center of an equal area of the hot face of the crown, will be mounted in blind holes with their junctions 1 inch from the hot face. These measurements will provide an important component of the analysis of heat transfer from the flames and combustion products to the crown, and from the crown to batch and glass.

In order to characterize the temperature distribution in the glass with the highest practical degree of spatial resolution, 19 tri-level thermocouples will be mounted through the bottom of the furnace at the locations shown in Figure 3-7. The arrangement places most of the thermocouples at the centers of equal areas of the melter. The exceptions are in the row closest to the glass drain and the thermocouple at the entrance to the drain bay. The total of 57 thermocouple junctions have been specified for a tank whose volume is approximately 270 ft^3, providing temperature measurements at an array of positions having an average separation of only 1.7 ft. The uppermost junction of the tri-level thermocouples is only 1 inch below the normal elevation of the glass surface.

Furnace Video Camera

A video camera is to be mounted on the front wall, providing a continuous record of batch distribution, the state of the glass surface, bubble size and frequency, and the shapes and luminosity of the flames. The location for the camera is the slanted port in the glass discharge end wall of the furnace in Figure 3-3, on the right hand side at the same elevation as the skews.
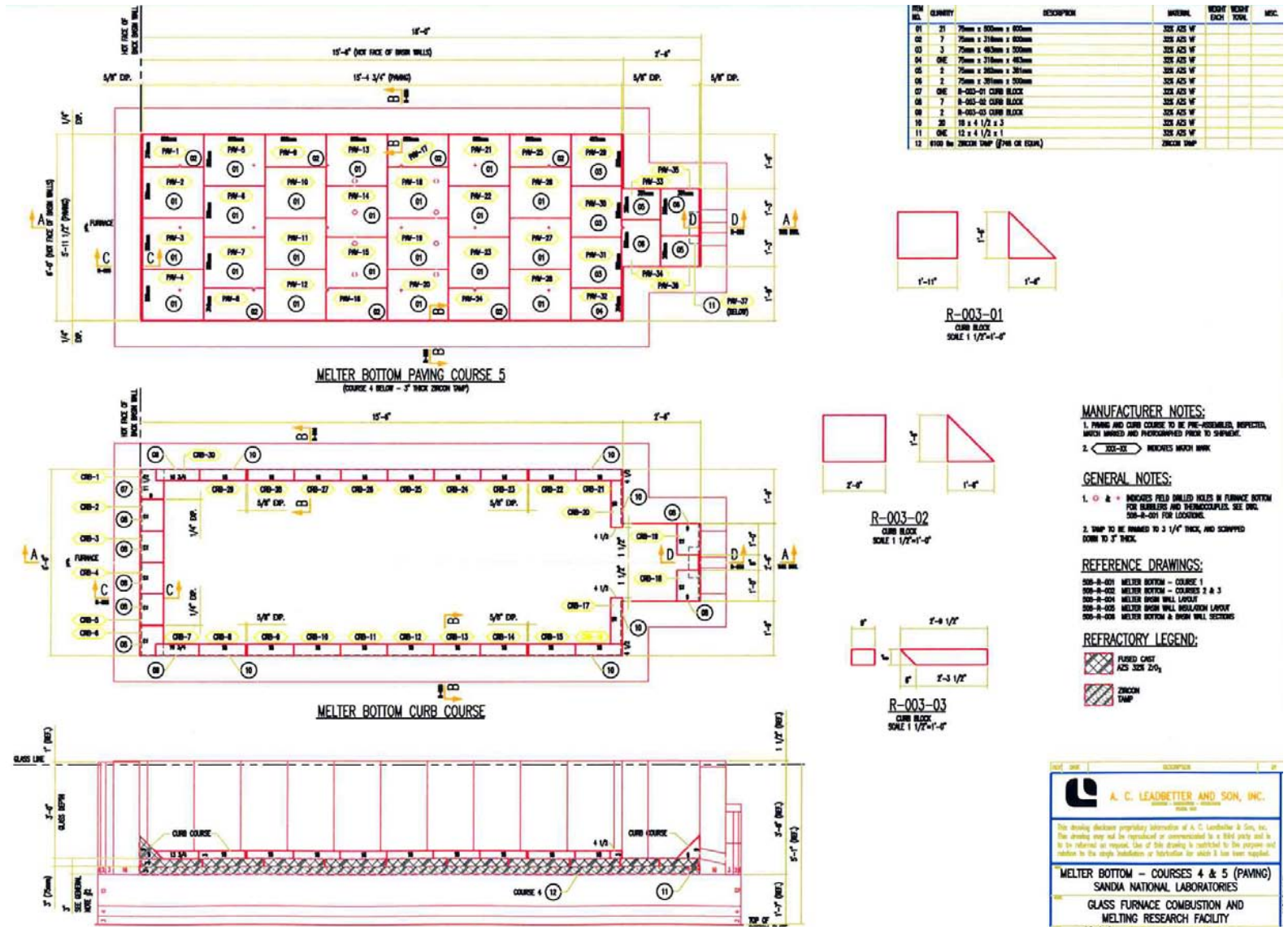
Figure 3-7. Tank bottom detail showing its construction and the arrangement of 8 bubblers and 19 tri-level thermocouples. Drawing by A. C. Leadbetter and Son, Inc.

4. AUXILIARY SYSTEMS

A side elevation of the entire laboratory is shown in Figure 4-1, including (moving from right to left) batch preparation and handling, furnace and flues, quench tank, and stack. The plan of the ground floor is shown in Figure 4-2, including (moving clockwise, beginning at the upper right) batch preparation, batch storage, cullet quench tank and conveyor, and combustion skids. These figures will be useful in the discussion of the auxiliary systems, below.

Natural Gas and Oxygen

Natural gas from the main is compressed and distributed to the combustion laboratories at 100 psig. To supply the melting research furnace the capacity of the system will be increased by the addition of a second compressor. The pressure will be reduced to 20 psig at the control and distribution skid.

Liquid oxygen will be stored in a 10,000 gallon tank to be installed in the Combustion Research Facility service area, next to an existing liquid nitrogen tank. Piping will be installed to deliver the gas to the laboratory at 40 psig, reduced at the control and distribution skid to 15 psig.

A provision has been made in the design of the control and distribution skid for introduction of nitrogen for study of the dependence of NO_X formation on the nitrogen contents of the natural gas and oxygen.

Batch Preparation and Feeding

The batching system, designed by the Lilja Corporation, is shown on the right in the elevation of the laboratory, Figure 4-1, and at the top right in the plan, Figure 4-2. It consists of the following equipment:

- Super sack 2000 lb Vac-U-Max loss of weight scale and support stand mounted on compression type load cells with summing box.
- Screw feeder to mixer, rated at 5 ton/h at a material density of 75 lb/ft^3, with zero speed switch and variable frequency drive.
- Cullet loss of weight dump hopper mounted on compression type load cells with summing box.
- Belt conveyor to mixer, rated at 5 ton/h at a material density of 75 lb/ft^3, with zero speed switch, variable frequency drive, and Process Sensors Corp. (Milford, MA) infrared moisture analyzer to measure the moisture content of the cullet.
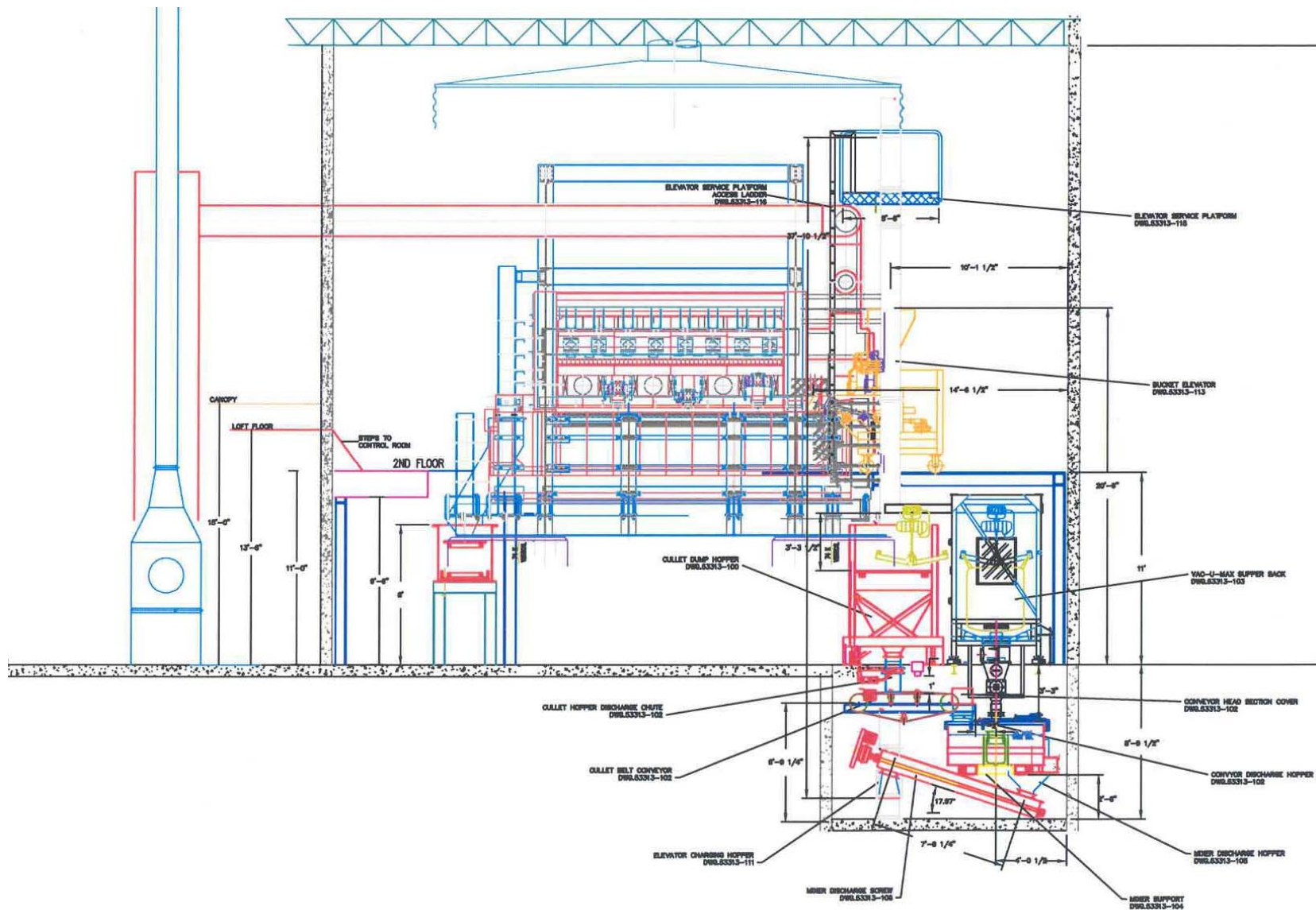
Figure 4-1. Side elevation of the laboratory showing (right to left) batch preparation and handling, furnace and flues, quench tank, and stack. Drawing by Lilja Corp., A. C. Leadbetter and Son, Inc., Merkle Engineers, Inc., and Sandia National Laboratories.
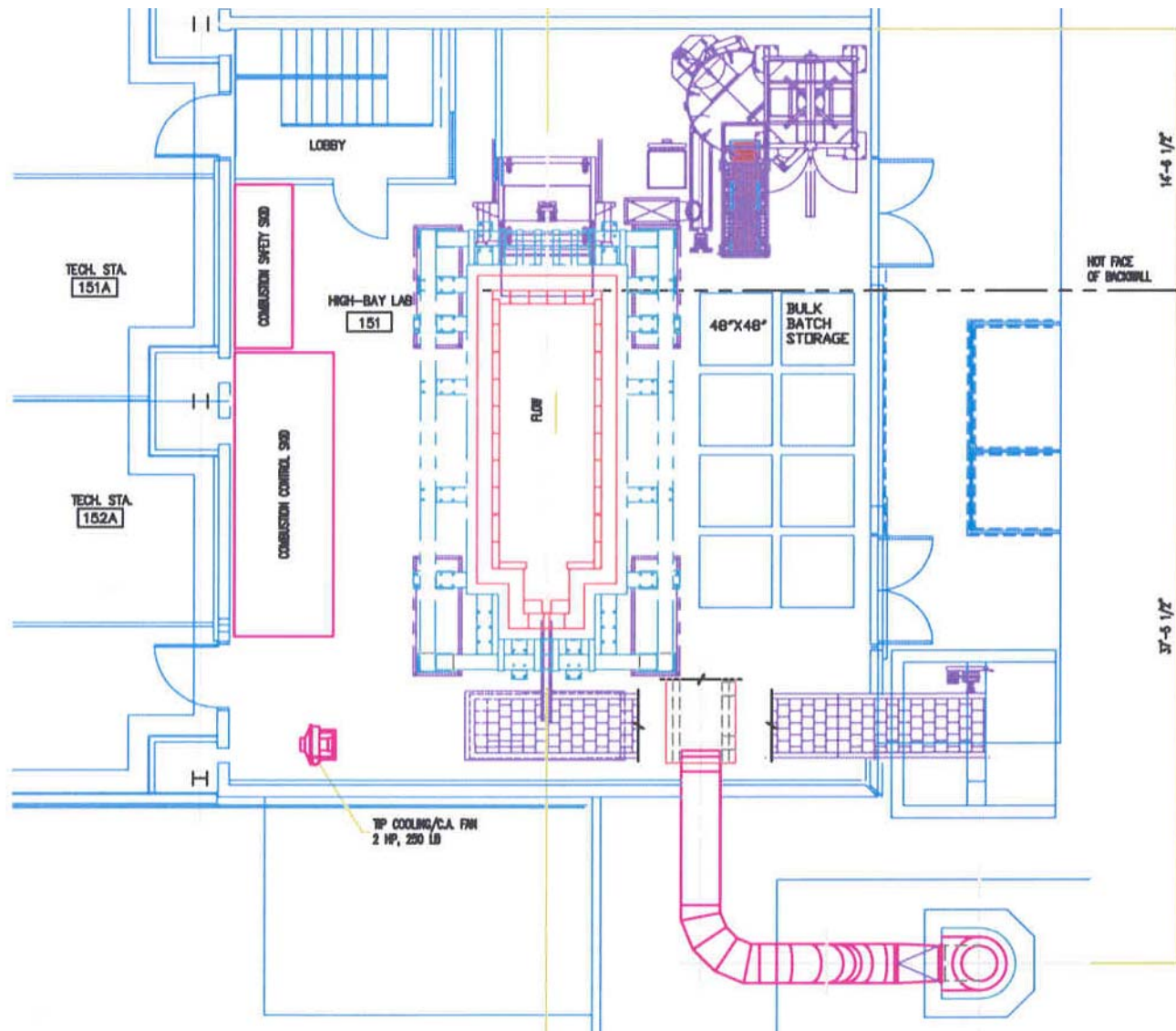
Figure 4-2. Plan of the ground floor of the laboratory, including (moving clockwise, beginning at the upper right) batch preparation, batch storage, cullet quench tank and conveyor, and combustion skids. Drawing by Lilja Corp., A. C. Leadbetter and Son, Inc., Merkle Engineers, Inc., and Sandia National Laboratories.

- Mixer Systems, Inc. (Pewaukee, WI) pan mixer, Model No. 1700, 20-ft³ capacity, with emergency stop switch, a limit switch to indicate discharge gate open, a limit switch to indicate discharge gate closed, and a water addition system with hot water tank to deliver water to the mixer at a temperature between 140 and 160 ºF.

- Screw feeder from mixer to bucket elevator, rated at 5 ton/h at a material density of 75 lb/ft^3, with zero speed switch and variable frequency drive.

- Bucket elevator, rated at 9 ton/h at a material density of 100 lb/ft^3, with zero speed switch, emergency stop switch, adjustable plugging detector in the elevator charging chute, and a plugging detector mounted in the elevator discharge.

- Flex-Kleen (Itasca, IL) dust collector, Model No. 58BVBS-9, with 1.5 hp blower and an 8 inch Meyers airlock, for dust and displaced air pickup at the mixer and the elevator charging chute.

- Flex-Kleen dust collector, Model No. 58BVBS-9, with 1.5 hp blower and an 8 inch Meyers airlock, for dust and displaced air pick up at the elevator discharge and at the charger hopper.

Important features of the system are its ability to feed any mixture from 100% batch to 100% cullet at the nominal maximum rate, corresponding to pull of 25 ton/day, automatic control of moisture content, and the ability to vary chemical compositions and particle size distributions over wide ranges.

The batch equipment will be turned on and controlled by furnace demand and pull. When more batch is required at the charger hopper a signal is sent to start all the equipment in the system. If cullet were the only material to be fed, the cullet dump hopper, mounted on compression load cells, would be filled by a front-end loader prior to starting up the batch system. The cullet dump hopper is a loss of weight scale that feeds cullet onto the belt conveyor that delivers it to the mixer. The conveyor runs until the required cullet weight loss set point is met and then shuts down. During the delivery of cullet on the belt, the Process Sensors infrared unit monitors its moisture content to determine the volume of water to be added by the Mixer Systems water addition system to maintain a specified moisture content in the batch. The water is supplied from the hot water tank at 140 to 160ºF.

If mixed batch is used, a 2000 lb super sack would be set in place on the Vac-U-Max support/weigh frame. The super sack discharges the mixed batch into a screw feeder for transfer to the mixer. The screw feeder delivers the mixed batch until a set point has been reached, when the screw shuts down.

The mixer goes through a set mixing cycle then discharges the mixed batch and/or cullet into a screw feeder for transfer to the elevator. The elevator draws the material from a boot and delivers it through a discharge chute into the charger hopper.

In the event of pluggage in the charging of the elevator the screw shuts down until the elevator has cleared material from the elevator boot charging section.

On shut down, after the system has purged itself, both dust collectors are left running for an additional 30 seconds to allow the dust collectors to pulse the bags clean and discharge collected dust.

The fill machine was designed by Merkle Engineers, Inc. (Galena, IL). The feeder tray is 5 ft wide, covering, except for side clearance, the full width of the doghouse and melter. The tray is equipped with five 1-ft wide gates for control of the width, configuration, and location of the batch raft. A slit raft, divided into two or three sections, can be generated by closing one or two of these gates.

Glass Discharge and Cullet Recycling

Molten glass leaves the tank through a notch in the end of the drain bay and falls into a water-cooled chute. Water is introduced at the top of the chute, above the glass. The chute discharges into a quench tank where the glass breaks up on cooling. A drag conveyor removes the cullet from the bottom of the tank and delivers it to a bin outside the laboratory. A front end loader moves the bins to storage or to the cullet hopper for reintroduction to the furnace.

The quench water is filtered to remove fines, sent to a cooling tower, and returned to the flow down the glass discharge chute. There is an exhaust hood over the quench tank to minimize the release of heat and moisture into the laboratory space.

Exhaust System

The general arrangement of the exhaust ducts for removal of combustion products from the furnace is most easily seen in the artist's rendering, Figure 3-1. A straight horizontal section with removable cover is provided on each of the connections to the furnace for cleaning out deposits and debris and to provide optical access to the axis of the flame opposite each exhaust port. The two exhaust headers are joined at the back end of the furnace where they also meet the flue serving as the exhaust for the single large burner mounted in the front wall. The arrangement of these flues is best seen in Figure 3-3. The single duct is routed above the right side of the furnace, through the wall to a down comer outside the laboratory, and connected to the base of the ejector, as shown on the left in Figure 4-1. Dilution air is added to cool the exhaust at the point in the flue just beyond where it passes the front wall of the furnace. The dilution air will be supplied by a dedicated fan mounted on the roof of the building. The duct carrying the dilution air and its connection to the flue can be seen at the upper left in Figure 3-4.

The Morgan Ejector System, Size No. 04, is to be provided by Laidlaw Drew Ltd. (Livingston, Scotland, UK). It will have a capacity of 55,000 scfh at a temperature of 1500 ^{o}F with a maximum draft of -4 in. w.c. The diffuser will be equipped with a damper and the fan motor equipped with an inverter type speed control.

Cooling Wind

Sufficient tank block cooling air will be provided to achieve an air velocity at the nozzle exits of 10,000 ft/min. Two fans to supply the air will be located outside the laboratory, one serving as backup. A generator will also be provided to keep a fan running in the event of power failure. The design and location of cooling wind nozzles to optimize heat transfer and minimize air infiltration are examples of the many aspects of engineering for glass melting that are worthwhile subjects for investigation.

Control System and Data Acquisition

A single control system will be used for both batch preparation and furnace operation. A controller was desired with which experimental work on control of the furnace could be done using new sensors and control strategies. The system chosen is the Fisher-Rosemount Systems DeltaV.

Continuous Emission Monitors

The composition of flue gas will be monitored continuously for O_2, CO_2, CO, NO_X, SO_2, and hydrocarbons. A good set of these instruments, including a pump and sample dryer, is available from the Sandia Burner Engineering Research Laboratory and will be transferred directly to the melting research laboratory. The dependence of emissions on batch composition, raft arrangement, firing configuration, burner stoichiometry, oxygen purity, and air infiltration are some of the investigations that can be conducted using this equipment.

Ventilation

Because the sophistication of the instrumentation that can be applied to glass melting problems depends to a significant extent on the quality of the environment that can be maintained in the laboratory, the work space around the furnace will be kept dust free and as cool as possible. A hood will be installed over the furnace with a curtain hanging from its rim, as shown in Figures 3-4 and 4-1, to collect and withdraw the hot air rising up the sides and ends of the furnace. Portable curtains mounted on casters will be placed around the furnace on the second floor to minimize radiation to people and equipment from the outer surface of the furnace and from openings in the combustion space. The effectiveness of current and proposed industrial practices for managing heat loss may also be evaluated. The air exhausted through the hood will be made up by air supplied from a conditioning unit on the roof, carried downward through ducts mounted on the walls of the room, and introduced into the laboratory on the ground and second floors.

5. RESEARCH AGENDA AND INSTRUMENTATION

A variety of types of investigation and different modes of operation are envisioned for the Combustion and Melting Research Facility:

- Fundamental studies of chemistry, heat transfer, mass transfer, melting, mixing, gas evolution, fining, and foam dissipation

- Collection of detailed data sets for model validation

- Specific tests, e.g. of burners, sensors, and batch formulations

- Adaptation of optical measurement techniques to melting tank furnaces

- Development of new sensors for industrial application

- Examination of transient behavior and refinement of model-based control

- Exploration of radical departures from accepted practice

The program and objectives for a given test campaign will be decided well in advance in consultation with the industrial sponsors and the advisory group to be formed by representatives from the glass industry, with advice from the Glass Manufacturing Industry Council and the DOE/OIT Glass Program.

The laboratory is to be thoroughly equipped with the lasers, optics, and detectors needed to apply measurement techniques developed during the study of flames, materials, and reacting flows in other laboratories in the Combustion Research Facility at Sandia. The optical techniques are especially attractive for measurements in glass furnaces because the conditions of temperature to which a conventional water-jacketed probe would be subjected are so severe. The basic optical equipment consists of:

> Large optical table shown on the left side of the furnace in Figure 3-2
> Smaller optical tables (4 ft x 4 ft) placed where needed for particular
>   experiments
> Nd:YAG laser
> Dye laser
> Laser Doppler velocimetry instrumentation
> Argon ion laser for laser Doppler velocimetry
> Visible, near UV, near IR spectrometer
> CCD camera

Examples of laser-based measurement techniques to be implemented in the research furnace and their state of development are summarized in Table 5-1. Use of near-infrared tunable diode lasers to monitor the gaseous species, O_2, H_2O, and CO, in products of oxygen/natural gas combustion is described by Von Drasek et al. (2000).

Table 5-1. Examples of laser-based measurement techniques for glass melting furnaces.

Technique	Acronym	Measurement	Advantages	Status
Laser Doppler Velocimetry	LDV, LDA	Gas velocity	Non-intrusive, Characterizes turbulence	Commercial
Coherent Anti-Stokes Raman Spectroscopy	CARS	Gas temperature O_2 concentration	Non-intrusive, No temperature limit, Observes fluctuations	N_2 CARS is the standard. O_2 is an option when N_2 is absent. O_2 CARS performed well in the lab.[a]
Laser-Induced Breakdown Spectroscopy	LIBS, LASS, LIPS	Concentrations of elements, e.g. Na, K, Ca, Mg, Fe, B, Si, Al	Distinguishes volatilization from carry-over, Observes particles in-situ, Good time response, High sensitivity, Portable	Measurements in the flue of an O_2/n.g.-fired container furnace at the Gallo Glass Co.[b]
Laser-Induced Fragmentation Fluorescence	LIFF	NaOH	Non-intrusive, NaOH is most important sodium-containing species	Measurements in PPG Industries float glass furnaces at Fresno, CA, and Meadville, PA.[c]
Raman Scattering	-	Glass surface temperature	Non-intrusive	Experimental

a. T. A. Reichardt, P. E. Schrader, and R. L. Farrow, 2001.
b. L. G. Blevins, A. Molina, S. M. Sickafoose, P. M. Walsh, and J. W. Neufeld, 2003b.
    L. G. Blevins, C. R. Shaddix, S. M. Sickafoose, and P. M. Walsh, 2003c.
    L. G. Blevins, A. Molina, S. M. Sickafoose, J. W. Neufeld, and P. M. Walsh, 2003a.
c. S. F. Rice, unpublished work, Sandia National Laboratories, 2003. See M. Allendorf and G. Pecoraro, 2003.

In spite of severe conditions, conventional sampling and measurement techniques using water-cooled probes are still expected to provide valuable data, perhaps not in the hottest regions of the oxygen/natural gas flames close to the burners, but in the far fields of the flames, in the combustion products surrounding the flames, and in the vicinity of the glass surface and crown. Probes specifically designed for research on flames and furnaces are available from the International Flame Research Foundation (IJmuiden, The Netherlands). Flow properties and furnace conditions that can be measured using these probes are:

Radiation heat flux - Narrow angle radiometer
                           Wide angle (ellipsoidal) radiometer
Convection plus radiation heat transfer - Total heat flux probe
Gas temperature - Suction pyrometer
Gas composition - Extractive sampling probe
Gas velocity - 5-hole Pitot/static probe

An excellent example of an analysis of radiation from a boiler-type flame was performed by Sayre and coworkers (1994), based upon their measurements of narrow angle radiation, gas temperature, and gas composition using conventional probes in the Sandia/Gas Research Institute/DOE-OIT Burner Engineering Research Laboratory.

In addition to highlighting the need for a central melting research facility, the Glass Industry Technology Roadmap (Jamison et al., 2002) identifies many specific research problems that are ideally suited for investigation using optical and conventional measurement techniques at semi-industrial scale. These and other research topics also appeared in the responses to the survey distributed by GMIC (Appendix A, pp. A4–A5) and at the meeting held at Argonne National Laboratory on September 15, 1999 (Appendix B, pp. B2–B3), following the OIT FY1999 Glass Industry Project Review.

The most promising subjects for research, from the points of view of importance to the industry and likelihood of success, are described below, in the order of preference indicated by the responses to the survey (Appendix A, p. A4), beginning with the highest. The proposed focus of the first measurement campaign is heat transfer, the first topic listed below.

Topic 1.   Mechanisms of heat transfer from flames to batch and glass. The relative contributions of soot (solid carbon particles) and gas (H_2O and CO_2) radiation to heat transfer from oxygen/natural gas flames and combustion products to the load is a continuing subject of debate. Each of the two diametrically opposed burner designs, concentric tube and wide flame, has its proponents. A quantitative treatment is needed, based upon measurements, of radiative exchange among all the major emitters and absorbers in the furnace: flames, combustion products, crown, superstructure, openings, batch, foam, and clear glass. Both conventional and optical methods will be applied to measurement of temperature, composition, and radiative properties of these media and the heat fluxes to and from all of the surfaces in the furnace.

Topic 2. Alkali volatilization and particulate matter formation. The mechanisms and pathways of alkali volatilization, transport, deposition, and emission will be examined by optical measurements of sodium species concentrations throughout the combustion space. The Sandia group has already contributed in this area by making laser-induced breakdown (LIBS) and line-of-sight emission/absorption spectroscopic measurements in Gallo Glass Co. tanks under a joint Cooperative Research and Development Agreement between Corning Inc., Visteon, and DOE/OIT (Buckley et al., 2000; Walsh and Moore, 2000) and a DOE/OIT Glass Industry of the Future project with Gallo Glass (Blevins et al., 2003a, 2003b, 2003c). A laser-induced fragmentation fluorescence (LIFF) technique, capable of spatially-resolved measurements, is also under development in a companion project (S. F. Rice and coworkers, unpublished work, 2003; M. Allendorf and G. Pecoraro, 2003). Both LIBS and LIFF are sufficiently well tested in glass furnace applications that both are expected to provide valuable data on volatilization and particulate matter formation during the first measurement campaign.

Topic 3. Improve understanding of the mechanisms of bubble formation, growth, and fining. The objectives here will be to identify the controlling processes, determine their dependence on process conditions, and provide measurements to guide the development of mechanistic models. The idea is to use a laser sheet to illuminate seeds and bubbles in the glass and to follow the growth and rise of the bubbles in images of the region illuminated by the laser. This is a challenging experiment in which the expertise of the Combustion Research Facility staff in optical diagnostics will be critical.

Topic 4. Increase knowledge of the physical and chemical properties of the glass melt. The emphasis will be on the influence of combustion space conditions (e.g. temperature, oxygen, carbon monoxide, and water vapor concentration) on the composition, viscosity, and redox state of the melt.

Topic 5. Develop and test sensors for melting parameters (e.g. temperature, viscosity, NO_x, colorants, redox state, velocity). Development of measurement techniques for industrial applications is one of the strengths of Sandia and Combustion Research Facility staff. An example is the oxygen-CARS measurement (Reichardt et al., 2001), specifically intended for use in oxygen-fired glass furnaces. Other sensors and measurement techniques are under development in programs supported by OIT and other sponsors and partners. The Combustion and Melting Research Facility will be an ideal place in which to evaluate their performance.

Topic 6. Data Sets for Model Validation. The simulation of melting tank furnaces by numerical solution of the governing equations is being vigorously pursued by a number of research groups. The velocity, composition, and temperature of glass in the tank and gas in the combustion space can now be calculated at unprecedented levels of detail. However, experimental data with which to test and validate the models are very scarce. Generation of accurate and detailed data sets for this purpose is among the most valuable contributions that the user facility can make.

Topic 7.   Design intelligent model-based control and process optimization systems.
The modeling group based at Sandia/CA has demonstrated its ability to implement effective model-based control in semiconductor processing and industrial welding applications. Sandia has one of the most powerful supercomputers in the world. Access to this machine is available, if needed, to develop and test the detailed physical models on which simplified control algorithms would be based. A companion project, "Sensor Fusion for Intelligent Process Control," supported by the Sensors and Controls Crosscutting Program in OIT, with PPG, the University of Utah, and Sandia as partners (Arbab et al., 2004; Desam and Smith, 2003), has prepared the Sandia controls group for experiments in model-based control for glass manufacturing, using the melting research furnace as a test bed.

Topic 8.   Observe glass circulation, its dependence on furnace conditions, and its relationship to defects in glass. Scattering of a sheet of visible laser light by particles and bubbles, in a variant of particle image velocimetry, is a possible approach to the observation of glass circulation. The concept, closely related to that proposed in Topic 3, is to use a laser sheet to illuminate seeds and undissolved sand grains and to follow their motion under the influence of gravity and glass circulation by recording and comparing successive images of the illuminated region.   These will certainly be difficult experiments, but non-intrusive optical and ultrasonic measurements under extreme conditions are a specialty of Sandia Laboratories.

Topic 9.   Improve understanding of combustion dynamics and emissions. The steady-state and transient behavior of the pilot-scale melting tank will be examined using traditional extractive probes, laser-based imaging techniques, and optical measurements of temperature and gaseous species concentrations. A particular emphasis will be on the minimization of NO_X emissions.

Topic 10. Mechanism of batch melting. The research melting tank will be an ideal place to probe the progress of batch melting with measurements of gas composition above the batch blanket and glass composition measurements below it as functions of distance along the batch pile in the direction of flow and as functions of distance above and below the surface.

Topic 11. Mechanisms of refractory corrosion. Measurements of corrosion rates, especially during oxygen-natural gas firing, will be made in conjunction with measurements of the attacking species concentrations and the gas flow field. The results will be applied to full-scale tanks through a coupled chemistry-transport-corrosion model. Work in the Combustion and Melting Research Facility is not intended to duplicate or reproduce refractory testing activities that have been underway at other laboratories for many years. It can however, make a unique contribution by application of optical measurement techniques to determine mechanisms of entrainment, volatilization, transport, deposition, and effects on refractory of corrosive species. Sandia and its partners at American Air Liquide, Penn State University, and PPG Industries have already demonstrated their expertise in this area with the publication of a major review of silica crown corrosion (Nilson et al., 2003).

6. ENVIRONMENTAL AND SAFETY CONSIDERATIONS

New projects are reviewed by Sandia Laboratories' Environmental Safety and Health (ES&H) Department to ensure that safety and environmental impact are given high priority in the planning and design of experimental facilities, and that all local, state, and federal regulations will be met during the installation and operation of a laboratory. The Melting Research Facility was reviewed by the ES&H Interdisciplinary Team on April 22, 1999. At that meeting a list of potential hazards was presented, shown in Table 6-1, along with the steps to be taken for their control.

No insurmountable barriers to implementation of the facility were identified by the Interdisciplinary Team, but the members responsible for air quality, fire protection, health physics, industrial hygiene, occupational safety, waste minimization, and wastewater requested that they be kept informed as the work proceeds and that additional discussions be conducted as the design evolves.

A second meeting with the Interdisciplinary Team was held on March 1, 2001. The report summarizing the findings of Safety Engineering, based on the information presented and discussed at the meeting, contains the following requirements and recommendations.

> Have the furnace manufacturer assemble, install, and certify the system on site at Sandia, including:
>
>> Initial testing and certification of the safety systems and ancillary components.
>>
>> Training of Sandia/CA site users in accordance with the requirements set forth in National Fire Protection Association (NFPA) 86.
>>
>> Periodic inspection, testing, and maintenance; and, or training of Sandia/CA personnel to perform these services. Code requirement of manufacturer: The equipment manufacturer shall inform the user regarding the need for adequate operational checks and maintenance *and shall provide complete and clear inspection, testing, and maintenance instructions* (NFPA 86, 10-1.1).
>
> Safety Engineering requests to be invited to perform a pre-startup, site safety assessment for this project.
>
> Lawrence Livermore National Laboratory Fire Department (provides fire protection for the Sandia site) should approve the process and be notified of furnace operation.

Table 6-1. Potential safety hazards and their control.

Hazard	Source	Control
Fire	Natural gas Solvents	Detector, interlock, alarm proper containment and disposal
	Oxygen	Proper storage, piping, valves, interlock
Electrical	480 VAC with water-cooled electrodes[a]	Proper enclosure, lockout/tagout water conductivity monitor, voltage monitor, interlocks
	208 and 240 VAC laser power supplies 120 VAC instruments high-voltage power supplies	Certified commercial instruments, proper wiring and connections, proper grounding, cables, and connectors
Class IV Lasers	Argon ion, Nd:YAG, tunable dye	Eye protection, interlocks
Pressure	Compressed gases	Relief valves, vents, interlocks
Crane	-	Inspection, certification, training
Burn	Hot surfaces of furnace, hot ductwork, hot glass	Insulation, barriers, labels, water quench
Chemical	Methanol, laser dyes	Proper containment and disposal, labels, goggles
	Toxic calibration gases: CO, NO	Relief valves, vents, gas detectors, interlocks
Dust	Sand, limestone, sodium carbonate, sodium sulfate	Proper containment
Noise	Flames, blowers, gas flows	Hearing protection
Earthquake	-	Interlocks on gas, oxygen, and power; secondary containment under glass tank

a.   In the final design there is no electric heating of the glass.

Mortar and brick used for refractory should be asbestos free. Avoid procuring asbestos-containing materials.

Avoid procuring raw materials or cullet containing arsenic.

Coordinate the use of any radioactive material with the Radiation Protection Department. [At the time of the meeting, it was planned to include a Differential Mobility Particle Sizer in the laboratory instrumentation, but this is no longer under consideration. Laser-based particle sizing will be adopted instead. The Differential Mobility Particle Sizer (TSI Inc., St. Paul, MN) contains a Krypton-85 source (beta emitter) to neutralize the charge on incoming particles.]

Recommendation to use isopropyl alcohol as the solvent of choice, in place of acetone or methanol.

Record and report to Pollution Prevention the weights of glass reused (re-introduced into the process) and recycled (to offsite recycler).

Recommendations by Industrial Hygiene on the need to "engineer out" potential health hazards.

The members of the Interdisciplinary Team responsible for air quality, fire protection, radiation protection, industrial hygiene, pollution prevention, waste minimization, safety, waste management, and wastewater requested continuing involvement as the project moves forward.

The proposed plan for the Melting Research Facility was submitted to the U.S. Department of Energy, Kirtland Area Office, for review in accordance with the National Environmental Policy Act. The Combustion and Melting Research Facility was granted a categorical exclusion from the need to prepare an environmental assessment or environmental impact statement.

Authority to Construct and Permits to Operate are required from the Bay Area Air Quality Management District (BAAQMD). Authority to Construct the two regulated components of the Melting Research Facility, the Research Glass Melting Furnace (Source 98) and the Raw Material Handling Operations (Source 99) was received in July 2003. Permits to Operate will be issued after verification that all conditions and specifications outlined in the Authorities to Construct have been met. The Authorities to Construct expire on July 10, 2005, unless substantial use of the authority has begun.

7. PROJECT SUMMARY, ACCOMPLISHMENTS, MILESTONES, SCHEDULE, AND COST

Project Summary and Accomplishments

The design of the melting research furnace and its auxiliary equipment and the research questions that they have been designed to address are the result of a thorough and painstaking process of inquiry into the current state of the art, identification of scientific and technical gaps that inhibit further progress, and specification of a research facility best equipped to provide answers to the most important problems. The following are the steps along the path that led to a facility able to reproduce the important characteristics of industrial tank furnaces, capable of operation at conditions far removed from conventional industrial practice, thoroughly instrumented, and accessible to the most advanced measurement techniques.

July - September 1999: A survey was distributed to members of the glass industry by the Glass Manufacturing Industry Council to assess industry need for the facility and the requirements that its design should meet. (The survey and responses are attached as Appendix A.)

September 15, 1999: A workshop was held following the OIT Glass Project Review in Argonne, IL, to solicit input from the glass industry on the objectives and capabilities of the melting research facility. (A summary of the workshop is attached as Appendix B.)

May 12-18, 2000: Detailed discussions with engineers at Pilkington, Philips Components, TNO, and Schott Glas.

July 6, 2000: Visit to PPG Industries Works 15, Fresno, CA.

October 2000: Observation of 2.5 ton/day research and production furnace at Philips Components, Eindhoven.

December 2000: Agreement between PPG Industries and Sandia to move forward on plans for a research facility dedicated to oxy-fuel melting.

January 25, 2001: Visit to PPG Industries Lake Charles, LA, Silica Products plant.

February 12-13, 2001: Meeting with Lilja Corp. at Sandia to consider space requirements, furnace design, and engineering issues. Proposal for general arrangement and dimensions of the melting tank.

April 23-25, 2001: Meetings at Sandia to address facility modifications, furnace design, and principal safety issues.

May 21-23, 2001: Meetings at Sandia with PPG Industries, A. C. Leadbetter and Son, and Lilja Corp., to assign responsibilities and set the schedule for engineering. Agreement on highest priorities for the research agenda.

June 12-13, 2001: Meeting of PPG Industries, Sandia, Merkle Engineers, and Maxon Corp. at A. C. Leadbetter and Son for review of preliminary furnace engineering design.

July 16, 2001: Meeting of PPG Industries, Sandia, and Maxon Corp. at A. C. Leadbetter and Son for review of detailed furnace engineering design.

September 4, 2001: Meeting of PPG Industries and Sandia at PPG Glass Technology Center for comprehensive program review.

November 6-8, 2001: John Connors, Bob Gallagher, and Peter Walsh present project to GMIC members and Board of Directors at OIT Glass Project Review in Richland, WA.

April 24-25, 2002: Meeting of PPG Industries and Sandia at A. C. Leadbetter and Son to resolve remaining engineering questions.

July 16, 2002: Furnace and batching system engineering complete.

July 18-19, 2002: Meeting at Sandia to review engineering packages and prepare cost estimate.

August 29, 2002: All drawings and bills of materials complete.

Milestones and Status

Milestone	Status
Industry Survey	Complete
Project Scope as Defined by Industry Survey	Complete
General Arrangement Drawings	Complete
Detailed Engineering, Drawings, Specifications	Complete
Detailed Project Review	Complete
Cost Estimate	Complete
Approval by Sandia Environ. Safety and Health	In process, up-to-date
Authority to Construct from BAAQMD	Received
Construction	Pending agreements with partners
Operations	On completion of construction

Results from each stage of the work were thoroughly reviewed with the industrial partner before proceeding to the next stage.

Schedule for Implementation

The following are the steps needed to bring the melting research facility on line (the timing is based on standard Sandia contracting and procurement procedures):

Task	Description	No. of Months Following Start
1.	Begin site engineering, Sandia and contractor	0
2.	Sandia and site contractor designs complete	3
3.	Bid cycle/approval, place orders	6
4.	Sandia installation work start	6
5.	Sandia first phase work complete/contractor work start	11
6.	All material on site	11
7.	Contractor work complete	14
8.	Sandia second phase complete/Heat up	16
9.	First measurement campaign	18
10.	Results of first measurement campaign to industry	24

Cost of Installation of the Facility, Including General Contractor's Profit and Overhead and Sandia National Laboratories' Overhead

Furnace (A. C. Leadbetter and Son, Inc.)	$6,018,428
Batching System (Lilja Corp.)	717,476
Ejector (Laidlaw Drew Ltd.)	59,144
Sandia Site Engineering	541,740
Site Modification and Utilities	1,785,571
Miscellaneous	250,800
Contingency	541,246
Total	$9,914,405

Of the total, $8,490,504, or 85% of the estimate is based on firm quotes.

8. SYMBOLS AND ABBREVIATIONS

A   Cross section area of tank perpendicular to the bulk glass flow direction, m^2

BAAQMD   Bay Area Air Quality Management District

c   Specific heat of molten glass, $J\ kg^{-1}\ K^{-1}$

CARS   Coherent anti-Stokes Raman spectroscopy

CCD   Charge coupled device

ES&H   Environmental Safety and Health Department, Sandia National Laboratories

g   Acceleration due to gravity, $= 9.8\ m\ s^{-2}$

Gr   Grashof number, $= \dfrac{g\ \beta\ (T_H - T_0)\ H^3}{\nu^2}$, dimensionless

GMIC   Glass Manufacturing Industry Council, Westerville, OH

H   Glass depth, m

k_{eff} Dimensionless effective thermal conductivity, $= k'_{eff}/k_{ref}$

k'_{eff} Effective thermal conductivity of molten glass, including the contribution from radiation, $J\ m^{-1}\ s^{-1}\ K^{-1}$

k_{ref} Reference effective thermal conductivity of molten glass, evaluated at a characteristic temperature, $J\ m^{-1}\ s^{-1}\ K^{-1}$

LDA   Laser Doppler anemometry

LDV   Laser Doppler velocimetry (same as LDA)

LASS   Laser spark spectrometry (same as LIBS)

LIBS   Laser-induced breakdown spectrometry

LIFF   Laser-induced fragmentation fluorescence

LIPS   Laser-induced plasma spectrometry (same as LIBS)

NFPA   National Fire Protection Association

OIT   Office of Industrial Technologies in the U.S. Department of Energy

Pr   Prandtl number, $= \nu/\alpha$, dimensionless

q_m Glass pull rate, $kg\ s^{-1}$

Ra	Rayleigh number $= \mathrm{Gr} \cdot \mathrm{Pr} = \dfrac{g\,\beta\,(T_H - T_0)\,H^3}{\nu\,\alpha}$, dimensionless
Re	Reynolds number $= u_{ref}\,H/\nu$, dimensionless
s	Parameter introduced by Wright and Rawson (1973) to describe the degree of nonuniformity of glass surface temperature, $= \dfrac{T_H - T_W}{T_H - T_0}$, dimensionless
t	Time, s
t_u	Time, scaled using the average glass velocity, $= t\ u_{ref}/H$, dimensionless
t_α	Time, scaled using the thermal diffusivity, $= t\ \alpha/H^2$, dimensionless
t_ν	Time, scaled using the kinematic viscosity, $= t\ \nu/H^2$, dimensionless
T	Glass temperature, °C
T_H	Glass surface temperature (uniform) or surface temperature at the hot spot (nonuniform), °C
T_W	Glass surface temperature at the end walls, °C
T_0	Glass temperature at the tank bottom, °C
u	x component of glass velocity, m/s
u_{ref}	Average glass velocity through the tank, the withdrawal current, m s^{-1}
u_u	x component of glass velocity, scaled using the average glass velocity, $= u\ /u_{ref}$, dimensionless
u_α	x component of glass velocity, scaled using the thermal diffusivity, $= u\ H/\alpha$, dimensionless
u_ν	x component of glass velocity, scaled using the kinematic viscosity, $= u\ H/\nu$, dimensionless
v	y component of glass velocity, m/s
v_u	y component of glass velocity, scaled using the average glass velocity, $= v\ /u_{ref}$, dimensionless
v_α	y component of glass velocity, scaled using the thermal diffusivity, $= v\ H/\alpha$, dimensionless
v_ν	y component of glass velocity, scaled using the kinematic viscosity, $= v\ H/\nu$, dimensionless
x	Distance in x direction, scaled using the glass depth, $= x\ /H$, dimensionless

x	Distance in x direction, m
y	Distance in y direction, scaled using the glass depth, $= y'/H$, dimensionless
y'	Distance in y direction, m
α	Thermal diffusivity of molten glass at characteristic temperature, $= k_{ref}/(\rho_{ref}c)$, m^2 s^{-1}
β	Thermal expansion coefficient of molten glass, $^{\circ}$C^{-1}
θ	Dimensionless temperature, $= \dfrac{T' - T_0}{T_H - T_0}$
μ	Dimensionless absolute viscosity of molten glass, $= \mu'/\mu_{ref}$
μ'	Absolute viscosity of molten glass, kg m^{-1} s^{-1}
μ_{ref}	Reference absolute viscosity of molten glass, evaluated at a characteristic temperature, kg m^{-1} s^{-1}
ν	Kinematic viscosity of molten glass at a characteristic temperature, $= \mu_{ref}/\rho_{ref}$, m^2 s^{-1}
ρ_{ref}	Density of molten glass at a characteristic temperature, kg m^{-3}

9. REFERENCES

M. Allendorf and G. Pecoraro, "Development of Models and On-Line Diagnostic Monitors of the High-Temperature Corrosion of Refractories in Oxy/Fuel Glass Furnaces," in: Proceedings of the FY 2003 Glass Industry Project Review, Industrial Technologies Glass Research Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, in association with the Glass Manufacturing Industry Council, Golden, CO, September 8-10, 2003.

M. Arbab, B. W. Binion, J. J. Connors, C. Dodge, M. A. DeYoung, A. R. Farrar, C. P. Gowin, W. F. Haley, D. Hanekamp, K. Hill, Yu Jiao, R. M. Mayer, R. W. Michael, A. J. Miller, M. R. Stokes, R. Tiwary, P. R. Desam, P. J. Smith, L. A. Bertram, R. J. Gallagher, R. G. Hillaire, W. G. Houf, D. A. Sheaffer, Jr., and P. M. Walsh, "Sensor Fusion for Intelligent Process Control," Final Report to the U.S. Department of Energy, Sandia National Laboratories, Livermore, CA, June 29, 2004.

L. G. Blevins, A. Molina, S. M. Sickafoose, J. W. Neufeld, and P. M. Walsh, 2003a, "Alkali Volatilization and Batch Carryover in a Natural Gas/Oxygen Fired Glass Melting Furnace," American Flame Research Committee International Symposium, Livermore, CA, October 15-17, 2003.

L. G. Blevins, A. Molina, S. M. Sickafoose, P. M. Walsh, and J. W. Neufeld, 2003b, "Alkali Metal Concentrations in an Oxy-Fuel Glass Furnace Exhaust," Proceedings of the Third Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, IL, March 16-19, 2003, Paper No. PG11, The Combustion Institute, Pittsburgh, PA, 2003.

L. G. Blevins, C. R. Shaddix, S. M. Sickafoose, and P. M. Walsh, 2003c, "Laser-Induced Breakdown Spectroscopy at High Temperatures in Industrial Boilers and Furnaces," *Applied Optics 42* (2003) 6107-6118.

S. G. Buckley, P. M. Walsh, D. W. Hahn, R. J. Gallagher, M. K. Misra, J. T. Brown, S. S. C. Tong, F. Quan, K. Bhatia, K. K. Koram, V. I. Henry, and R. D. Moore, "Measurements of Sodium in an Oxygen-Natural Gas-Fired Soda-Lime-Silica Glass Melting Furnace," *Ceramic Engineering and Science Proceedings*, J. Kieffer (Ed.), Volume 21, Issue 1, 2000, pp. 183-205.

M. Cable and D. Martlew, "The Effective Binary Diffusivity of Silica in Sodium Silicate Melts: A Review and Recommendation," *Glass Technology 25* (1984) 270-276.

P. R. Desam and P. J. Smith, "NOx Validation Study in an IFRF Glass Furnace: The influence of subgrid scale models on predictions," American Flame Research Committee International Symposium, Livermore, CA, October 15-17, 2003.

J. Eisenhauer, P. Donnelly, S. McQueen, A. Monis, J. Pellegrino, and J. Julien, *Report of the Glass Technology Roadmap Workshop*, Sponsored by U.S. DOE/OIT, Corning Inc., Ford Motor Co., Pilkington Libbey-Owens-Ford, Praxair, Inc., and Techneglas, Inc., Report prepared by Energetics, Inc., Columbia, MD, September 1997.

S. Goldstein (Ed.), *Modern Developments in Fluid Dynamics*, Vol. I, Oxford, 1938.

W. Hufen, *Glastechnische Berichte 38* (1965) 33. Figures reproduced in Trier (1987) as Figures 3.1 and 3.20, on pp. 14 and 22, respectively.

K. Jamison, J. Eisenhauer, and J. Rash with M. Greenman and E. Levine, *Glass Industry Technology Roadmap*, Glass Manufacturing Industry Council, Westerville, OH, and the U.S. Department of Energy/Office of Industrial Technologies, Washington, DC, April 2002. Available on the World Wide Web at <http://www.oit.doe.gov/glass/pdfs/glass2002roadmap.pdf>.

G. Leyens, 1974a, "Contribution to the Calculation of Two Dimensional Convection Currents in Continuous Glass Tank Furnaces. Part 1. Mathematical Model," *Glastechnische Berichte 47* (1974) 251-259.

G. Leyens, 1974b, "Contribution to the Calculation of Two Dimensional Convection Currents in Continuous Glass Tank Furnaces. Part 2. Results of Calculations," *Glastechnische Berichte 47* (1974) 261-270.

R. H. Nilson, S. K. Griffiths, N. Yang, P. M. Walsh, M. D. Allendorf, B. Bugeat, O. Marin, K. E. Spear, and G. Pecoraro, "Analytical Models for High-Temperature Corrosion of Silica Refractories in Glass-Melting Furnaces," *Glass Science and Technology 76* (2003) 136-151.

J. J. Noble, L. A. Clomburg, A. F. Sarofim, and H. C. Hottel, "Mathematical and Experimental Modeling of the Circulation Patterns in Glass Melts," Transactions of the ASME, Series C, *Journal Heat Transfer 94* (1972) 149-154.

T. A. Reichardt, P. E. Schrader, and R. L. Farrow, "Comparison of Gas Temperatures Measured by Coherent Anti-Stokes Raman Spectroscopy (CARS) of O_2 and N_2," *Applied Optics 40* (2001) 741-747.

A. Sayre, N. Lallemant, J. Dugué, and R. Weber, "Effect of Radiation on Nitrogen Oxide Emissions from Nonsooty Swirling Flames of Natural Gas," Twenty-Fifth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1994, pp. 235-242.

H. Schlichting, *Boundary-Layer Theory*, 7th edition, McGraw-Hill, New York, 1979.

W. Trier, *Glass Furnaces: Design, Construction, and Operation*, translated by K. L. Loewenstein, Society of Glass Technology, Sheffield, England, 1987.

U.S. Department of Energy, Office of Industrial Technologies, *Glass: A Clear Vision for a Bright Future*, Technology Vision and Research Agenda, Washington, DC, January 1996. Available on the World Wide Web at <http://www.oit.doe.gov/glass/pdfs/glass_vision.pdf>.

W. Von Drasek, O. Charon, K. Mulderink, D. Sonnenfroh, and M. Allen, "Multi-Functional Industrial Combustion Process Monitoring with Tunable Diode Lasers," in: *Optical Methods for Industrial Processes*, S. Farquharson (Ed.), Proceedings of SPIE, Vol. 4201, 2001, pp. 133-141.

P. M. Walsh and R. D. Moore, Na Vapor and Gas Temperature Measured in Glass Container Furnaces, *The Glass Researcher*, Vol. 10, No. 1, 2000, pp. 6-8.

S. Wright and H. Rawson, "Calculation of Natural Convection in a Rectangular Cell Containing Glass with Specified Temperatures on the Boundaries," *Glass Technology 14* (1973) 42-49.

APPENDIX A

Results of the Survey Distributed by the Glass Manufacturing Industry Council

INTRODUCTION TO THE SURVEY

The Glass Technology Roadmap developed by the US glass industry, in collaboration with the DOE Office of Industrial Technologies' Glass Program, identified the need for an advanced facility for glass furnace combustion and melting research, testing, and model validation. Visteon Glass Systems was chosen to lead in establishing such a facility, and the Combustion Research Facility at Sandia National Laboratories was selected as the site of the experimental melting tank. The melting laboratory will be a User Facility open to all U.S. glass manufacturers for joint work with Sandia scientists and engineers on the solution of practical problems.

The project, presently in the design stage, will be completed shortly. Installation of a melting tank satisfying the requirements agreed upon by interested members of the glass industry will begin soon, with heat-up of the fully instrumented facility expected in August 2001.

In its role as promoter of glass industry interests and optimum utilization of DOE resources to that end, GMIC offered to help determine the industry's opinion on the direction of the work by distributing a survey to leaders in glass manufacturing. The results, summarized on the following pages, have been very useful in guiding the design of the melting furnace. Additional advice on the configuration of the tank and the choice of problems to be investigated is always welcome. Please contact Peter Walsh,* the Principal Investigator at Sandia, by telephone (925-294-3726), fax (925-294-2595), or e-mail (pwalsh@sandia.gov) if you would like to discuss any aspect of the project. Thanks to all those who participated in the survey and the many others who have offered suggestions on the design of the tank and selection of research topics. We hope you will join in the work to be done in the glass User Facility.

_____

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SURVEY RESULTS: TYPE OF MELTING TANK

In this section respondents were asked to specify the type of melting tank, type of glass, pull rate, and furnace dimensions that would produce melting conditions and results of interest to their companies.

Firing:	air/natural gas	38%
	oxygen/natural gas	50%
	electric	boost 31%, electrodes from top 6%, all electric 6%
	other	-
Glass type:	soda-lime	47%
	E-glass	13%
	borosilicate	27%
	TV panel and funnel	7%
	experimental compositions	7%
Feed:	continuous	100%
	intermittent	(in addition to continuous) 9%

Pull (please enter recommended rate in lb/hour or ton/day):

2 - 5   ton/day
4.5
5
5 - 20
6 - 12
12
30
150
200

Tank length and breadth (specify tank inside dimensions):

3 x 6 ft = 18 ft^2
4-5 x 15-20 ft = 60-100 ft^2
100-150 ft^2
10(min) x 20 ft = 200 ft^2
10 x 25 ft = 250 ft^2
17 x 46 ft = 780 ft^2
width:length 1:3

Glass depth (minimum realistic depth): 12, 20-24, 24-36, 24-36, 30, 36, 42, 48 inches

Comments and Suggestions on the Tank:

Supply single shop

High pull to ft^2 ratio

Cover range from all gas to all electric.

Automatic level control (chargers on/off)

Design steel so crown, breastwalls, and glass contact refractories can be changed
   independently.

If the furnace is narrower than 10 ft, the opposing flames will fight each other.

Need a forehearth channel 24-in. wide x 10-in. deep x 10-ft long for testing new sensors.

TV monitoring of melter interior

Melter area and volume should be scaled for the chosen pull, so that glass convective
   flows and residence time accurately reflect the characteristics of production
   furnaces, i.e. scaled as one would to design a physical model.

Include provision for batch wetting.

Utilize the latest low-NO$_X$ gas/oxygen burners, preferably with staged combustion
   for increased luminosity.

Heat-up and cool-down of the furnace between trials is critical.

SURVEY RESULTS: RESEARCH PRIORITIES

In this section respondents were asked to indicate the relative importance to their companies of the possible research topics.

	High	Medium	Low	Zero
	------------------------ (%) ------------------------			
Develop new gas-phase sensors	15	46	31	8
Develop new glass property sensors	46	31	15	8
Evaluate control strategies	38	31	31	-
Mechanism of batch melting	38	23	31	8
Evaluation of batch formulations	15	31	38	15
Volatilization and particulate formation	54	31	15	-
Glass circulation	38	31	23	8
Bubble formation, growth, and fining	62	15	15	8
Coupling of combustion and redox state	46	46	-	8
Data for Model validation	31	54	12	4
Performance of materials	19	58	15	8
Burner testing	23	31	46	-
NO_X emissions	31	38	31	-

Research on other processes, in addition to melting, could be associated with the user research facility. The level of interest in other aspects of glass manufacturing is as follows.

	High	Medium	Low	Zero
	------------------------ (%) ------------------------			
Forming	8	38	31	23
Coating	42	-	42	17
Annealing	15	-	54	31
Others _____	-	-	-	-

	Precompetitve	Proprietary	Postcompetitve
	---------------------------- (%) ----------------------------		
Should the research in the areas given high priority be (please circle one or more)	71	21	7

Comments and Suggestions on Research Priorities:

> All of the topics listed need further R&D effort; some are leading edge technology, some will assist in model validation.
>
> Model validation is important for processes dependent on reaction kinetics, such as fining.
>
> Materials performance probably can be evaluated at the screening level only. True performance can only be determined in a production furnace. It seems unlikely that a pilot-scale tank could perform long-term (6 mo. – 1 year) testing of refractories or sensors.
>
> Assess performance of "smart" sensors.
>
> Priorities should include all facets of environmental impact: NOx, volatilization, and particulate matter.
>
> Priorities should pertain to glass quality: bubble formation and fining, redox state of the glass, and mechanism of batch melting.
>
> Interested in modeling the melting mechanism as well as investigating redox phenomena.

SURVEY RESULTS: INTEREST IN PARTICIPATION

Involvement in, and support of, the work at the User Facility can take many forms. Preferences for various forms of collaboration were as shown below.

	Likely	Possible	No interest
	----------------------- (%) ---------------------------		
Visits by your company's staff to Sandia to participate in research projects	21	79	-
Direct financial support from your company for proprietary research and sole ownership of the results	9	55	36
Participation in an industry consortium supporting precompetitive research	20	80	-
Participation as member of advisory board, meeting once or twice a year	25	75	-
Donation or loan of equipment	8	58	33

If visits to Sandia are likely or possible,
for how long? (Could be days to years.) . . . .   1-5 days, days, days, few days,
several days, day to weeks,
days to weeks, 1-3 weeks, up to 2 weeks,
weeks, days to years

Comments and Suggestions on Participation:

      Most likely in-kind support of precompetitive research.

APPENDIX B

Summary of the Discussion of the Objectives and Requirements for the
Glass Furnace Combustion and Melting User Research Facility at the
Meeting held in Argonne, Illinois, on September 15, 1999

The meeting was hosted by Vincent Henry of Visteon Automotive Systems, the first industry leader of the project, and by Robert Gallagher and Peter Walsh of Sandia National Laboratories, Livermore, CA, where the User Facility will be located. The attendees, in addition to the three just mentioned, were: Mike Carroll, Knauf Fiber Glass GmbH; Ed Boulos and Kwaku Koram, Visteon Automotive Systems; Michael Greenman, Glass Manufacturing Industry Council; Marvin Gridley, Ball-Foster Glass Container Co.; Christopher Jian, Owens Corning; Moe Khaleel and Chet Shepard, Pacific Northwest National Laboratory; Elliott Levine, U.S. DOE Office of Industrial Technologies; Jim McGaughey, Libbey Inc.; and Philip Ross, Glass Industry Consulting Inc. Ronald Schroeder of Praxair, who was not able to attend, offered several suggestions during the Glass Industry Project Review on September 13-14.

Vincent Henry opened the meeting with a summary of the present status of the project and the purpose of the meeting, stressing that, although Visteon is the present project leader, all members of the glass industry are invited and welcome to participate. Bob Gallagher followed with an introduction to the Sandia Combustion Research Facility and a brief history of Sandia's work on both glass and combustion. Peter Walsh expanded on some of the points made in his presentation at the Glass Industry Project Review the day before, summarizing the objectives of the User Facility, the intention to make nonintrusive, laser-based, optical measurements in the melting furnace, and the rationale behind the choice of tank dimensions and pull rate. Peter concluded with a request for advice on a number of questions, including the arrangement of the tank superstructure for air and oxygen firing, the placement of bubblers, electrodes, and weir, the mode of glass withdrawal, high temperature capability, refractories, and the sealing of optical ports against air inleakage. The following suggestions were offered by the participants:

The tank as shown in the review meeting needs to be raised to allow access for work on electrodes and bubblers.
A pit or moat is needed to contain glass in the event that the tank develops a leak.
Several suggestions and offers were made, of companies and people having experience with small melting tanks.
The superstructure should be built to be durable and long-lasting. Materials testing can be done by installing test bricks or coupons. For maximum durability, monolithic crown and bottom should be considered.

Need positive control of the furnace pressure.

The facility needs to be flexible in order to be able to satisfy specific industrial requests.

Need a drain at the lowest point in the furnace.

Need electric heating (~ 50 kW) of the throat to prevent it from freezing in the absence of pull, for example on weekends and holidays.

Steel gets in the way of probe and optical access to the furnace.

Need probe and optical access through both crown and breastwalls.

Give more thought to batch preparation and dust control: scale, mixer, hopper, batch can, dust collector, filter.

Periodic review of the design and oversight by GMIC are needed.

It was pointed out that the capabilities that one would like to incorporate in the tank are practically unlimited, and it was suggested that the first experiments to be performed should guide the initial configuration of the tank. It was also noted that research priorities are likely to change by the time the facility comes on line, so that the research agenda and the tank itself need to be flexible and continually updated. With these points in mind, reaching a consensus on present research needs appeared to be the most important step remaining to be taken before beginning the detailed design work on the experimental melting furnace. The group was then invited to generate a list of important aspects of glass melting best-suited for quantitative study in a pilot-scale facility, and the attendees produced the following list:

Simulation of batch pile melting

Distributions of temperature, gaseous species, soot, velocity, and radiation in the fuel and air or fuel and oxygen jets from the burners

Glass circulation and heat transfer

Furnace design

Provision for testing different burner types and locations

Effect of water vapor on melt properties

Foam formation and dissipation and effects on furnace operations

Fining

Bubbler location and gases (oxygen, air)

Means to reduce residence time (increase pull rate) and maintain quality

Verify combustion models for furnace modeling and design

Emissions of nitrogen oxides, carbon monoxide, unburned hydrocarbons, and particulate matter versus furnace conditions and glass composition – exhaust monitoring and treatment

Evaluate furnace controls - open control environment - rule-based expert systems

Sensor development, testing, and evaluation

Refractory testing

Alternate raw material evaluations

Minimize time for color transitions

Effect of variation of cullet ratio and cullet properties

Stirrer evaluation

Online data server for remote furnace monitoring (model after Sandia/DOE Diesel collaboratory?)

Vacuum fining

Heat recovery (combined heat and power)

Continuous glass property measurement (redox, seed count, etc.)

Include capability to exercise and validate models

Test products (models, sensors, etc.) of existing OIT projects

Provision for end and side feeding (but end feeding is the most important)

Cameras to record batch distribution pattern (front, back, and crown) with on-line image analysis

Temperature measurements as a function of depth in the furnace and forehearth

Probe to characterize solids moving from batch blanket into melt

Method for collecting glass samples from inside the furnace

Variable batch configuration

Batch blanket measurements: temperature and composition profiles in gas above blanket, emissivity of top surface, temperature profile through blanket, temperature and velocity profiles in glass underneath blanket, grab samples

Foam bubble size distribution

Follow glass movement using tracers

It was agreed that, as the facility concept evolves, comments, suggestions, and advice on the research problems and facility requirements will be sought from industry representatives at frequent intervals, both directly and through GMIC.

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