Physical Modeling of Joule Heated Ceramic Glass Melters for High Level Waste Immobilization

**M. S. Quigley
D. K. Kreid**

March 1979

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SUMMARY

This study developed physical modeling techniques and apparatus suitable for experimental analysis of joule heated ceramic glass melters designed for immobilizing high level waste. The physical modeling experiments can give qualitative insight into the design and operation of prototype furnaces and, if properly verified with prototype data, the physical models could be used for quantitative analysis of specific furnaces. In addition, the results of the model experiments provide a data base for evaluating the performance of the VECTRA analytical models developed in parallel with this study.

The general principles of modeling formed a basis for the specialized set of equations derived for the study of joule heated ceramic glass melters. Properties of a reference glass BNW 72-68 were used with the modeling equations to select an appropriate geometric scale and modeling fluids. For this study, a scale of approximately 1/3 in conjunction with modeling fluids composed of 7.5% LiCl in glycerine gave satisfactory results. The scale factors relating model performance to prototype furnace operation were calculated from the modeling equations using this geometric scale and these modeling fluid properties.

The 1/3-scale physical model was a clear plexiglass, double-walled rectangular box with a solid plexiglass floor. The annulus surrounding the model melter cavity was divided into four separate thermostatically controlled water jackets to establish the appropriate boundary conditions. A removable flat top water jacket simulated the prototype liquid feed cold cap. Different types of water-cooled electrodes were installed for studying different prototype electrode configurations. Electrical power to the electrodes was supplied by a pair of phase angle-fired SCR power controllers. All water jacket operating conditions, electrode power data, model surface temperatures, and model fluid internal temperatures were recorded automatically by a data logging system and stored on magnetic tape for computer analysis.

Flow fields in the model fluid were measured qualitatively using streak photography and quantitatively with strobe photography. Small, neutrally buoyant light-scattering particles added to the model fluid were illuminated through the floor of the model by a thin vertical sheet of laser light. The light sheet (data plane) could be positioned to record the fluid motion for any plane parallel to the front wall. Fluid temperature profiles corresponding to those planes were measured using six type T thermocouples inserted through the top water jacket. The thermocouple outputs were monitored automatically by the data logger system.

Seven model data runs representing four different examples of prototype operating conditions were completed. Four of those runs simulated a liquid feed cold cap without feeding. Of these, three used triple pairs of horizontal bar electrodes to investigate the effects of firing pattern on the physical model performance. The fourth data run in the set examined the influence of electrode configuration with plate electrodes and the same boundary conditions as the bar electrode cases. A convex top water jacket modeled a calcine feed cold cap in a fifth experiment to determine the effects of cold cap intrusion into the melting zone. The remaining two runs used a flat top water jacket to simulate an idling calcine-fed melter and liquid feeding with throughput.

The flow fields for all seven modeling cases were continuously changing, usually well-mixed and often quite turbulent. Each exhibited numerous small turbulent eddies near the top surface with two or more larger counter-rotating cells occupying the bulk of the model fluid. These cells apparently never reached steady-state during the tests and randomly changed position and size. The general flow pattern in all experiments was downward at the face of the electrode, across the floor toward the center of the model and upward near the center. This circulation was clearly evident for the plate electrode model runs and the uniformly powered bar electrode case.

The lowest velocities and poorest mixing were observed in the bottom 25% of the model, indicating a potential zone for particle settling and accumulation. However, the fluid flow along the bottom tended to sweep

particles away from the base of the electrodes toward the center in front of the overflow drain. Nonuniform firing patterns created more turbulent flows with substantial three-dimensional fluid motion.

Mixing near the bottom was poorest with plate electrodes and improved substantially with bar electrodes powered more strongly through the bottom set of electrodes. These results suggest an electrode design and operational strategy that might partially alleviate the problems associated with particle settling in the prototype furnace. This is an example of the type of work that will be stressed in future studies.

Principal effect of the simulated calcine cold cap was a reduction in the number of large-scale eddies and increased turbulence. However, model liquid feeding did not significantly alter the general flow pattern in the two-dimensional viewing plane but appeared to increase the flow normal to that plane. The average velocity for all cases was of the order 0.1 to 1.0 mm/sec.

Model fluid temperatures were nearly uniform for a given horizontal plane through the model melter for all cases investigated. For the bar electrode configuration the vertical temperature profiles were also quite uniform. Such uniform temperature profiles were a product of the well-mixed flows observed in the streak photographs. On the other hand, the plate electrode temperature profiles exhibited a more gradual gradient corresponding to less turbulent flow conditions than the bar electrode cases. The strongest temperature gradient for each data run was in the upper 20% of the model fluid. The effect of the simulated calcine cold cap was depression of the local fluid temperature below the average in the vicinity of the intrusion zone. Outside the cold cap intrusion the fluid temperature profile looked similar to a typical flat top case. The temperature profiles for the liquid feed run were also very similar to the corresponding steady-state case. If these results were prototypic, they would indicate that higher feed rates could be employed without adversely affecting the glass temperature.

The limited results to date are sufficient to make a few observations relevant to the design and operation of the prototype furnaces in general. However, the results of the physical modeling study have unproven accuracy

for quantitative analysis of specific prototype melters due to the current lack of adequate glass property and operating data.

The subject of particle settling was not addressed directly by this study. However, the evidence indicates a tendency for particles to be swept away from the base of the electrodes by the downwash along the electrode face. The fluid upwelling at the model center presents a low velocity region near the floor where potentially significant particle settling and accumulation could occur. In all cases the slowest flow was along the floor of the model, providing a region for general particle deposition. However, it was not demonstrated whether any of the flows in the model were sufficient to keep heavy particles entrained in the fluid because most of the light-scattering particles used for this study were neutrally buoyant.

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PHYSICAL MODELING OF JOULE HEATED CERAMIC GLASS MELTERS FOR HIGH LEVEL WASTE IMMOBILIZATION

1.0 INTRODUCTION

The goal of the work described here is to develop physical modeling techniques suitable for experimental analysis of joule heated ceramic glass melters. The modeling expertise developed will be used to design and analyze furnaces for the Continuous Melting Task of the High Level Waste Immobilization Program at the Pacific Northwest Laboratory (PNL). The purpose of this report is to summarize the relevant modeling theory, the design of the model and instrumentation, the experimental plan and the progress toward this goal.

1.1 THE ISOLATION OF HIGH LEVEL WASTE

Military and civilian applications of nuclear technology in the U.S. and throughout the world have generated an inventory of high level radioactive wastes. This material is being accumulated in temporary storage facilities where it has been effectively isolated from the environment. The volume of wastes is expected to expand due to continued military applications and the expansion of nuclear power plant capacity. However, most of the temporary storage facilities have limited capacity and it is therefore desirable to develop a permanent, environmentally acceptable storage/disposal technology as soon as possible.

The vitrification process has good potential as a means for safe immobilization of waste. In the glass fixation process, nuclear wastes would be added to frit and melted in an electric furnace. The molten glass mixture would then be sealed in metal canisters suitable for permanent storage or disposal. This waste fixation process is attractive because the product is relatively insoluble, resistant to chemical attack, physically durable and well suited for dissipating decay heat and resisting radiation damage.

There are two fundamentally different approaches to the glass fixation process: continuous melting and in-can melting. The joule heated continuous melter process would accept the frit/waste mix in a continuous or semi-continuous mode. After melting has taken place, the glass is subsequently poured into canisters and sealed. Two alternative feed techniques are being studied. In the dry mix technique, liquid waste is dried (calcined), mixed with granular frit and fed to the melter. In the direct liquid fed process, the glass formers and liquid waste are fed separately and the water is driven off in the furnace.

The in-can melter process uses canisters enclosed in a radiant heating furnace and slowly filled as melting occurs. The present modeling task is directed at the continuous melter, but there is no inherent reason why a similar physical modeling approach could not be used for the in-can melter process.

1.2 MODELING PROGRAMS

Parallel experimental programs at PNL are underway to develop these waste fixation processes. In the developmental process, it is often necessary to investigate numerous design alternatives and operational processes that are difficult to investigate in the prototype system. The extreme environment in the furnace seriously hinders measurements of properties and observation of physical processes in the melt. Moreover, the prototype furnace is relatively large and highly complex. Changes in the prototype are costly and time consuming so that experimentation with the prototype configuration is often impractical. For these and other reasons, the glass melter development program can be considerably enhanced by using physical modeling techniques.

The goal of the present modeling program is therefore to develop suitable fluids, model facilities and measurement techniques to suit the specific needs of the High Level Waste Immobilization Program. Scale models will be used to investigate fundamental physical phenomena in the glass melting process. These models will provide a means of investigating the effects of changing the

furnace geometry and operating conditions, changes in glass properties and other factors which may be of interest. In addition, the physical model will provide verification of the numerical model VECTRA, which has been developed as an additional tool for studying the glass furnace. This latter application is particularly important due to the difficulty in gathering a sufficiently large quantity of meaningful data from the prototype for direct comparison with the models.

2.0 PHYSICAL MODELING DEVELOPMENT

The development of a general model theory is briefly reviewed and then a more rigorous treatment of physical modeling in molten glass is offered. The fundamental modeling criteria relevant to an electric glass melting furnace are summarized, and previous experience with physical models in the glass industry is reviewed and cited in support of the analysis. In addition, the important thermophysical properties and processes relevant to molten glass are discussed and sample data typical of the waste glasses are given. Similar data are provided for model fluids that have been used for modeling glass and for a specific model fluid (glycerine/lithium chloride).

2.1 GENERAL PRINCIPLES OF MODELING

The important physical processes that occur in complex systems, including fluid mechanics, heat transfer and electromagnetism, can usually be described adequately by a set of differential equations. When coupled with a set of boundary conditions and subjected to various simplifying assumptions, these equations can frequently be solved to yield solutions that predict the behavior of the system.

A common technique for solving the set of model equations is to first convert them to dimensionless form incorporating reference values of length, velocity, temperature, etc., that characterize the system. When this is done, a set of dimensionless parameters appears as coefficients of various terms in the equations. These dimensionless parameters (i.e., Re, Pr, Gr, etc.) are the primary independent variables that govern the physical phenomena. They are sometimes called "similarity" variables because physical systems with similar geometries but different sizes, fluids, velocities, temperatures, etc., will yield identical dimensionless solutions.

For most engineering systems, closed form analytical solutions cannot be found because the geometry and equations are too complex. Even for numerical solutions, the degree of complexity that can be handled is limited by the

computer memory available and by the cost of computational time. Therefore, in some cases, purely mathematical models may be impractical (or even impossible) and other approaches such as physical modeling may be required.

2.2 PHYSICAL MODELING OF MOLTEN GLASS

In physical modeling, the behavior of a prototype system is deduced from observations or measurements obtained with a model. Several aspects of the glass melter prototype design and operation, including mapping of the velocity, temperature and potential fields, can be studied with models. This allows study of various electrode designs, relative power level, geometry changes, wall temperature and various other characteristics that affect the operation of the prototype. The rate of throughput is governed by the rate of melting, rate of mixing and other factors that may be related directly to the velocity, temperature and potential distribution. The problem of particulate settling and accumulation can be studied directly or indirectly by analysis of the velocity fields. Modeling these accurately requires that there be a known correspondence between the geometry and processes in the model and those in the prototype. This is accomplished by establishing geometric similarity between model and prototype and by assuring that the appropriate set of dimensionless similarity variables and boundary conditions are identical for model and prototype.

One very useful technique for defining the appropriate set of similarity variables is to create the set of dimensionless equations and boundary conditions, exactly as though a complete mathematical solution were sought. Where practical, this is probably the most valuable approach because it gives the most insight into the nature of the problem (see Appendix B).

For some systems, though, the physical phenomena may be so complex that specifying the appropriate model equations may not be possible. In such cases, a more generalized approach of dimensional analysis may be employed. This technique, based on the Buckingham Pi theorem,⁽¹⁾ involves listing all the variables known to affect a given phenomenon. The variables are then

subjected to a systematic procedure that generates the set of dimensionless similarity variables governing the behavior of the system in question. These variables (or their products) are the same set that would arise from the appropriate set of nondimensionalized differential equations.

The fundamental theory for modeling the circulation of molten glass was first treated in 1937 in a classic paper by E. Buckingham,⁽¹⁾ expounding his well-known Pi theorem. However, Buckingham reached the pessimistic conclusion that insufficient similarity criteria could be adequately satisfied to accurately model a glass furnace. Unfortunately, he did not have the means to test his theory experimentally.

Subsequent model studies of molten glass processes using small-scale, low temperature models have been quite successful in matching the most important modeling criteria.⁽²⁻⁴⁾ Both gas-fired⁽²⁾ and electric^(3,4) furnaces have been successfully modeled with excellent results. In fact, modeling has proven so consistently reliable that large-scale glass production and handling equipment are routinely designed and tested primarily with physical modeling techniques.^(2,5) There is a considerable volume of literature available on modeling of molten glass, concentrated primarily in foreign journals. Very recently, Stanek's excellent book,⁽⁵⁾ devoted entirely to electric glass melting with sections on modeling, has become available. We have drawn heavily upon the analysis and results in this book for the discussions that follow.

2.3 THERMAL AND HYDRODYNAMIC MODELING CRITERIA

The governing similarity parameters for the glass-melter system were deduced by reducing the relevant differential equations to dimensionless form. The details of the analysis are given in Appendix B. The resulting equations, for steady flow of an incompressible fluid with constant properties, may be given as

Continuity

$$\vec{\nabla} \cdot \vec{U} = 0 \quad (1)$$

Momentum

$$\text{Re } \vec{U} \cdot \vec{\nabla} \vec{U} = -\text{Gr } \text{Re}^{-1} \vec{\nabla} \frac{\vec{g}}{g} + \vec{\nabla}^2 \vec{U} \quad (2)$$

Energy

$$\text{Pe } \vec{U} \cdot \vec{\nabla} \theta = \vec{\nabla}^2 \theta + \text{Ec } \text{Pr} \ \vec{\nabla} \cdot \vec{\nabla} \phi_v + \phi_s \quad (3)$$

Boundary Conditions

$$\theta_i = \delta_i \phi_s \text{Nu}_i^{-1} \quad (4)$$

In the above, $\vec{U}$, θ , and $\vec{\nabla}$ are the dimensionless velocity, temperature and gradient, respectively. The dimensionless groups are defined in Table 2-1 and in the nomenclature. ϕ_v is the dimensionless dissipation function and ϕ_s is the dimensionless source term that accounts for self-heating due to chemical reaction, nuclear decay and electrical heating. The boundary condition gives the dimensionless wall temperature, assuming that a fraction δ_i of the total internal heat generation is transferred through the "ith" wall.

The continuity equation is seen to contribute no dimensionless groups because all properties may be cancelled. The momentum equation is expressed in terms of Re and Gr. The energy equation contributes $\text{Pe} = \text{RePr}$, the product EcPr and the dimensionless source term or power number ϕ_s . At this point the list of independent similarity variables numbers six: Re, Gr, Pr, Ec, Nu and ϕ_s . In addition, variables formed by products of the above, such as $\text{Ra} = \text{GrPr}$ and $\text{Pe} = \text{RePr}$, may be included.

For the glass melter, the primary list can be reduced to just Ra, Pe, Nu, and ϕ_s by eliminating Ec and Pr as modeled parameters. The term involving

TABLE 2-1. Dimensionless Similarity Variables

<u>Parameter Name</u>	<u>Symbol</u>	<u>Interpretation</u>	<u>Equivalent Forms</u>
Prandtl No.	Pr	= $\frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}$	= $\frac{\mu C}{\lambda} = \frac{\nu}{\alpha}$
Reynolds No.	Re	= $\frac{\text{inertial forces}}{\text{viscous forces}}$	= $\frac{\rho V L}{\mu} = \frac{V L}{\nu}$
Peclet No.	Pe	= $\frac{\text{convection energy}}{\text{conduction energy}}$	= $\frac{\rho C V L}{\lambda} = \frac{V L}{\alpha} = \text{RePr}$
Grashof No.	Gr	= $\frac{\text{buoyancy forces}}{\text{viscous forces}}$	= $\frac{g \beta L^3 \Delta T}{\nu^2}$
Rayleigh No.	Ra	= $\frac{\text{buoyant transport of energy}}{\text{conduction of energy}}$	= $\frac{g \beta L^3 \Delta T}{\alpha \nu} = \text{GrPr}$
Galileo No.	Ga	= $\frac{\text{buoyancy forces}}{\text{viscous forces}}$	= $\frac{g L^3}{\nu^2} = \frac{\text{Gr}}{\beta \Delta T}$
Nusselt No.	Nu	= $\frac{\text{convection heat flux}}{\text{conduction heat flux}}$	= $\frac{h L}{\lambda}$
Eckert No.	E _c	= $\frac{\text{viscous energy dissipation}}{\text{convection energy flux}}$	= $\frac{\nu^2}{C \Delta T}$
Power No. ^(a)	$\frac{\gamma}{\phi_s}$	= $\frac{\text{source heat flux}}{\text{conduction heat flux}}$	= $\frac{\phi_s L^2}{\lambda \Delta T}$

(a) No commonly accepted name has been assigned to this parameter.

Ec number is negligible for this system because heat input by viscous dissipation would normally be very small. Similarly, the inertial terms on the left of Equation (2) may be neglected for the process in the glass melter. The product in the buoyancy term may be given by the alternative form, $GrRe^{-1} = RaPe^{-1}$.

It is very important to emphasize that, by absorbing the effects of Pr into Pe and Ra, it is no longer necessary to account for Pr or Re as independent variables. Therefore, it is not necessary to require equality of the model and prototype Prandtl and Reynolds numbers as long as Pe and Ra are matched. This greatly eases the requirements for selecting a model fluid because both Ra and Pe contain length scales that can be adjusted to account for differences in fluid properties. In theory, it would still be advantageous to provide for independent equality of all six primary similarity variables including Pr. However, this would rarely, if ever, be possible.

Note that Ra can be subdivided into other products involving other dimensionless similarity variables. In the current problem it is convenient to regroup Ra as

$$Ra = \frac{g\beta\Delta TL^3}{\nu\alpha} = (\beta\Delta T) \left(\frac{gL^3}{\nu^2} \right) \left(\frac{\nu}{\alpha} \right) = \beta\Delta T Ga Pr. \quad (5)$$

The product $\beta\Delta T$ is dimensionless; however, it has never been assigned a specific name. If we require this product to be equal in the model and prototype, the requirement for equality of Ra reduces to the equality of the product GaPr where Ga is the Galileo number.

In summary, the requirements for similarity between model and prototype may be given as

$$\beta_m \Delta T_m = \beta_p \Delta T_p \quad (6)$$

$$\frac{gL_m^3}{\nu_m \alpha_m} = \frac{gL_p^3}{\nu_p \alpha_p} \quad (7)$$

$$\frac{V_m L_m}{\alpha_m} = \frac{V_p L_p}{\alpha_p} \quad (8)$$

$$\frac{\phi_{sm} L_m^2}{\lambda_m \Delta T} = \frac{\phi_{sp} L_p^2}{\lambda_p \Delta T} \quad (9)$$

In addition, the model wall temperatures must be maintained so that each surface in the model transfers the same proportion of the total heat load δ_i as the surfaces in the prototype. Then, when all of these conditions are met we will also have equality of Nusselt number,

$$\frac{h_m L_m}{\lambda_m} = \frac{h_p L_p}{\lambda_p} \quad (10)$$

Equation (8) has two interpretations. The throughput of fluid in the model must be maintained so that Equation (8) is satisfied. This requirement must be fulfilled for similarity. In addition, however, Equation (8) gives the relationship between the free convection flow velocities that will result when all the other modeling criteria are fulfilled. The use of Equation (8) in both contexts is discussed further in Section 4.

Finally, it is reemphasized that the above conditions for similarity can also be derived by the generalized Buckingham Pi approach. In Buckingham's original work,⁽¹⁾ these similarity conditions were obtained, except for the

condition on ϕ_s , since heat sources were not considered in that analysis. Buckingham points out that modeling can be done by degrees, depending on which dimensionless parameters are chosen to be matched. The choice of parameters to match must be based on an understanding of the physics of the problem, an insight not obtained with the generalized approach. In contrast, the reduction of the governing differential equations, as done here, affords an orderly means for assessing which parameters should be modeled and which can be safely neglected.

2.4 THERMAL AND ELECTROMAGNETIC MODELING CONSTRAINTS

The assumption of geometric similarity plus the constraints of Equations (6) through (10) describe conditions that are necessary for thermal and hydrodynamic similarity between model and prototype. However, other constraints related to the thermal and electromagnetic fields and boundary conditions must also be satisfied.

In the electric glass melting furnace, heat is supplied by applying an alternating current (ac) potential. The resulting joule heating is non-uniformly distributed throughout the molten glass volume due to spatially varying field strength and resistivity. Heat is lost by conduction due to cooling in the walls and electrodes. In addition, heat is lost out of the top of the melt due to the sensible and latent heat absorbed by the melting batch (and due to vaporization of water in the liquid-fed melter). If the glass is optically transparent, there is radiation heat transfer within the glass, and between the glass and the inner surfaces of the furnace. The hydrodynamic, thermal (heat transfer) and electromagnetic effects are thus intimately coupled in this system. Therefore, accurate modeling of this system requires simultaneous correspondence of all three phenomena.

Accurate modeling of the heat inputs and the resulting temperature fields requires similarity between the model and the prototype in terms of the spatial distribution of the electric fields and the fluid resistivity. Electric field similarity is accomplished by similar geometry and placement of the

electrodes and by providing bounding surfaces with similar dielectric properties (i.e., electrically nonconducting). To assure similar spatial distribution of resistivity, there must be correspondence in the variation of resistivity with temperature.

The electrical power input to the model must be sufficient to assure that the power number for the model equals that of the prototype, as in Equation (9). However, note that ϕ_{sp} could contain source terms for chemical reaction and nuclear decay as well as electrical heating. Therefore, such processes must be carefully accounted for in designing and operating the model.

Complete similarity would require that all scale factors be independent of temperature. By careful selection of the model fluid, some of these conditions can sometimes be satisfied for a limited range of temperatures. However, exact scaling is usually possible for only a single temperature (if at all).

The problem of radiation heat transfer is accommodated by assuming that the glass is opaque, and by lumping radiation and conduction effects into an effective conductivity. This is known as the Rosseland diffusivity model.⁽⁶⁾ This is helpful in the analysis; however, in practice, the effective conductivity of molten glass is extremely difficult to obtain.

The melting of the batch mixture on the top surface of the molten glass is simulated approximately in the model with a thermostatically controlled cooling jacket. This provides a heat sink that simulates the combined heat losses due to sensible and latent heat absorption by the batch. The top surface boundary condition is especially hard to match when direct liquid feeding is used, due to the chaotic nature of the boiling process. However, the velocity and temperature fields in the melt below the cold cap should not be greatly affected by the chaos above. Hopefully then, the processes below the surface in the furnace may be modeled reasonably well.

The heat transfer boundary conditions at the walls of the model should be simulated so that the relative heat loss through all surfaces corresponds to that of the prototype. This requires prior knowledge of the prototype

operating conditions plus a means of maintaining similar heat loadings in the model. In principle this can be accomplished by proper materials selection and careful design and operations of the water jackets in the walls. However, this is generally very difficult to accomplish in practice due to the requirement the floor and walls of the model be transparent. Accurate measurement of small values of heat transfer and a means to isolate or eliminate heat transfer between the model and the environment are also required.

Boundary conditions in the present model were simulated with individually controlled water jackets in the walls, electrodes, and top. Thus, an isothermal boundary was established. The relatively thick bottom was exposed to the environment and heat transfer at the surface was through natural convection. The limited prototype measurements available indicate this is a reasonable approximation for the geometries of interest. However, determination of the appropriate boundary conditions was severely handicapped by the almost total lack of prototype wall temperature data. The small quantity of existing data was measured by touching the inside surface of the melter with a long temperature-sensing probe. The heat balance on the prototype system had also been difficult to measure because the heat energy released and absorbed by chemical reaction in the glass is mainly an unknown quantity. Another unknown was the amount of heat transferred from the model melter cavity to the surrounding water jackets. The design and materials used in the model prevented thermally insulating each surface. Consequently, the cooling jackets exchanged heat with each other and the environment at unknown rates. Therefore, the distribution of heat losses in the model depended on the approximate method of setting isothermal boundary conditions.

Many of the questions concerning modeling boundary conditions could be answered by carefully measuring the prototype wall temperatures. Combined with accurate measurements of the heat losses through the walls it should be possible to determine the correct distribution of heat transfer from the prototype melter cavity. As for the physical model, it may be possible to

design water jackets that do not communicate heat or use other materials which combine adequate thermal insulation and optical visibility. Both improvements would lead to better simulation of the prototype boundary conditions.

2.5 PROPERTIES OF MOLTEN GLASS

The thermophysical and electrical properties of molten glass are strongly dependent upon the glass composition and the temperature. Prediction of glass properties based on composition has not generally been possible so that experimental data are normally required for each type of glass. Such measurements are difficult to obtain. As a consequence, property data for molten glass are not readily available and the precision of the available data is limited.

A number of glasses have been studied for use in the nuclear waste fixation process. A particular glass, designated BNW type 72-68,⁽¹⁾ has been investigated as a potential candidate for the High Level Waste Fixation Program. Data for this glass will be used here because they are the only adequate property data available. If other glasses are to be modeled, the model scale factors and possibly the model fluid would have to be changed. The procedures and ultimate results would not, however, be significantly altered from those described here.

The required property data for type 72-68 glass are given in Figures 2-1, 2-2 and 2-3, and in Table 2-2. The density ρ_p , thermal diffusivity α_p , and thermal conductivity λ_p are given in Figure 2-1. The data for λ_p are subject to considerable uncertainty due to the extreme difficulty in obtaining the required measurements. The data given are for the simple conductivity λ_p , although the effective conductivity λ_p^o would be more useful, if it were available.

The specific heat of this glass may be given by $C_p \simeq 0.24 \text{ cal/gm}^0\text{C}$, which is essentially constant over the temperature range of interest. The dynamic and kinematic viscosities μ_p and ν_p are given in Figure 2-2. The Prandtl numbers have also been computed and plotted with the viscosities on Figure 2-2. The electrical resistivity is shown in Figure 2-3.

FIGURE 2-1. BNW 72-68 Thermal Diffusivity (α_p), Thermal Conductivity (λ_p), and Density (ρ_p)

2.6 MODEL FLUID PROPERTIES

The selection of an appropriate model fluid is subject to a number of constraints. The most important requirements are related to the need for similarity in the temperature dependence of the various properties between the model and prototype fluids. In addition, the fluid must be nonvolatile and chemically stable in the temperature range of interest. It must be optically transparent because flow visualization is to be employed. For electrically heated melters, the fluid must be electrically conductive and the temperature dependence of the resistivity must be similar to that of glass.

FIGURE 2-2. BNW 72-68 Prandtl Number (Pr), Dynamic Viscosity (μ_p), and Kinematic Viscosity (ν_p)

FIGURE 2-3. BNW 72-68 Electrical Resistivity

Because of the many constraints, few model fluids have been identified which are acceptable for modeling molten glass in electrically heated furnaces. According to Stanek's extensive summary,⁽⁵⁾ the most successful model fluids have been mixtures based on glycerine. Additives including water, glucose, sodium hydroxide, lithium chloride, and citric acid are used

TABLE 2-2. Properties of BNW 72-68 Glass and Representative Glycerine/LiCl Model Fluids

Fluid	T °C	$\frac{\rho}{\text{gm}} \frac{1}{\text{cm}^3}$	$\frac{\mu}{\text{gm}} \frac{1}{\text{cm sec}}$	$\frac{\nu}{\text{cm}^2} \frac{1}{\text{sec}}$	$\frac{c}{\text{cal}} \frac{1}{\text{gm } ^\circ\text{C}}$	$\frac{\lambda(a)}{\text{cal}} \frac{1}{\text{sec cm } ^\circ\text{C}}$ $\times 10^{-3}$	$\frac{\alpha}{\text{cm}^2} \frac{1}{\text{sec}}$ $\times 10^{-3}$	Pr $\times 10^3$	$\frac{\sigma}{\Omega\text{cm}}$	$\frac{\beta}{^\circ\text{C}^{-1}}$ $\times 10^{-4}$
BNW 72-68	800	3.05	6800	2230	0.24	5.17 $\times 10^{-3}$	7.06 $\times 10^{-3}$	316 $\times 10^3$	635	0.986 $\times 10^{-4}$
	900	3.01	310	103		6.21	8.60	12.0	114	
	1000	2.98	42.5	14.3		7.24	10.1	1.41	31.8	
	1100	2.94	12.4	4.22		8.27	11.7	0.36	11.9	
	1200	2.90	4.80	1.66		9.31	13.4	0.124	5.08	
	1300	2.87	2.30	0.80		10.3	15.0	0.054	2.54	
Model A	30	1.274	6.60	5.18	0.550	0.780	1.11	4.65	1840	5.66
	40	1.268	3.30	2.60	0.560	0.776	1.09	2.38	950	
	50	1.263	1.90	1.51	0.575	0.773	1.06	1.42	550	
	60	1.257	1.09	0.87	0.590	0.769	1.04	0.84	340	
	70	1.251	0.65	0.52	0.603	0.765	1.01	0.51	225	
	80	1.246	0.45	0.36	0.615	0.761	0.99	0.36	160	
Model B	30	1.286	12.3	9.57	0.550	0.780	1.10	8.68	2700	5.25
	40	1.281	5.75	4.49	0.560	0.776	1.08	4.15	1470	
	50	1.273	2.95	2.31	0.575	0.773	1.06	2.19	820	
	60	1.270	1.70	1.34	0.590	0.769	1.03	1.31	480	
	70	1.265	1.00	0.79	0.603	0.765	1.00	0.79	290	
	80	1.259	0.79	0.63	0.615	0.761	0.98	0.64	210	
Model C	30	1.290	17.5	13.6	0.550	0.780	1.10	12.37	3350	5.34
	40	1.285	7.60	5.91	0.560	0.776	1.08	5.48	1680	
	50	1.280	3.80	2.97	0.575	0.773	1.05	2.83	915	
	60	1.274	2.10	1.65	0.590	0.769	1.02	1.61	520	
	70	1.269	1.20	0.95	0.603	0.765	1.00	0.95	320	
	80	1.264	0.80	0.63	0.615	0.761	0.98	0.64	220	

(a) Properties for MF-1 prepared for this study

to adjust the various properties to suit the needs of the experiment. Other materials such as silicone oils and mineral oils have also been used in some cases.⁽⁵⁾

The most successful fluids for modeling electric melting furnaces have been glycerine/LiCl mixtures. By varying the composition and preparation techniques, the density, viscosity and resistivity curves can be accurately matched to a wide range of glasses at reasonable model temperatures (20°C to 80°C). The mixture is transparent, chemically stable and nonvolatile for this temperature range. For these reasons, glycerine/LiCl was selected as the model fluid for this study.

All of the property data required for glass are also required for the model fluid. Property data for a wide range of model fluids based on glycerine/LiCl mixtures are available in Stanek,⁽⁵⁾ portions of which are reproduced here in Figures 2-4 through 2-7 and in Table 2-2. All of these data are for 7.5% LiCl in glycerine where the parameters on the graphs are the temperatures and holding times at temperature used in preparation. Stanek also gives similar data for 5% and 10% LiCl, which changes the magnitude of the properties and alters their dependence on temperature.

Data for the thermal conductivity λ_m and specific heat C_m for glycerine/LiCl mixtures are not currently available in the literature and must be determined experimentally for each mixture. The values measured for an arbitrary mixture of 7.5% LiCl in glycerine baked at 180°C for 1 hour (similar to Fluid C) are plotted in Figure 2-5 and summarized in Table 2-2. These data were also used for Fluids A and B with the assumption that the preparation technique will not significantly alter these properties.

The thermal expansion coefficient β_m is given in Figure 2-4 for the three model fluids described in Figures 2-4 through 2-7. This parameter determines the relationship between the units of temperature in the model and the prototype as given by Equation (6),

FIGURE 2-4. Model Fluids A, B, C Density

$$\epsilon_T = \frac{\Delta T_m}{\Delta T_p} = \frac{\beta_p}{\beta_m} = \frac{1}{\epsilon_\beta} \quad (11)$$

where ϵ_T is the temperature scale factor. The density data for the model fluid and the molten glass are both essentially linear so that β_m , β_p , and ϵ_T may be assumed constant.

FIGURE 2-5. Model Fluids A, B, C Specific Heat (C_m), Thermal Conductivity (λ_m), and Thermal Diffusivity (α_m)

Comparison of the property data for glass in Figures 2-1, 2-2, and 2-3 with those for the model fluids in Figures 2-4 through 2-7 shows that most of the properties vary similarly with temperature. The quantitative relationships between the model and prototype fluid properties and temperature scales are established in Section 4.

2.7 DESCRIPTION OF THE PROTOTYPE FURNACE

The design of the PNL liquid-fed ceramic melter (LFCM)⁽⁸⁾ is illustrated schematically in Figure 2-8 and by the photograph in Figure 2-9. The inside dimensions of the rectangular melting cavity are approximately 86.4 cm by 121.9 cm by 71.1 cm deep. The glass depth is maintained at about

FIGURE 2-6. Model Fluids A, B, C Viscosity

FIGURE 2-7. Model Fluids A, B, C Electrical Resistivity (σ_m)

48.3 cm by a "gooseneck" overflow attached at the bottom center of one side. The frit and calcined waste are mixed and fed from a hopper above. When liquid feed is used, the glass formers and waste are a well mixed slurry. Off gases are exhausted out through a vent in the lid and the system is maintained at a slight vacuum.

The refractory lining the inner surface of the melting cavity is Monofrax[®] E, a high temperature ceramic composed primarily of aluminum and chromium oxide. The inner wall is backed by a second, and in some cases a third, layer of insulation followed by a stainless steel water jacket on the outside.

FIGURE 2-8. Liquid Feed Ceramic Melter (LFCM) Schematic

[®] Trademark of the Carborundum Co.

FIGURE 2-9. Liquid Feed Ceramic Melter

During a melting run, molten glass is drawn off through the side port continuously or in batch mode by tipping the entire furnace about a horizontal axis. A drain in the bottom center of the furnace also allows draining of the melter contents.

The electrodes are made of nickel chromium alloys (inconel). Various electrode configurations have been investigated, including continuous plates and strip (bar) electrodes with individual power controls. The electrode configurations of interest to this study are three horizontal half-round inconel bars (LFCM) or a single inconel plate (calcine fed ceramic melter) located at each end of the melter cavity. For the bar electrodes the pair near the floor is fired by one power supply while the other two pairs located approximately 1/4 of the glass depth below the top crust are powered by a separate supply. Cooling is provided through the wall behind the electrodes or, in the case of the plate electrodes, by integral coolant channels inside the plates. The power is provided by phase angle-fired Silicone Controlled Rectifier (SCR) circuits controlled through temperature feedback. Current or power feedback can also be used.

3.0 DEVELOPMENT OF THE SCALING EQUATIONS

In the analysis that follows, the similarity criteria are employed to develop scaling factors for hydrodynamic, thermal and electromagnetic parameters of interest. The scaling factors are required to compute the quantitative relationship between parameters measured in the model and in the prototype.

3.1 ANALYSIS

The primary similarity requirements governing the model/prototype relationships are defined by Equations (6) through (10). The geometric scale that defines relationships between the model and the prototype is defined by

$$\epsilon_L = \frac{L_m}{L_p} \quad (12)$$

where L_m and L_p are characteristic lengths in the model and prototype systems. In some cases, it is advantageous or even necessary to have different length scales for vertical and horizontal dimensions. However, in the present case, all lengths scale in the same proportion.

The similarity criteria require fixed relationships between the fluid properties. Equation (7), matching of Ra number, may be given in terms of scale factors as

$$\epsilon_L = \epsilon_v^{2/3} \epsilon_{Pr}^{-1/3} = \epsilon_v^{1/3} \epsilon_\alpha^{1/3} \quad (13)$$

The choice of the model length scale ϵ_L is thus intimately tied to the selection of the fluid through the properties ν and α . Assuming that a fluid is chosen to satisfy Equations (6) and (7), the scale factors for other variables of interest may be derived.

The criterion of Equation (8) requires similarity in fluid throughput for the model and prototype. Assuming that this is accomplished (i.e., by impressing the appropriate throughflow in the model), then Equation (8) also relates the convective velocities in the model to those in the prototype. The scale factor delineating the relationship between velocities in the model and the prototype is defined by

$$\epsilon_u = \frac{u_m}{u_p} \quad (14)$$

such that equality of Pe, Equation (8), may be given by

$$\epsilon_u = \epsilon_\alpha \epsilon_L^{-1} \quad (15)$$

When this criterion is fulfilled for throughput, the scale for convective velocities can be obtained by substituting Equation (13) for ϵ_L :

$$\epsilon_u = \epsilon_\alpha^{2/3} \epsilon_v^{-1/3} \quad (16)$$

When proper scaling and boundary conditions are achieved, Equations (15) and (16) must hold for all velocities in the system.

The scale factor for time relates the ratio of residence times or other characteristic times in the two systems. By definition, ϵ_τ may be given by

$$\epsilon_\tau = \frac{\tau_m}{\tau_p} = \frac{L_m/u_m}{L_p/u_p} = \epsilon_L \epsilon_u^{-1} \quad (17)$$

From Equations (13) and (16), alternative forms for ϵ_τ are then obtained:

$$\epsilon_\tau = \epsilon_L^2 \epsilon_\alpha^{-1} = \epsilon_\alpha^{-1/3} \epsilon_v^{2/3} \quad (18)$$

The thermal modeling criterion requires proportional heat loadings on the system walls and equality of the dimensionless source term ϕ_s , by Equation (9). In terms of scale factors, this gives

$$\left(\frac{\phi_{sm} L_m^2 / \lambda_m \Delta T_m}{\phi_{sp} L_p^2 / \lambda_p \Delta T_p} \right) = 1.0 \quad (19)$$

$$\epsilon_\phi = \epsilon_\lambda \epsilon_T \epsilon_L^{-2} \quad (20)$$

Substituting Equation (13) for ϵ_L then gives

$$\epsilon_\phi = \epsilon_\lambda \epsilon_T \epsilon_\alpha^{-2/3} \epsilon_v^{-2/3} \quad (21)$$

The heat source ϕ_s in the prototype is due to electrical heating, chemical reaction and nuclear decay. If chemical reaction is neglected and attention is limited to pure glass or old wastes with low decay rates, voltage and power ratings of the model and prototype can be related. In this case the heat source term in either system can be given by the power per unit volume,

$$\phi = \frac{P}{V_0} = \frac{V^2}{\sigma L^2} \quad (22)$$

where P is the electric power input, V is the applied voltage, L is the electrode separation and σ is the fluid resistivity. The scale factors are then related by

$$\epsilon_\phi = \frac{\epsilon_p}{\epsilon_L^3} = \frac{\epsilon_v^2}{\epsilon_\sigma \epsilon_L^2} \quad (23)$$

The scale factor for the input power is then given by

$$\epsilon_p = \epsilon_\phi \epsilon_L^3 = \epsilon_T \epsilon_\lambda \epsilon_L \quad (24)$$

and the scale factor for the applied voltage is

$$\epsilon_v = \epsilon_\phi^{1/2} \epsilon_\sigma^{1/2} \epsilon_L = \epsilon_T^{1/2} \epsilon_\sigma^{1/2} \epsilon_\lambda^{1/2} \quad (25)$$

The relationship between heat transfer coefficients in the model and prototype may be computed from the equality of Nusselt numbers. From Equation (10) we obtain

$$\left(\frac{h_m L_m / \lambda_m}{h_p L_p / \lambda_p} \right) = 1.0 \quad (26)$$

$$\epsilon_h = \epsilon_\lambda \epsilon_L^{-1} = \epsilon_\lambda \epsilon_\alpha^{-1/3} \epsilon_v^{-1/3} \quad (27)$$

The above results for the scale factors are summarized in Table 3-1. Alternate, equivalent equations are given in some cases.

TABLE 3-1. Derived Modeling Relationships

Parameter	Units	Symbol	Equivalence Criterion	Modeling Equation(s)
Temperature	$^{\circ}\text{C}$	T	$\beta\Delta T$	$\epsilon_T = \epsilon_{\beta}^{-1}$
Dimensions	cm	L	Ra	$\epsilon_L = \epsilon_{\alpha}^{1/3} \epsilon_v^{1/3}$
Velocity	cm sec^{-1}	U	Pe	$\epsilon_u = \epsilon_{\alpha} \epsilon_L^{-1} = \epsilon_{\alpha}^{2/3} \epsilon_v^{-1/3}$
Time	sec	τ	Pe	$\epsilon_{\tau} = \epsilon_u^{-1} \epsilon_L = \epsilon_{\alpha}^{-1/3} \epsilon_v^{2/3}$
Power Density	watts cm^{-3}	ϕ	$\tilde{\phi}_s$	$\epsilon_{\phi} = \epsilon_T \epsilon_{\lambda} \epsilon_L^{-2} = \epsilon_T \epsilon_{\lambda} \epsilon_{\alpha}^{-2/3} \epsilon_v^{-2/3} = \epsilon_T \epsilon_C \epsilon_{\alpha}^{1/3} \epsilon_v^{-2/3}$
Power	watts	P	$\tilde{\phi}_s$	$\epsilon_P = \epsilon_{\phi} \epsilon_L^3 = \epsilon_T \epsilon_{\lambda} \epsilon_{\alpha}^{1/3} \epsilon_v^{1/3} = \epsilon_T \epsilon_C \epsilon_{\alpha}^{4/3} \epsilon_v^{1/3}$
Voltage	volts	V	$\tilde{\phi}_s$	$\epsilon_V = \epsilon_{\phi}^{1/2} \epsilon_{\sigma}^{1/2} \epsilon_L = \epsilon_T^{1/2} \epsilon_{\sigma}^{1/2} \epsilon_{\lambda}^{1/2}$

3.2 COMPUTATION OF TEMPERATURE CORRESPONDENCE AND SCALE FACTORS

The design of the model system requires thorough knowledge of the design and characteristics of the prototype. The most important requirement is that prototype fluid properties be accurate. The design of the furnace is briefly described in Section 2.7 and illustrated in Figures 2-8 and 2-9. The prototype fluid is assumed to be glass of the type BNW 72-68 described in Section 2.5 and in Figures 2-1, 2-2, and 2-3. The glycerine/LiCl solutions used as model fluids in the experiments are discussed in Section 2.6 and illustrated in Figures 2-4 through 2-7. This section establishes an acceptable model scale and model fluid mixture to satisfy the modeling criteria. The relationship between the temperature scales and the relevant scale factors for the model system are then established.

Early in the design of the experiment it was determined that the practical upper limit on the model scale due to power, cooling water, and photography illumination requirements would be approximately 1/2 scale. The lower bound was determined to be approximately 1/6 scale to assure reasonable spatial resolution. Preliminary examination of model fluid characteristics indicated that this range was compatible with glycerine/LiCl mixtures.

A model scale of 1/3 was then selected based primarily on convenience since this gave a reasonable size to work with in the laboratory. Preliminary computations were performed indicating that 1/3 scale is compatible with the glass/model fluid property relationships. Once this choice was made, the next step was to select a specific model fluid and determine the relationship between model and prototype temperature scales.

To begin, the relationship between the unit of temperature in the model and prototype was computed using Equation (6) and β values in Table 2-2. Next, the relationships between temperature levels in the model and prototype were determined by requiring equivalence of Ra as expressed by Equation (7),

$$\epsilon_L = \epsilon_\alpha^{1/3} \epsilon_v^{1/3} = \frac{(\alpha_m^{v_m})^{1/3}}{(\alpha_p^{v_p})^{1/3}}$$

The products $(\alpha\nu)^{1/3}$ for prototype and model fluids are tabulated in Table 3-2 as functions of prototype and model temperatures, respectively. The temperature at which exact temperature scaling is required was selected as the average glass bulk temperature during continuous melting, $T_{po} = 1100^{\circ}\text{C}$, and the apparent length scale ϵ_L' was computed as

$$\epsilon_L'(T_m) = \frac{[\alpha_m(T_m)\nu_m(T_m)]^{1/3}}{[\alpha_p(T_{po})\nu_p(T_{po})]^{1/3}}$$

These results are given in Table 3-2 and in Figure 3-1 for the three different modeling fluids proposed for this study. The model temperatures, T_{mo} , that correspond to T_{po} can be determined by locating the temperatures where ϵ_L' is equal to the chosen model scale. The procedure is illustrated in Figure 3-1 and the results for ϵ_T and T_{mo} are summarized in Table 3-2. The corresponding temperature scales were then computed using ϵ_T and T_{mo} . The results are given in Table 3-2 and in Figure 3-1.

Note that the fluid properties vary differently as a function of temperature; consequently, the apparent scale factors also vary with temperature. This can be illustrated by computing the various scale factors as a function of model temperature by taking the ratios of parameters at equivalent model and prototype temperatures. The results of these computations are illustrated in Figure 3-2 and Table 3-3 for model Fluid C. The results for the other fluids are similar in trend although the magnitudes of the scales vary.

The data of Figure 3-2 indicate that many of the scale factors are relatively constant over the range of model temperatures. Because experience has shown that temperature variations in the furnace are modest, the scale factors were assumed constant. The scale factors for the three modeling fluids have thus been computed at T_{mo} and are tabulated in Table 3-4. Variation of the scale factors with temperature will be neglected from here on.

TABLE 3-2. Computations for Determining Temperature Scales for Fluids A, B, C

<u>Fluid</u>	<u>T(°C)</u>	<u>($\nu\alpha$)^{1/3}</u>	<u>$\epsilon_L' = \frac{(\nu\alpha)_m^{1/3}}{(\nu\alpha)_p^{1/3}}$</u>	<u>Equivalent Prototype Temperature</u>	<u>T_{mo} (°C)</u>
BNW 72-68	1100	0.367	1.000	1100 = T _{po}	
A	30	0.179	0.488	997	48.0
	40	0.142	0.387	1054	
	50	0.117	0.319	1112	
	60	0.097	0.264	1169	
	70	0.081	0.221	1227	
	80	0.071	0.193	1284	
B	30	0.219	0.597	967	55.0
	40	0.169	0.460	1020	
	50	0.135	0.368	1073	
	60	0.111	0.302	1127	
	70	0.092	0.251	1180	
	80	0.085	0.232	1233	
C	30	0.246	0.670	943	59.0
	40	0.186	0.507	997	
	50	0.146	0.398	1051	
	60	0.119	0.324	1105	
	70	0.098	0.267	1159	
	80	0.085	0.232	1214

FIGURE 3-1. Model Fluids A, B, C Temperature Correspondence

FIGURE 3-2. Model Fluid C Scale Factor Variation with Temperature

TABLE 3-3. Fluid C Scale Factor Variation with Temperature

Fluid A T_M (°C)	T_p (°C)	Viscosity ϵ_v	Diffusivity ϵ_α	Conductivity ϵ_λ	Resistivity ϵ_σ	Length ϵ_L	Time ϵ_τ	Velocity ϵ_u	Power ϵ_p
30	943	0.354	0.119	0.117	54.95	0.346	0.994	0.344	0.0075
40	997	0.391	0.107	0.108	50.88	0.348	1.134	0.307	0.0070
50	1051	0.405	0.096	0.100	48.68	0.343	1.225	0.280	0.0063
59	1100	0.403	0.087	0.093	46.22	0.335	1.229	0.260	0.0058
70	1159	0.401	0.079	0.086	43.44	0.326	1.347	0.242	0.0052
80	1214	0.430	0.072	0.081	46.82	0.327	1.486	0.220	0.0049

TABLE 3-4. Scale Factors, $T_{po} = 1100^{\circ}\text{C}$

Parameter	Scale Factor	Model Fluid		
		A $T_{mo}=48.0^{\circ}\text{C}$	B $T_{mo}=55^{\circ}\text{C}$	C $T_{mo}=59^{\circ}\text{C}$
Thermal Expansion	ϵ_{β}	5.740	5.325	5.416
Thermal Conductivity	ϵ_{λ}	0.094	0.093	0.093
Thermal Diffusivity	ϵ_{α}	0.091	0.089	0.087
Thermal Capacity	ϵ_c	1.025	1.050	1.063
Dynamic Viscosity	ϵ_v	0.391	0.415	0.403
Prandtl Number	ϵ_{Pr}	4.297	4.663	4.632
Electrical Resistivity	ϵ_{σ}	50.42	52.94	46.22
Temperature	ϵ_T	0.174	0.188	0.185
Length	ϵ_L	0.329	0.333	0.327
Velocity	ϵ_u	0.277	0.267	0.266
Time	ϵ_{τ}	1.189	1.246	1.229
Power Density	ϵ_{ϕ}	0.151	0.158	0.161
Power	ϵ_p	0.0054	0.0058	0.0056
Voltage	ϵ_V	0.908	0.963	0.892

4.0 DESIGN OF THE EXPERIMENT

This section describes the design of the current PNL glass melter physical modeling facility and the procedures used to model a particular prototype melter and simulated waste glass.

4.1 DETERMINATION OF THE SPECIFIC MODELING PARAMETERS

Selection of the specific modeling fluid from the three main candidate fluids described in Section 2.6 was tempered by considering the prototype melter operating temperature range and the desired modeling temperature range. Operating data from the prototype LFCM indicated the glass temperature range of interest spanned 850 to 1200°C with the average bulk temperature approximately 1100°C. However, the cold cap above the molten glass regularly ranged only 500 to 700°C. This cool boundary was an important condition to attempt matching due to the large heat losses through that surface.

The desired model temperature scale was based on two factors: the amount of cooling/heating available for the water jackets surrounding the model and the operating temperature limit for the model materials and construction. The lower limit was imposed by the water temperature available for cooling from a small refrigeration coil which could maintain about 14°C. Plexiglass was chosen for the melter model because it is easily fabricated, optically transparent, reasonably durable, and relatively inexpensive. This restricted the highest operating temperature to approximately 80°C. Thus a practical range for the model temperatures was 14 to 80°C. Recall that all three fluids described in Section 2.6 are acceptable for modeling BNW 72-68 glass under the proper conditions. However, from the temperature correspondence curves similar to Figure 3-1, Fluid C more nearly satisfied the temperature requirements. Thus the first modeling fluid prepared for this study was patterned after Fluid C, 7.5% LiCl in glycerine heated to 180°C and held for 1 hour.

Measured property data for this new fluid, labeled MF-1, and two other fluids, MF-2 and MF-3, are shown in Figures 4-1 and 4-2 and in Table 4-1. The temperature correspondence curves shown in Figures 4-3 and 4-4 were based on the calculations in Tables D-1 and D-2 and a summary of the scaling factors for these fluids is provided by Tables D-3 and D-4. Model Fluid MF-2 resulted from an accidental discharge of water from the top cooling jacket into a model full of MF-1. Even so, the resulting fluid was suitable for modeling and was used for several experiments. MF-3 was created to replace MF-1 but was prepared with slightly different techniques at 165°C for 1 hour.

Two different furnace configurations and sizes were modeled with the same apparatus (see Section 4.5). The primary differences for the physical model were the electrodes and the length scales. A calcine fed ceramic melter (CFCM) with plate electrodes was modeled at $\epsilon_L = 0.33$. However, the liquid fed ceramic melter (LFCM) was designed with a different length/width/depth ratio and bar electrodes. It was physically modeled using a length scale $\epsilon_L = 0.27$. These two different length scale factors, 0.27 and 0.33, are included in Figures 4-1 through 4-4 and Table 4-1. Note also that temperature correspondence was computed for glass bulk temperatures $T_{po} = 1100^\circ\text{C}$ and 950°C .

4.2 DESIGN OF THE PHYSICAL MODEL

A schematic of the 0.27 scale LFCM model is given by Figure 4-5 and a photograph is shown in Figure 4-6. The 0.33 scale CFCM model was identical except for the plate electrodes, which changed the model length-to-width aspect ratio. Therefore the following description applies equally well with minor variations to either model. The uninsulated clear plexiglass model was essentially a double-walled rectangular box with inside dimensions of 23.81 cm wide by 33.02 cm between electrodes. For the 0.27 scale LFCM model the bottom surface of the top cooling jacket was located 13.02 cm above the floor of the cavity (10.16 cm for the CFCM model) but was adjustable upward to approximately 25.4 cm if required. Operating fluid volume for the LFCM model was 10.3 l. The annulus surrounding the cavity was divided into four separate

FIGURE 4-1. MF-1, MF-2, MF-3 Density

cooling jackets, each supplied from a different thermostatically-controlled reservoir. The circuits were the top, front face, electrodes, and rear face. The bottom was a single sheet of 12.7-mm plexiglass cooled by natural convection to the air. All remaining interior surfaces were 1.59-mm or 3.18-mm material. A gooseneck overflow tube through the rear wall allowed simulating throughput and maintained a constant fluid depth.

The 0.69-cm thick by 2.74-cm high bar-type copper electrodes were fastened three to a panel to two separate cooling panels that could be removed from the central cavity. These panels were coupled in series to form a single water circuit, and the water flow rate was kept as high as possible to minimize the temperature gradient between the electrodes. The full width

FIGURE 4-2. MF-1, MF-2, MF-3 Kinematic Viscosity (ν_m) and Electrical Resistivity (σ_m)

TABLE 4-1. Average Fluid Properties for Scaling Factor Calculations

Fluid	T (°C)	ρ (gm/cm ³)	μ (gm/cm sec)	$\nu = \mu/\rho$ (cm ² /sec)	c_p (a) (cal/gm°C)	λ (a) (10 ⁻³ cal/cm sec°C)	$\alpha = \frac{\lambda}{\rho c_p}$ (10 ⁻³ cm ² /sec)	Pr= ν/α (X 10 ⁻³)	σ (Ωcm)	$(\nu\alpha)^{1/3}$
BNW 72-68 $\beta=0.986(10^{-4})$	800	3.05	6800	2230	0.24	5.17	7.06	315.9	635	2.506
	900	3.01	310	103		6.21	8.60	12.0	113	0.960
	950	3.00	103	34.3		6.73	9.35	3.67	57.2	0.684
	1000	2.98	42.5	14.3		7.24	10.12	1.41	32.0	0.525
	1100	2.94	12.4	4.22		8.27	11.72	0.36	11.68	0.367
	1200	2.90	4.8	1.66		9.31	13.38	0.12	5.21	0.281
	1300	2.87	2.3	0.80		10.30	14.95	0.05	2.54	0.229
MF-1 $\beta=5.972(10^{-4})$	20	1.2894			0.54	0.783				
	30	1.2836	13.35	10.40	0.55	0.780	1.105	9.41	2375	0.226
	40	1.2775	6.60	5.17	0.56	0.776	1.085	4.76	1396	0.178
	50	1.2717	3.42	2.69	0.58	0.773	1.048	2.57	779	0.141
	60	1.2657	1.88	1.49	0.59	0.769	1.030	1.45	462	0.115
	70	1.2596	1.10	0.87	0.60	0.765	1.012	0.86	285	0.096
	80	1.2538	0.68	0.54	0.62	0.761	0.979	0.55	197	0.081
	90	1.2478			0.63	0.757				
	100				0.64	0.753				
MF-2 $\beta=5.512(10^{-4})$	30	1.2808	10.40	8.12	0.55	0.780	1.107	7.34	1842	0.208
	40	1.2753	4.85	3.80	0.56	0.776	1.087	3.50	1112	0.160
	50	1.2698	2.49	1.96	0.58	0.773	1.050	1.87	614	0.127
	60	1.2643	1.38	1.09	0.59	0.769	1.031	1.06	383	0.104
	70	1.2588	0.81	0.64	0.60	0.765	1.013	0.63	246	0.087
	80	1.2533	0.52	0.41	0.62	0.761	0.979	0.42	167	0.074
MF-3 $\beta=5.582(10^{-4})$	30	1.2835	13.80	10.75	0.55	0.780	1.105	9.73	2522	0.228
	40	1.2780	6.20	4.85	0.56	0.776	1.084	4.47	1478	0.174
	50	1.2725	3.10	2.44	0.58	0.773	1.047	2.33	811	0.137
	60	1.2668	1.69	1.33	0.59	0.769	1.029	1.29	476	0.111
	70	1.2612	0.95	0.75	0.60	0.765	1.011	0.74	298	0.091
	80	1.2556	0.64	0.51	0.62	0.761	0.978	0.52	205	0.079

(a) All model fluids based on MF-1 values.

FIGURE 4-3. MF-1, MF-2, MF-3 Temperature Correspondence,
 $T_{po} = 1100^{\circ}\text{C}$

electrode bars could be adjusted vertically to model several electrode configurations. All electrical leads to the dual power supplies passed through dry wells in the panels so that no fluid contact occurred.

The top cooling jacket was one of two forms of perforated panel designed to allow access to the model's interior for temperature or electric field measurements. One type had a flat lower surface and contained 100 small drywells through the cooling jacket. It was used to simulate either steady-state or continuous liquid waste feeding conditions. The other top jacket had a convex, dome-shaped lower surface that protruded 2.54 cm into the modeling fluid in a fashion similar to the prototype cold cap during calcine feeding. This top had six small drywells through the cooling jacket and was used for modeling steady-state conditions only.

FIGURE 4-4. MF-1, MF-2, MF-3 Temperature Correspondence,
 $T_{po} = 950^{\circ}\text{C}$

Filtered tap water was pumped to all cooling/heating jackets from individual thermostatically-regulated constant temperature reservoirs. Each circuit was manifolded and valved on the inlet and outlet to provide evenly distributed, well-mixed flows. The flow rate for each circuit could be monitored automatically by turbine flowmeters connected to the data acquisition system and/or manually using rotameters. The inlet/outlet temperatures were measured with platinum RTDs. A typical circuit is shown in Figure 4-7.

Single-phase power for the electrodes was supplied by two phase angle-fired SCR power controllers. The current or power feedback signal was generated by an rms power transducer that measured the true rms value of

FIGURE 4-5. Model Liquid Feed Melter Schematic

FIGURE 4-6. Model Liquid Feed Melter

FIGURE 4-7. Typical Water Jacket Circuit and Model Apparatus Layout

voltage, current, and power, and provided a proportional dc voltage output. A temperature controller was also available for power control based on a characteristic temperature. However, power feedback was used exclusively for this study, because power instead of temperature was chosen to be the independent variable. The power controllers fired into large isolation transformers and the whole system had a floating ground. This effectively prevented crossfiring between the two power supplies when they were used simultaneously to power the upper and lower electrodes at different voltage potentials. A schematic diagram of the power supply system is given by Figure 4-4.

4.3 INSTRUMENTATION AND MEASUREMENT TECHNIQUES

The following section describes the apparatus and techniques used to gather the large volume of data required to characterize the model glass melting process. The two most significant parameters measured were the fluid velocities and temperatures. The investigation of the electric potential field is also discussed, and a brief description of the model fluid characterization is included.

4.3.1 Velocity Measurement

The driving force for the convective flow in the glass melter model was the temperature difference between the internally-heated fluid and the water-cooled electrodes or the cold top. The front and back walls were maintained at a temperature near the bulk fluid temperature in an attempt to simulate the well-insulated walls of the prototype. As expected, the major flow pattern consisted of two or more large counterrotating cells aligned along a vertical (X-Z) plane between the two sets of electrodes. Figure 4-5 describes the model coordinate system. Preliminary investigations showed that these flow cells and numerous smaller vortices were not structured and orderly but changed shape, size, and flow direction with time. Therefore, it was important to develop a nonintrusive velocity measurement technique that could instantaneously look at a given X-Z plane through the model. This two-dimensional technique should also be capable of describing both magnitude and direction of flow in the plane.

FIGURE 4-8. Power Supply Schematic

Currently, several methods are available for satisfying the preceding criteria; some are state of the art, but most are well established and relatively simple to implement. Examples are streak photography, photochromic dye tracing, strobe photography, and speckle interferometry. Of the four, speckle interferometry is perhaps the most sophisticated and difficult to use. Its application to fluid velocity measurement is well documented in the literature^(9,10) and at least one camera system is commercially available off-the-shelf. With this method, highly accurate measurements of velocity magnitude and direction are possible on a point-by-point basis and, in some instances, isovelocity contours can be realized. However, analyzing the entire photographic plane to establish the total velocity profile at a single point in time could be tedious. On the other hand, photochromic dye tracing provides an excellent means of flow visualization but a poor method of extracting accurate quantitative data. Likewise, simple streak photography can image the total flow field at any point in time but the accuracy of measuring streak lengths to determine the velocity is questionable. A reasonable alternative is strobe photography, whereby either the light source or the camera shutter is strobed repeatedly for a predetermined length of time. This technique combines the flow visualization capability of streak photography with a good means of measuring the velocity as well. Moreover, analysis of the data is much simpler than that of speckle interferometry. For these reasons, strobe photography was chosen as the principal velocity measuring tool for this study.

The three items required for successful strobe pictures are the light source, camera system, and light-scattering particles that are neutrally buoyant in the modeling fluid. Because the flows in the melter model were induced by temperature differences, it was important to employ a photographic light source that would not add any heat to the system. A continuous 4-W argon-ion laser was chosen for this reason. It had the added advantage of being easily collimated into a thin sheet of light and could be polarized at any required angle. For this study the laser beam was expanded into a sheet

33.02 cm wide by 0.64 cm thick and reflected vertically by a mirror up through the transparent floor of the melter. The mirror was mounted on a traversing mechanism that allowed positioning the light sheet within ± 2.54 mm of any reference point in the melter. All measurement locations relative to each other were known within ± 0.025 mm. These X-Z measurement planes were $Y^* = 0.257, 0.500, \text{ and } 0.743$, where $Y^* = Y/Y_{\max}$.

The PNL camera system was designed around a 10.16 cm x 12.70 cm view-camera with an f5.6 lens. The electronic shutter was driven by a timing circuit that allowed exposures of 0.1 to 1.1 seconds (or multiples of 6 thereof) to be continuously repeated at intervals ranging from 5.0 to 50.0 seconds. The shutter system could also trigger the automatic film advance after a specified number of exposures when the roll film back was used. A separate timing system was used to provide single-exposure streak photographs from 30.0 to 180.0 seconds duration.

A wide variety of light-scattering particles in the 100- μm to 800- μm size range were investigated, including hollow and solid glass and ceramic spheres, anthracene crystals, glassy carbon particles, and ion-exchange resin beads. The primary difficulty in selecting an appropriate scattering particle was finding one that was neutrally buoyant. This was important to assure that the particles would accurately follow the low velocity flows expected in the model melter. The glass and ceramic spheres were either too heavy when solid or too light when hollow. Anthracene crystals were neutrally buoyant in MF-1 over the temperature range of interest but the only form commercially available had a plate-like structure. This caused them to sparkle as they moved about with the fluid, often reflecting no light back to the camera when oriented edgewise to the lens. The irregularly-shaped glassy carbon particles were more omnidirectional scatterers than anthracene and were also neutrally buoyant over the range of 25 to 70°C. However, they were not ideal light scatterers due to their heavily faceted surfaces, and appeared to sparkle in the laser light sheet. A more desirable spherical shape was provided by a type of charcoal resin bead. This particle reflected light uniformly and steadily as

long as it remained in the light sheet. Most of the ion-exchange resin beads were excellent light scatterers with particle densities that could be modified slightly. However, none of the seven or eight resins investigated could be made completely neutrally buoyant over the range of temperatures encountered in the model. Glassy carbon particles were found to best fit the needs of the experiments, so were used in most cases.

4.3.2 Temperature Measurement

Most temperatures were measured in the glass melter physical modeling apparatus by copper/Constantan (type T) insulated junction thermocouples and electronic thermometers. Platinum RTDs were used for the inlet/outlet of the water jackets. Thirty 1.02-mm diameter thermocouples were imbedded in the plexiglass walls and floor of the model cavity and an additional three thermocouples were buried in the front face of each bar electrode panel between the upper and lower electrodes (Figure 4-9). The plate electrodes each contained nine thermocouples. Each thermocouple tip was carefully potted into the wall with acrylic cement, 0.79 mm from the inside surface of the cavity. All thermocouples were connected in parallel to one of several switch panel/electronic thermometer combinations and to an automatic data logger. The total temperature measurement system accuracy was $\pm 1.4^{\circ}\text{C}$. Internal modeling fluid temperatures were measured with six or more 3.18-mm diameter individually calibrated thermocouples inserted through the small drywells in the top cooling jacket. These temperatures were accurate to $\pm 0.5^{\circ}\text{C}$. Data were generally taken along the model centerline ($Y^* = 0.500$) between the electrodes because this corresponded to the calculation plane used by the VECTRA computer code. However, fluid temperatures were occasionally measured along $Y^* = 0.257$ and $Y^* = 0.743$ to investigate symmetry effects.

4.3.3 Electric Potential Field

The electric potential field was investigated with a probe constructed of #12 wire insulated over its length except for a small portion of the exposed tip. The probe was connected to one terminal of a true rms voltmeter and one of the electrodes was connected to the other. It was necessary to measure the potentials relative to an electrode because the system ground was floating.

FIGURE 4-9a. Model Thermocouple Placement, Elevation

FIGURE 4-9b. Model Thermocouple Placement, Plan

4.3.4 Data Acquisition System

All temperature data, water jacket flow rates, and power supply information were recorded by a data acquisition system consisting of a Fluke 2240A data logger and a 9-track Kennedy model 9832 magnetic tape recorder. The 60-channel data logger scanned at the rate of 2.5 channels/second and recorded the data on paper tape while identical information was sent to the tape recorder for magnetic storage. This system was highly flexible and could be programmed to scan any or all of the 60 channels at preselected intervals.

4.3.5 Model Fluid Characterization

The specific heat and thermal conductivity measurements were conducted by Dynatech R/D Company, Cambridge, Massachusetts. Fluid viscosity was determined in the laboratory using a Brookfield viscometer. The density of the modeling fluid was measured using a Weld's type specific gravity flask and a precision analytical balance. The electrical conductivity measurements were made by Three E Laboratories, Lansdale, Pennsylvania, using a combination capacitance/ resistance null ac bridge and bright platinum electrodes.

The electrical conductivity data reported are the values measured at 2000 Hz frequency after the model fluid temperature stabilized 2 hours. These measurements were very difficult to obtain because of the high fluid capacitance (in excess of 10,000 pf over much of the temperature range). This made balancing the bridge difficult and required bright platinum electrodes. Moreover, glycerine/LiCl is strongly hygroscopic and slowly changed conductivity with time. This characteristic necessitated waiting at least 2 hours at a given temperature before making the measurements. The 2000 Hz frequency provided the sharpest null on the ac bridge and provided the most accurate conductivity values, which are equally valid over the SCR frequency range centered around 60 Hz.

4.4 DATA REDUCTION AND ANALYSIS

This section describes the computerized reduction of the automatic data acquisition tapes, the manual analysis of the strobe photographs, and the accuracy of the data.

4.4.1 Computer Data Analysis

The 9-track magnetic data logger tape containing all of the model temperature, power, and water jacket flow data was analyzed by a PDP 1170 computer. The data reduction program converted the raw data to consistent engineering units, then tabulated or plotted the results as a function of time.

4.4.2 Strobe Photograph Analysis

Strobe photographs generally covered only the left or right half of the model as viewed from the front face. This allowed maximum camera magnification and corresponding resolution. Each light-scattering particle produced a string of images; the distance between images was the product of the particle velocity and the time between exposures. Several image strings from regions evenly spaced across each photograph were randomly selected for study. The X-Z location of the image string centroid was established first. Then, the distance from the center of the first image to the center of the last in the string was measured with a dial micrometer. For image strings with a high degree of curvature, the distance measurement was shortened to span only linear portions of the curve. These measurements were divided by the product of the total magnification of the photograph and the total elapsed time between the measured images to yield a mean particle velocity. Velocity direction was given by a "tail" (single long exposure) added to the end of each image string.

4.4.3 Accuracy of the Data

An error analysis using the error and uncertainty methods of Schenck⁽¹¹⁾ was performed to estimate data accuracy. The methods and analysis are presented in detail in Appendix C. Table 4-2 is a summary of the results of the uncertainty analysis that was based on the nominal values experienced.

As stated in Section 4.3.1, the uncertainty of the position of the center of the light sheet was ± 2.54 mm relative to any given reference point on the model. All other positions relative to each other were known to ± 0.254 mm. The light sheet thickness was defined as the $\frac{1}{e^2}$ limits of the intensity

TABLE 4-2. Uncertainty Analysis Summary

<u>Model Parameter</u>	<u>Nominal Value</u>	<u>Uncertainty Value</u>	<u>Percent Uncertainty</u>
Viscosity (MF-1)	1335 cps @ T=30°C 107 cps @ T=70°C	13.4 cps 0.7 cps	1.0 1.0
Electrical Conductivity (MF-1)	297 μS/cm @ T=30°C 1941 μS/cm @ T=70°C	1.5 μS/cm 9.7 μS/cm	0.5 0.5
Thermal Conductivity	$0.780(10^{-3}) \frac{\text{cal}}{\text{cm sec}^{\circ}\text{C}}$	$0.02(10^{-3}) \frac{\text{cal}}{\text{cm sec}^{\circ}\text{C}}$	3.0
Specific Heat (MF-1)	0.550 cal/gm°C	0.02 cal/gm°C	3.0
Density (MF-1)	1.27 gm/cm ³	negligible	
Temperature for Fluid Property Measurement	30°C	1.0°C	3.3
Water Jack Temperature RTD	100 mV	0.15 mV	0.2
Fluid Temperature (TC)	70°C	0.5°C	0.7
Wall Temperature (TC)	50°C	1.4°C	2.8
Water Jacket Flow Rate	11.95 l/m	0.085 l/m	0.7
Laser Light Sheet Position Relative to Model	y = 11.43 cm	2.54 mm	2.2
Laser Light Sheet Thickness	6.35 mm	1.52 mm	24
Fluid Velocity (Strobe Technique)	0.43 mm/sec	0.009 mm/sec	2.1
Voltage	120 VAC	5.1 VAC	4.2
Current	3.0 A	0.14 A	4.6
Power	300 W	14.9 W	5.0

distribution. The large uncertainty was due to the diffusion of the laser light caused by the plexiglass and the modeling fluid. However, this did not affect the velocity measurements parallel to the light sheet. Its primary effect was to confuse the exact position of the sheet relative to the model.

Velocity measurement accuracy was based on the uncertainty of three separate measurements: photograph magnification, particle transit time, and image string length. For this study the transit time was measured electronically and automatically with an accuracy equal to that of the power line frequency. A conservative value of 1 part in 60 was assumed for the analysis. The total magnification of the photographs was determined from physical measurements and was repeatable to approximately $\pm 1.0\%$. The remainder of the uncertainty was attributed to the image string length. Although a micrometer accurate to ± 0.025 mm was used for these measurements, the center-to-center distances between images were repeatable to ± 0.254 mm.

The voltage and current into the melter model were sensed by transformers accurate to $\pm 2.0\%$ and $\pm 3.0\%$, respectively. The remainder of the uncertainty was due to the power transducer.

All measurement devices used in this study, except the thermocouples imbedded in the model, were individually calibrated against instruments traceable to the National Bureau of Standards by Hanford Engineering Development Standards Laboratory.

4.5 OPERATING CONDITIONS

The operating conditions for the physical model data runs were appropriately scaled from a set of "typical" LFCM prototype operating conditions using the scaling factors of Table D-3 and D-4. These conditions shown in Table 4-3 were assembled from a variety of sources as there were not enough data from any given run to completely describe the temperatures, power settings, feed rates, and heat losses needed for accurate physical modeling. However, the prototype feed rates, electrode temperatures, and power settings were usually known for each run and the wall temperatures were measured on a

TABLE 4-3. Typical Prototype Operating Conditions

<u>Type</u>	<u>Material</u>	<u>Feeding Rate (ℓ/hr)</u>	<u>Total Electrode Power (kW)</u>	<u>Temperatures (°C)</u>			<u>Bulk Fluid</u>
				<u>Electrodes</u>	<u>Walls</u>	<u>Top</u>	
A	Liquid	Not Deter- mined	70.0	1038	1061	797	1125
B	Calcine	Not Deter- mined	80.0	1050	1070	700	1140
C	—— Idling ——		50.0	900	950	875	950
D	Liquid	100.0	90.0	1050	1070	770	1100

few occasions by pushing a thermocouple attached to an inconel rod against the inside refractory surface. This technique was also used periodically to sample the molten glass or cold cap temperatures. Due to the extra water-cooling in the electrodes, they were always cooler than the heavily insulated walls by approximately 20 to 50°C, so a corresponding temperature difference was maintained in the model.

The cold cap or crust on top of the molten glass in the prototype was much more difficult to model. In general, the cold cap material exhibited nearly uniform temperature somewhere between 300°C and 700°C depending on the feeding conditions, except for the thin layer just above the melt line where the temperature approached the average bulk glass temperature. Moreover, heat losses through the crust were unpredictable for calcine feed runs and poorly defined for most liquid feed cases. These cold cap properties made the selection of a characteristic temperature for modeling difficult. However, it was generally accepted that most of the heat losses in the prototype melter, perhaps 75% or more, were through the cold cap. On this basis it was decided to operate the top cooling jacket in the model as cold as possible with the existing equipment, approximately 12°C to 20°C. This would assure that most of the heat losses in the model would also be through the top because the temperature gradient in the vertical direction would be at least twice that of the horizontal gradient.

The floor of the LFCM was relatively well-insulated by dead airspace and layers of block insulation. However, the floor of the model could not easily be correspondingly well-insulated and still provide a window for the laser light sheet. An early version of the physical model was constructed with a double thickness floor as a cooling water jacket. This was not acceptable for photographic lighting due to bubble accumulation in the gap. The model used in the present study had a single thickness of plexiglass skirted by the support stand, which reduced forced convection cooling of the model floor. This second model was much more satisfactory for using the laser lighting technique. Calculations indicate that the relatively low heat loss from the bottom of the model due to free convection adequately simulated the well-insulated bottom in the prototype.

All but one of the physical model data runs reported here were zero throughput with no simulated feeding. The early phase of the PNL physical modeling program was devoted to the development of modeling techniques, more easily accomplished without the complication of simulated feeding. However, an average prototype liquid feed rate was selected for study in one model run. A small metering pump was used to transfer modeling fluid from the melter cavity through a closed loop and deposit it on the center of the top cooling jacket. This procedure allowed the modeling fluid to gradually cool to the top temperature and helped reduce jetting of cold fluid downward through the holes in the top jacket.

A flat cooling jacket was used on the top of the model to simulate both calcine and liquid feed cold caps during most model runs. This reasonably approximated the liquid feed case but probably was not prototypic of the calcine feed crust. Calcine feed cold caps were known to extend as much as 20% of the maximum glass depth into the melting cavity, much like a floating membrane weighted in the center. This was due to the calcine piling up in the center of the prototype cold cap during feeding and pushing down on the underlying material. A special top cooling jacket (Section 4.2) with a curved lower surface simulated a prototype calcine crust for one of the steady-state model data runs.

4.5.1 Data Run Matrix

A comprehensive model data run matrix with measured data is presented by Table 4-4. All of the controlled variables are shown along with several of the resulting dependent parameters. The latter are the power supply voltage and current and the bulk fluid temperature. Model fluid depth for $\epsilon_L = 0.27$ model LFCM runs was $D = 13.02$ cm and for $\epsilon_L = 0.33$ model CFCM runs $D = 10.16$ cm. These corresponded to prototype glass depths of 48.3 cm and 30.5 cm, respectively. The actual operating conditions shown were attempts to simulate the corresponding prototype cases identified in the second column (see Table 4-3). Using the proper scaling factors from Tables D-3 and D-4, these model parameters were converted into prototype values, shown in Table 4-5. All model runs except 015 used $T_{po} = 1100^\circ\text{C}$. Exact temperature matching for 015 was $T_{po} = 950^\circ\text{C}$. If the model and modeling fluid combination correctly simulate the prototype, then the values shown in Table 4-5 represent the full-scale operating conditions modeled. However, this study did not prove the accuracy of the scaling factors because there were insufficient prototype data for comparison with the model data. The proper scaling criteria were identified and the scaling factors were correctly derived but the boundary conditions and glass properties were not known well enough to guarantee accurate scaling. The preceding qualification applies to all of the prototype values predicted from model data reported in this study.

4.5.2 Operating Procedures

A typical model data run consisted of four separate operational phases. The prerun was used to set up the modeling apparatus with the proper electrodes, modeling fluid, thermocouples, and top cooling jacket. During this time the water jacket storage reservoirs were brought to the desired temperature and the data acquisition system programmed to collect the necessary data. Six type T thermocouples were lowered through the top water jacket into the model fluid along $Y^* = 0.500$ to a depth of $Z^* = 0.500$. This was the reference position for the fluid temperatures reported in Table 4-4.

The next phase began with adjusting the electrode power supply to maximum power output (220 vac) and simultaneously starting the circulation of

TABLE 4-4. Physical Model Data Run Matrix

Run Number	Prototype Simulated	Model Fluid	Electrodes		Average Total Power ^(a) (W)	Upper Electrodes ^(a)			Lower Electrodes ^(a)			Average Temperature (°C)			
						Power (W)	Volts (VAC)	Current (A)	Power (W)	Volts (VAC)	Current (A)	Electrodes ^(b)	Walls ^(c)	Top ^(d)	Bulk Fluid ^(e)
003	A	1	Bar	0.27	286.8	286.8	87.03	3.55	Connected to Upper Electrodes			58.3	62.0	18.80	72.5
004	A	1	Bar	0.27	286.9	216.0	80.79	2.69	70.9	58.42	1.23	58.0	62.0	19.05	64.5
005	A	1	Bar	0.27	286.7	72.0	63.52	1.13	214.7	95.21	2.38	58.1	62.0	21.46	70.0
006 ^(f)	B	1-2 ^(g)	Bar	0.27	331.8	249.7	91.17	2.76	82.1	84.06	0.96	60.8	63.5	19.43	70.1
012	A	2	Plate	0.33	384.9	384.9	140.13	2.94				41.2	45.5	12.26	65.8
014 ^(h)	D	3	Plate	0.33	492.9	492.9	141.96	3.75				46.3	50.2	17.48	74.1
015	C	2	Plate	0.33	325.3	325.3	172.31	1.97				25.2	28.3	14.98	55.8

- (a) During temperature profile and flow field measurements.
(b) Average of 3 left and 3 right electrode temperatures at $Z^* = 0.5$ depth.
(c) Average of 6 front wall and 6 back wall temperatures.
(d) Average of cooling flow inlet and outlet.
(e) Average of 6 thermocouples along the model centerline $Y^* = 0.5$ at $Z^* = 0.5$ depth.
(f) Convex top.
(g) Run 006 started with MF-1; accidental water discharge into MF-1 resulted in MF-2.
(h) Feed rate = 49.27 ml/min.

TABLE 4-5. Prototype Operating Conditions Corresponding to Model Data Run Matrix

Model Run Number	Electrodes Type	Feed Rate (g/hr)	Average Total Power (kW)	Upper Electrodes			Lower Electrodes			Average Temperatures (°C)			
				Power (kW)	Volts (VAC)	Current (A)	Power (kW)	Volts (VAC)	Current (A)	Electrodes	Walls	Cold Cap	Bulk Glass
003	Bar	0.0	69.95	69.95	135.8	515.1	Connected to Upper Electrodes			1038	1060	797	1124
004	Bar	0.0	69.98	52.68	126.0	418.1	17.29	91.1	189.8	1036	1060	798	1076
005	Bar	0.0	69.93	17.56	99.1	177.2	52.37	148.5	352.7	1037	1060	813	1109
006	Bar	0.0	77.16 ^(a)	58.07	136.5 ^(b)	425.4	19.09 ^(a)	125.8 ^(b)	151.8	1070 ^(c)	1085 ^(c)	828 ^(c)	1124 ^(c)
012	Plate	0.0	69.98	69.98	153.3	456.5	--	--	--	1040	1064	878	1177
014	Plate	99.5	89.62	89.62	148.8	602.3	--	--	--	1051	1073	888	1208
015	Plate	0.0	49.29	49.29	199.7	246.8	--	--	--	933	950	876	1103

(a) Average of MF-1 and MF-2 power scale factor, $\epsilon_p = 0.0043$

(b) Average of MF-1 and MF-2 voltage scale factor, $\epsilon_v = 0.668$

(c) Average of MF-1 and MF-2 temperature scale factor, $T_p = 5.840 T_M + 714.560$

preheated water through all water jackets except the top. At this point the data acquisition started scanning at 3.0-minute intervals. When the model fluid temperature exceeded the wall temperatures, the top cooling jacket flow was gradually brought up to full flow. Electrode power was gradually decreased to the level required by the run plan and the model fluid temperature was allowed to seek its final steady-state value at the reference position described above. Warmup was always accompanied by expansion of the modeling fluid which flowed out the overflow tube. However, the design of the overflow maintained the proper operating level. This warmup phase usually required 3 to 4 hours and ended when the model fluid temperature and electrode voltage stabilized. However, at no point during any of the model data runs was a well-ordered steady-state fluid flow pattern achieved. (See Section 5.0.) The criteria for beginning the temperature and flow field measurements were the onset of steady time-averaged fluid temperature at the reference position $Y^* = 0.500$, $Z^* = 0.500$ and steady power supply voltage. The term "steady" applied to temperature refers to the fact that the mean of the temperature fluctuations was constant with time.

The third operational phase followed, characterized by steady-state power input and fluid temperatures, during which fluid temperature profiles and flow patterns were measured. The six thermocouples inserted through the top water jacket were adjusted as a unit with a special holding jig to simultaneously sample six X locations at a given Z elevation. Occasionally, a free thermocouple was used to probe other regions of the model but the limited number of data logger channels (60) prevented using more than seven thermocouples for fluid temperature measurement. The data logger was operated in the interval scan mode with data collected automatically every 3.0 minutes. This interval was much greater than the response time of the thermocouples so that only thermal transients on the order of 3.0 minutes or longer were measured. However, at least three complete data logger scans were completed before moving the thermocouples to a new position. This allowed some determination of temperature ranges and random fluctuations.

Photographic flow field measurements were made concurrently with and following the fluid temperature measurements. The camera system and laser light sheet were aligned and the position of the light sheet relative to the origin was determined. Photographs were taken along $Y^* = 0.257, 0.500,$ and 0.743 during and after the period when thermocouples were inserted into the fluid to measure the effect of their intrusion on the flows. Each photograph was accompanied by a measurement of the camera magnification and the distance from the lens to the light plane. The usual practice was to shoot strobe and streak photographs back-to-back using ASA 400 Polaroid film. Then each shot was duplicated using Plus X sheet film (ASA 125). Occasionally, the still camera with the roll film back or a special animation movie camera was used to provide nearly real time streak records of the physical model flow patterns. These latter two photograph types were quite useful for studying the larger-scale circulations and for providing some insight into the flow perpendicular to the plane of the light sheet (the Y component). The Y component could be estimated from the residence time of the particles in the light sheet.

A cooldown period completed each model data run, during which the plexi-glass model was allowed to cool gradually to room temperature. The data acquisition system, which had been scanning continuously since the beginning of the warmup phase, was then reset and unloaded. A model data run usually required approximately 9 to 12 hours for completion.

Post-run operations consisted of reducing the magnetic data tape on a PDP 1170 computer and processing the photographic film. (All film processing, printing, and movie production were handled by specialists from PNL Photography.) Spot checks of model fluid resistivity, viscosity, and density were also made periodically but no significant changes in any of these properties were seen except following model Run 006. During that experiment the top cooling jacket cracked and an unknown quantity of water mixed with the MF-1 in the model. Subsequently, samples of the resulting fluid were heated to approximately 120°C for several hours to drive the water off. However, the

water had apparently combined permanently with the MF-1 and would not bake out of solution. The fluid was labeled MF-2 and used successfully for several more data runs.

5.0 EXPERIMENTAL RESULTS AND DISCUSSION

The fluid temperature profiles and flow field measurements for the seven physical model data runs listed in Table 4-4 are presented in this section. Due to the symmetry and uniformity of the data, only those temperature and velocity profiles that illustrate significant differences are included. The discussion is grouped according to the four sets of typical prototype operating conditions A through D described in Table 4-3. Observations of particle settling and a brief summary of electric field measurements are also included in separate subsections.

5.1 STEADY-STATE FLAT TOP CALCINE FEED SIMULATION

Four model data runs, 003, 004, 005, and 012, were completed using the set of typical prototype operating conditions designated type A in Table 4-7. The first three cases modeled an LFCM at $\epsilon_L = 0.27$. The last case attempted to simulate the same boundary conditions at $\epsilon_L = 0.33$ in a CFCM (see Section 2.7). Runs 003, 004, and 005 can be compared directly to study the effects of electrode firing pattern. These three can also be compared to data Run 012 for some insight into the effects of electrode configuration on the temperature and flow profiles.

5.1.1 Temperature

Model fluid temperature profiles for selected X^* , Y^* locations are shown in Figures 5-1 to 5-4. X , Y , and Z were nondimensionalized with the maximum length in the corresponding direction. Each figure also illustrates the corresponding prototype temperatures predicted. These were time averaged temperatures measured over a time period of three data logger scans, 9.0 minutes. A typical variation of temperature with time trace is shown in Figure 5-5. The model fluid temperature was nearly uniform across a given horizontal X - Y plane for the six steady-state cases studied and was symmetric about $X^* = 0.500$. Figure 5-4 illustrates the typically small variation observed for Run 012. The $Y^* = 0.500$ plane results were normally the only location plotted. However, Appendix D provides a complete listing of all the model fluid temperatures measured for each case.

FIGURE 5-1. Data Run 003, $Y^* = 0.500$ Temperature Profiles
Bar Electrodes, Flat Top, Uniform Power Input

FIGURE 5-2. Data Run 004, $Y^* = 0.500$ Temperature Profiles
Bar Electrodes, Flat Top, Upper:Lower Power
Ratio = 3:1

FIGURE 5-3. Data Run 005 $Y^* = 0.500$ Temperature Profiles Bar Electrodes, Flat Top, Upper:Lower Power Ratio = 1:3

FIGURE 5-4. Data Run 012 Temperature Profiles Plate Electrodes, Flat Top

FIGURE 5-5. Time Variation of Model Fluid Temperature
 $Y^* = 0.500$, $Z^* = 0.683$

The relatively flat profiles for bar electrode Cases 003, 004, and 005 near the center and close to the electrodes indicate that the modeling fluid was well mixed. On the other hand, the greater curvature of the profiles in Figure 5-4 suggests that the flows for the plate electrode data Run 012 were more structured and less well mixed. The difference between the temperature profile near the center and that near the electrodes in Figure 5-3 was probably due to the general large-scale counterrotating eddies that were observed (see Section 5.1.2). The fluid upwelling near the center smoothed the vertical temperature gradient and somewhat flattened the profile into a more nearly uniform distribution.

The temperature profiles at the center of the model were converted into corresponding prototype values for all four cases and plotted on Figure 5-6. This figure shows the effects of electrode firing pattern in Cases 003, 004, and 005 for the same boundary conditions and energy input. The amount of mixing and the proximity of the heating zone to the heat sink determined the

FIGURE 5-6. Comparison of Data Runs 003, 004, 005, 012 Prototype Temperature Predictions, $X^* = Y^* = 0.500$

shape of the fluid temperature profile and the average model fluid temperature. For example, during model Run 004 75% of the energy input was to the upper third of the fluid directly below the top cooling jacket. Heat was removed quickly because the source was near the sink. Consequently the average fluid temperature was relatively low.

As the ratio of upper electrode power to lower electrode power was reduced to a uniform power distribution for Run 003, heat was generated uniformly throughout the fluid causing the average temperatures to be higher than for Case 004. Moreover, the uniform heating seemed to reduce the amount of fluid mixing near the top resulting in a lower temperature gradient in that region compared to the unbalanced power cases. The net effect was higher internal fluid temperatures compared to Cases 004 and 005.

When the upper to lower power ratio was reduced still further to a 1:3 distribution in Run 005 the average fluid temperatures dropped below those of the uniform power distribution but remained higher than Case 004. This

unusual result was probably caused by a combination of two effects induced by increasing the heat addition in the bottom fluid layers. First, the top heat sink was much further away from the heat source. This elevated the average temperatures above those in data Run 004. However, an unstable density gradient was imposed by warming the fluid below the cooler top layers. This apparently created higher convective flows and greater mixing so that the average temperature was lower than the uniform power Case 003.

Using a nondimensionalizing scheme suggested by Kulacki and Nagle,⁽¹²⁾ the fluid temperature measurements from Runs 003, 004, 005, and 012 were plotted on the same set of axes in Figure 5-7. This figure provides some insight into the effects of electrode configuration and firing pattern discussed previously. Here the temperature difference between a point in the fluid and the average temperature of the top cooling jacket ($T - T_t$) was nondimensionalized with the average volumetric heat generation rate, H , fluid depth, D , and fluid thermal conductivity. When plotted in this fashion the

FIGURE 5-7. Data Runs 003, 004, 005, 012 Nondimensional Temperatures, $X^* = Y^* = 0.500$

data for Cases 003 (bar electrodes, uniform power input) and 012 (plate electrodes) collapse to essentially the same dimensionless temperature. This implies a certain degree of similarity in the thermal/hydraulic phenomena. However, the more uniform temperature profile observed in Case 003 suggests better mixing, an interpretation reinforced by examination of the streak and strobe photographs in the following section. The significance of these findings is discussed later.

The data for Cases 004 and 005 are also plotted in Figure 5-7 for reference. Because these data are for significantly different power input distributions they do not collapse on the same curves as 003 and 012. However, they retain their same relative positions at lower average temperatures.

5.1.2 Flow Field and Velocity

Selected streak and strobe photographs from model data Runs 003, 004, 005, and 012 are reproduced in this section along with detailed mean velocity measurements. All photographs were taken at least 3.0 hours after the onset of the steady-state temperature and power conditions described in Section 4.5.2. None of the seven experimental run conditions investigated during this physical modeling study resulted in stable or coherent flows. The flow patterns continually changed in time and space, except for the plate electrode cases where the bottom half of the flow field appeared to be relatively stable.

Visual observations at angles to the laser light sheet and movies produced with a special animation movie camera confirmed that the flows were three-dimensional. This was the reason for the apparent chaos observed in the two-dimensional data plane utilized for this study. This high degree of three-dimensionality prevented the growth of stable longitudinal roll cells like those reported for externally heated natural convection in an enclosure.⁽¹³⁾ Any of the eddies or cells observed in the photos at the end of this section were only temporary and either disappeared because the light-scattering particles left the light sheet or the flow itself changed.

Figure 5-8 illustrates the continuously evolving flow patterns for Case 012. These eight consecutive 30-second exposures, starting with (a) were shot 15 seconds apart. The first three photographs show thermocouples inserted into the model fluid slightly behind the light sheet. These were withdrawn between exposures (c) and (d) to study their effect on the flow field. The thermocouple probes caused a slight increase in the scattered light but did not appear to adversely affect the flows near the top. This was due primarily to the continuously changing flow patterns. Note that the only portion of the flow that does not appear to be time dependent is for $Z^* < 0.500$.

Figures 5-9 and 5-10 show the instantaneous flow field in $Y^* = 0.518$ near the left-hand electrode for model Run 003 (bar electrodes, uniform power) at two different times. Both illustrate a characteristic general flow pattern exhibited by most of the photographs taken during this study, i.e., downwash at the relatively cool electrode face and lateral flow across the model floor toward the center. At the center the two fluid streams from each half of the model collided, causing an upwelling of warm fluid that gradually cooled as it travelled slowly along the top cooling jacket toward the electrode. This large-scale motion was difficult to observe directly in real time because of the interference of the numerous small-scale eddies, but it is apparent in most of the time elapse pictures reported here.

Some of the model features seen in these photographs are the thermocouples imbedded in the floor just below the lower edge of the light sheet, front and back wall thermocouples running vertically upward from the photo midplane, and the overflow tube nozzle (white and black rings in background). Occasionally a few of the screws in the outer box appear in the extreme foreground and background. In some instances, such as Case 003, there were air bubbles in the side wall cooling jackets stuck to the outer surface of the model cavity. Most photographs also contain bright reflections from air bubbles on or inside the top cooling jacket. This latter problem was never successfully eliminated from any of the model data runs.

a.

b.

c.

d.

e.

f.

g.

h.

FIGURE 5-8. Data Run 012 Sequential Streak Photographs, $Y^* = 0.522$, $t = 30$ sec, $\Delta t = 15$ sec

The relatively poor quality streaks and dot strings in Figures 5-9 and 5-10 were caused by using carbon particles that were too small to function effectively as light scatterers. It may be possible to use optical and/or digital image enhancement to improve the resolution of photographs like these, but such techniques were not available at the time of this study.

Figure 5-10a is the actual strobe photo and Figure 5-10b shows tracings of selected image strings on an X^*-Z^* coordinate system drawn to the same scale as the strobe photograph. Each image string is labeled and the corresponding mean velocity is tabulated at the right of the figure. The arrows indicate the direction of motion.

Case 004 (3:1 power ratio) exhibits an interesting departure from the flow pattern observed for Run 003. The streak lines in Figures 5-11 and 5-12 suggest the large cell occupying the left half of the model fluid rotated clockwise, creating an upwash a short distance in front of the electrodes. However, this flow was countered by small cells circulating in the opposite direction against the face of the electrodes and above the intersection of the two large cells from each side. The flow at points N and I, Figure 5-12b, seems to oppose the general pattern described above and illustrates the three-dimensionality of the flow.

Few if any stable circulation regions were observed for the upper:lower power ratio 1:3, data Run 005. Figure 5-13 is typical of the random, turbulent fluid motion which resulted from powering the lower electrodes at three times as high as the upper electrodes. The predominance of near-vertical streaks indicates mostly vertical local mixing without the large cells observed in the other cases. This might indicate a cell structure extending from the bottom to the top of the fluid. Such an interpretation is consistent with the corresponding strobe photograph, Figure 5-14a. In particular, the region around $X^* = 0.200$, $Z^* = 0.900$ and $X^* = 0.600$, $Z^* = 0.800$ exhibits the effect of a strong Y velocity component. The area

$X^* < 0.250$, $Z^* < 0.800$ did not contain any satisfactory image strings due apparently to a localized reduction of scattering centers during the exposure.

Figure 5-15 was included to show the symmetry of the flow field characteristic of the CFCM model plate electrode configuration. This particular photograph lacks good definition in the left-most quarter of the model but has enough streaks to show that the uniform, well-defined flow in the lower half of the model is similar for either half. Similar photos taken in the model LFCM using bar electrodes do not show the same degree of instantaneous symmetry. However, because there is overall symmetry in the model geometry and boundary conditions it is reasonable to assume a time averaged symmetry existed for the bar electrode configuration.

The photographs in Figures 5-15 and 5-16 both illustrate the characteristic flow pattern achieved with the plate electrodes: downward flow at the electrodes, coherent laminar-like flow along the floor, upwelling near the center, and turbulence in the upper half of the model. The upwelling near the center has a strongly pronounced backward sweep toward the electrodes. This overall large-scale circulation was apparently quite stable because it is seen in varying degrees in later photographs.

The distinctly different flow patterns observed in the bar and plate electrode models were apparently caused by the different electric potential fields and corresponding heat flux distributions. However, the phenomena are not understood sufficiently to explain the observed difference.

A strobe photograph and corresponding vector plot for data Run 012 are shown in Figure 5-17. These data illustrate the magnitude of velocities present during the exposure.

FIGURE 5-9. Data Run 003 Streak Photographs, $Y^* = 0.518$,
 $t = 30.0$ sec (uniform power input)

a.

b.

LOCATION	U mm/sec
A	0.279
B	0.254
C	0.457
D	0.152
E	1.372
F	1.397
G	0.889
H	0.965
I	0.178
J	0.279
K	0.584
L	0.508
M	0.457
N	0.559
O	1.067
P	1.194
Q	1.372

FIGURE 5-10. Data Run 003 Strobe Photograph and Vector Plot, $Y^* = 0.518$, $t = 1.0$ sec, $\Delta t = 5.0$ sec (uniform power input)

FIGURE 5-11. Data Run 004 Streak Photograph, $Y^* = 0.534$,
 $t = 2.0$ min (3:1 power ratio)

a.

b.

FIGURE 5-12. Data Run 004 Strobe Photograph and Vector Plot,
 $Y^* = 0.518$, $t = 1.0$ sec, $\Delta t = 5.0$ sec
 (3:1 power ratio)

FIGURE 5-13. Data Run 005 Streak Photograph, $Y^* = 0.527$,
 $t = 2.0$ min (1:3 power ratio)

a.

b.

FIGURE 5-14. Data Run 005 Strobe Photograph and Vector Plot, $Y^* = 0.527$, $t = 1.0$ sec, $\Delta t = 5.0$ sec (1:3 power ratio)

FIGURE 5-15. Data Run 012 Streak Photograph, Full View
 $Y^* = 0.535$, $t = 2.0$ min

FIGURE 5-16. Data Run 012 Streak Photograph,
 $\gamma^* = 0.522$, $t = 2.0$ min

a.

b.

FIGURE 5-17. Data Run 012 Strobe Photograph and Vector Plot,
 $Y^* = 0.522$, $t = 1.0$ sec, $\Delta t = 10.0$ sec

5.2 STEADY-STATE CONVEX TOP CALCINE FEED SIMULATION

The effects of cold cap intrusion into the melting zone were studied in model Run 006. Boundary conditions and power inputs were scaled from the type B prototype conditions, Table 4-7. The curved lower surface of the special top cooling jacket, the simulated melt line, protruded approximately 20% of the fluid depth into the model melter cavity. Figure 5-18 presents the fluid temperature profiles for three X^* locations along the model centerline. The arrows trailing from the plotting symbols indicate the penetration of the simulated melt line relative to the corresponding temperature measured. The effect of the convex top water jacket is clearly indicated as a decrease in the local fluid temperature compared to the region outside the simulated cold cap intrusion. Note, however, that the fluid temperature in the lower half of the fluid was not affected by the decreased fluid depth even at the center of the tank. When compared to the temperature profiles in Figure 5-2 for Run 004, the general shape of both profiles are similar in the lower half of

FIGURE 5-18. Data Run 006, $Y^* = 0.500$ Temperature Profiles, Bar Electrodes, Convex Top, Upper:Lower Power Ratio 3:1

the fluid. The increased cooling depth provided by the convex top affected only the upper 50% of the fluid. In that region the temperature gradients for Run 006 were more gradual than the flat top case.

The corresponding prototype cold cap temperature was nearly uniform at $T_p \approx 847^\circ\text{C}$ substantially higher than the desired value of $T_p = 700^\circ\text{C}$. This was due to inadequate cooling for the top water jacket. However, sometime during the run a small crack opened around one of the drywell thermocouple penetrations and leaked an undetermined amount of water into the model fluid MF-1. Therefore the fluid properties during data Run 006 were assumed to be the average of MF-1 and the resulting fluid MF-2. Attempts to bake off the water in the MF-2 by heating the fluid to 120°C for prolonged periods failed to reduce the fluid back to MF-1. Consequently, it was used as MF-2 for model Runs 012 and 015.

The general circulation pattern described in Section 5.1.2 for Cases 003 and 012 was also evident for data Run 006 (Figure 5-19). The cells were smaller and less structured in the latter case and the flow across the floor was more chaotic. There were three clearly defined counterrotating cells in $Y^* = 0.530$ at the time of the photograph as well as some apparent three-dimensional motion around $0.500 < X^* < 0.600$. One narrow cell extending from floor to top rotated clockwise in front of the electrodes. Centered around $X^* = 0.700$, $Z^* = 0.500$ was a larger counterclockwise circulation with a diameter approximately equal to the fluid depth. The third cell was less evident than the other two but appears in the upper left-hand portion of the photograph. Combination of those flows apparently subdued the lateral fluid motion across the floor of the model seen in Figures 5-9 and 5-16. The principal effect of the convex top was to break up the relatively large circulation pattern seen in Figure 5-11 for a similar 3:1 power case into smaller, more three-dimensional eddies.

FIGURE 5-19. Data Run 006 Streak Photograph, $Y^* = 0.530$,
 $t = 30.0$ sec (3:1 power input ratio)

Figure 5-20 presents the strobe photograph and corresponding vector plot for data Run 006. Again, this figure illustrates the magnitude of the velocities at various locations in the model.

5.3 IDLING SIMULATION

Typical LFCM idling conditions were modeled by data Run 015 using plate electrodes and temperature correspondence based on $T_{po} = 950^{\circ}\text{C}$ (CFCM idling data were not available until after Run 015). Results of the fluid temperature measurements are shown in Figure 5-21 for a vertical profile near the model center and another near the electrode. A temperature profile from an actual LFCM idling run and a CFCM idling run are included on the figure for comparison. The modeling results compare favorably to the CFCM data despite the difference in glass composition, power input, and boundary conditions modeled by Run 015. This indicates that the CFCM model reasonably simulates the prototype melter. The LFCM data were included on Figure 5-21 to demonstrate that the effects of electrode configuration on the temperature profiles observed for model Runs 004 and 012 were consistent with temperature measurements in the two prototype furnaces.

Figures 5-22 and 5-23 contain the flow field information for the idling simulation, model Run 015. A streak photograph for the data plane around $Y^* = 0.500$ was not available but would be nearly identical to Figure 5-22, based on past experience with data Run 012. In fact, the only significant difference between these results and Case 012, Figures 5-16 and 5-17, is the magnitude of the velocities. The velocities in the simulated idling case were generally slower than Run 012 by at least 10%. This was a consequence of the lower temperature gradients of an idling melter. (Recall the average fluid temperature for Case 015 was approximately 10°C lower than for Case 012.)

a.

b.

FIGURE 5-20. Data Run 006 Strobe Photograph and Vector Plot,
 $Y^* = 0.530$, $t = 1.0$ sec, $\Delta t = 5.0$ sec
 (3:1 power input ratio)

FIGURE 5-21. Data Run 015, Idling Temperature Profiles Compared to LFCM and CFCM Data

5.4 LIQUID-FEED SIMULATION

Standard procedure during prototype liquid fed operations was to maintain a pool of liquid over the molten glass. The result was a shallow cold cap covered by a rapidly boiling, chaotic layer of liquid feed, an impossible condition to simulate in the model. The nearest approximation to these conditions was to pump the modeling fluid from the overflow drain through a long hose and dump it into the center of the top cooling jacket. No LFCM feed or cold cap temperatures were available for setting up the model but it was assumed that the top should be as cold as possible to simulate the high heat losses suggested by other prototype data. The long tube leading to the feeding point helped cool the model fluid below the average temperature in the model tank but not low enough to immediately cause jetting through the top water jacket holes. Instead, the relatively warm fluid tended to flow over

FIGURE 5-22. Data Run 015 Streak Photograph, $Y^* = 0.766$,
 $t = 2.0$ min (Idling simulation)

a.

b.

LOCATION	U mm/sec
A	0.533
B	0.102
C	0.114
D	0.066
E	0.046
F	0.737
G	0.079
H	0.124
I	0.213
J	0.066
K	0.269
L	0.036
M	0.056
N	0.086

FIGURE 5-23. Data Run 015 Strobe Photograph and Vector Plot, $Y^* = 0.520$, $t = 1.0$ sec, $\Delta t = 10$ sec (Idling simulation)

the cold top before gradually cooling enough to flow through the perforations. This procedure was reasonably successful although substantial quantities of modeling fluid also flowed around the front and back edges of the top cooling jacket and down the walls of the model. The resulting density gradients near the front wall made observation of the interior flows difficult.

Fluid temperatures measured along $Y^* = 0.257$ are shown in Figure 5-24 both for the steady-state case prior to feeding and for the feeding case. This data plane was chosen for study because it was near the model overflow drain, and the apparatus holding the fluid thermocouples would not interfere as greatly with the fluid discharged on the top water jacket. It was not surprising to observe such small changes in the temperature profile. The simulated feed rate was much smaller than the average fluid velocity in the

FIGURE 5-24. Data Run 014, $Y^* = 0.257$ Temperature Profiles Plate Electrodes, Flat Top

model so that the effects of throughput were minor. Some decrease in temperature near the top was noted but it was apparent that the feeding simply induced greater mixing near the floor. The net result was that temperatures there actually increased slightly over the steady-state, no-feed case. If this were prototypic it would indicate that higher feed rates could be employed without adversely affecting melter temperatures.

The photographic plane $Y^* = 0.257$ was selected for its proximity to the overflow tube nozzle and because correspondence with the temperature measurements was desirable. The camera's electronic strobe timing system malfunctioned during the test so only the streak photographs in Figures 5-25 and 5-26 are available. The former illustrates the no-feed "steady-state" flow field just prior to starting throughput. Notice the uniform region near the floor and turbulent structure near the top characteristic of the model CFCM. The bright flash near the upper middle of the photo was caused by a persistent air bubble attached to the top cooling jacket. Figure 5-26 shows the same data plane $Y^* = 0.257$ approximately 2.0 hours after feed startup. Recall that the model fluid was being deposited at $X^* = Y^* = 0.500$ and spread over most of the top cooling jacket before flowing through the perforations into the model cavity. The primary effects of the fluid throughput were felt in the uniform flow region below $Z^* = 0.500$ where the vertical component of the fluid velocity increased relative to the horizontal component. Streak lines curve sharply upward along $Z^* \approx 0.300$ in Figure 5-26 and continue vertically for an appreciable distance before becoming mixed in the upper flow region. This apparent increase in vertical flow may have been simply the distortion of the streak lines in Figure 5-25 caused by drawing the fluid toward the overflow. Figure 5-26 does not show the penetration of cold fluid into the uniform flow zone or the expected disruption of that region with increased mixing. The only obvious difference between the two photos, except where noted previously, is the bright band of closely spaced streaks near the model midplane. Their appearance suggests a high concentration of light-scattering particles, which could not be explained by any of the observations made during Run 014. The fuzzy appearance of some of the streaks was due to

FIGURE 5-25. Data Run 014 Streak Photograph, No Feed,
 $Y^* = 0.276$, $t = 2.0$ min

erratic thermal gradients near the front wall caused by cold fluid flowing down the wall and mixing unevenly with the warmer fluid in the model cavity.

5.5 PARTICLE SETTLING

A primary impetus for conducting a physical modeling study of the waste fixation glass melting process was the question of unmelted particulates, especially heavy metals, settling out of the melt. It was suggested that these particles could eventually form a continuous conductive layer across the floor of the melter, thus providing a short between the lower electrodes (or between the plates). This could lead to catastrophic failure of the furnace due to overheating the floor and the electrodes. Physical modeling was

FIGURE 5-26. Data Run 014 Streak Photograph, Feeding,
 $Y^* = 0.276$, $t = 2.0$ min

proposed to search the melter flow fields for areas of low velocity or poor mixing that would be candidates for particle buildup. If possible, actual particles of the proper size and density were to be added to simulate the fallout directly. However, this specific study has not yet been attempted due to changes in program priorities. Nevertheless, some insight into where particles settle out of the fluid was obtained by observing the accumulation of light-scattering particles that settled out of the fluid after several data runs. Figure 5-27 illustrates that particles tended to collect in front of the electrodes but were swept away from the base of electrodes by the relatively high velocity flow at the floor-electrode junction. It appears

FIGURE 5-27. Data Run 005 Particle Settling

that this would prevent the buildup of a continuous short circuiting layer although many more particles of the appropriate size and density would need to be added for conclusive results.

A potentially serious prototype operating problem also caused by particle settling was identified after the physical modeling program began. This was the accumulation of various nonmelting or nonreactive glass crystal phases in a sludge layer on the floor of the melter. The sludge not only decreased the working glass depth but also had the potential to severely restrict the flow of molten glass out of the overflow tube. Another problem associated with sludge buildup was a phenomenon labeled "reboil" by the prototype melter operators. This apparently occurs when the temperature of the sludge layer increases to the point where melting or chemical reaction begins and quantities of gas or other lightweight material are evolved. The resultant glass foaming creates serious operating problems and always drastically reduces the melter glass production rate. Figure 5-27 shows simulated sludge buildup in the earliest stage and suggests the possibility for a detailed particle settling study.

5.6 ELECTRIC FIELD

The electric field was probed at various locations in the model using either the fluid thermocouple sheaths or a special probe fully insulated except for the tip. In either case the results were essentially the same. One of the electrodes was chosen as a reference and the potential difference between that reference and a point in the model fluid was measured. For a given Y-Z plane parallel to the electrodes the potential was constant except in a narrow region against the front and back walls where the values dropped approximately 4 to 5% below the average potential. In every case the electric potential varied linearly between the electrodes regardless of flow or temperature conditions. It became apparent early in the course of this physical modeling study that there was little or nothing to gain from a detailed investigation of the electric field for melter configurations similar

to those described in Section 2.7. Therefore only periodic checks of the electric potential were made for the seven data runs described in Table 4-8. The results were always consistent with those described above.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study developed physical modeling techniques and apparatus for experimental analysis of joule heated ceramic glass melters designed for high level waste immobilization. The models were used to investigate the fundamental physical phenomena in melting glass for several prototype designs and simulated operating conditions. Data from this study cannot be used for quantitative analysis of prototype designs and operation without verification by the appropriate corresponding prototype melter and glass property data. However, the physical modeling data can be used for qualitative analysis and investigating trends while providing a data base for verifying analytical models. Conclusions that may be drawn from this study are of two types:

- conclusions relating to the general usefulness and applicability of the modeling technique
- conclusions based on model simulations of prototype designs and operating conditions.

These conclusions are summarized separately below, followed by recommendations to consider in future work in this area.

6.1 CAPABILITIES OF THE MODELING TECHNIQUE

Several aspects of physically modeling molten glass were developed and demonstrated in this study.

- Specialization of the generalized principles of similitude to joule-heated melting of glass resulted in the derivation of the appropriate modeling equations, scaling criteria, and temperature correspondence.
- Design, assembly, and successful operation of 1/3-scale transparent plexiglass models including water circulating apparatus, controlled power supplies, and sophisticated data acquisition systems, were demonstrated.
- Appropriate model fluid compositions, manufacturing procedures, and characterization techniques were developed.

- A narrow beam sheet laser optical system to illuminate the model interior for photographic studies was designed and applied.
- Neutrally buoyant, efficient light-scattering particles for flow visualization studies were developed.

The flexibility of the modeling apparatus to investigate a wide range of operating conditions and physical configurations was demonstrated during this study. Predetermined electrical power inputs and operating temperatures were routinely matched and could be replicated as desired. The techniques for measuring temperatures, fluid velocities, electrical power, and model fluid properties were highly successful. However, the uncertainty in determining and modeling the temperature and heat flux boundary conditions in the prototype was not resolved by this study. In addition, the only complete set of glass property data available did not correspond to the glasses used during the prototype operations documented. Until better prototype data are available the results of this modeling study must be considered qualitative within unproven quantitative accuracy.

6.2 EXPERIMENTAL RESULTS

The experimental results of the seven model runs were similar in several respects. In every case the temperature of the modeling fluid was nearly isothermal for a given horizontal plane. The temperature gradients were primarily in a narrow region near the walls. This was especially true for the LFCM bar electrode configuration where the temperature variation in the vertical direction was also minimal except for the upper 20% of the model fluid. The nearly uniform fluid temperatures were due to the well-mixed, essentially turbulent three-dimensional flows observed in the streak photographs and movies.

Despite the instantaneous random nature of the smaller eddies, a general overall circulation was implied by the data for most model runs. Flow was downward at the electrode faces, across the floor toward the center of the model and upwelling at the center. Only the CFCM plate electrode

configuration consistently produced a well-defined flow independent of the boundary and fluid temperature conditions. In those cases, the lower half of the modeling fluid continuously swept down the electrode face toward the model center. The steady flow appeared laminar in contrast to the turbulent upper fluid layers. Such flows produced relatively smooth vertical temperature gradients instead of the nearly isothermal conditions exhibited by the model LFCM cases.

Specific particle settling experiments were not conducted during this study. It is not known whether the fluid flow rates measured were high enough to keep nonbuoyant particles in suspension. Neither were enough heavy particles added to the fluid to conclusively identify where particles might accumulate in the long term. However, a minor deposit of nonbuoyant light-scattering particles did build up during some of the model runs. These were swept away from the base of the electrodes and tended to accumulate near the center of the model. The results indicated that the fluid circulation tended to sweep particles away from the electrodes but that a significant deposit near the model center was possible. The ramifications to melter operation are that the potential for accumulating particles on the floor near the electrodes may be reduced, thereby decreasing the likelihood of shorting the electrodes through a conductive layer along the floor. However, particle or sludge buildup on the floor, particularly in the center near the opening to the overflow drain, may be a potential threat to successful melter operation.

Additionally, more specific conclusions for each model data run are listed below.

Bar Electrodes/Flat Top

- For the same total power input and boundary conditions, uniform power to all electrodes produced higher fluid temperatures and more uniform flows than the unbalanced power input cases.
- The upper electrode/lower electrode power ratio of 3:1 significantly reduced the average fluid temperature below the 1:3 and 1:1 cases.
- The fluid flow for a 1:3 power input was highly mixed and more turbulent than the 3:1 and 1:1 cases.

Bar Electrodes/Convex Top

- The effect of the simulated calcine cold cap upon the model fluid temperature was not significant outside the immediate intrusion zone. Outside the cold cap intrusion the temperature profiles were nearly identical to the corresponding flat top case.
- Flows were more chaotic and the turbulent eddies smaller than the corresponding flat top case.

Plate Electrodes/Flat Top

- The lower half of the fluid flow pattern appeared entirely laminar, independent of boundary conditions, power input or simulated liquid feeding.
- Liquid feeding corresponding to a prototype feed rate of 100 l/hr did not significantly alter the average fluid temperature or flow pattern, except in the immediate vicinity of the overflow drain. A potential was indicated for substantially increasing the melter feed rate without adversely affecting performance.

6.3 RECOMMENDATIONS

Based on evaluation of the results of this study, it is recommended that the following actions and investigations be undertaken:

- It was not shown that the isothermal boundary conditions imposed by this study established prototypic heat losses through the boundaries of the model. Prototype wall temperatures and heat fluxes should be measured to provide better verification of the accuracy of the physical model.
- The VECTRA computer code is a two-dimensional analytical model. Physical model runs which are isothermal in the Y direction should be made to provide two-dimensional data for more direct comparison to the VECTRA predictions.
- The ability of the physical model to accurately predict prototype operating conditions should be proven before the model can become a reliable design tool. This will require significantly more prototype

operating and glass property data than were available at the time of this study. A complete set of measurements covering power input, heat balances, wall temperatures, glass temperatures, and glass properties should be attempted for at least one prototype run. The information could be used to verify both physical and analytical models.

- Particle settling and/or sludge buildup should be studied directly by observing the accumulation of the appropriate size and density particles during feeding in the physical model.
- New designs should be formulated and modeled to minimize the potential problems with melter operation identified by this study.

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APPENDIX A

NOMENCLATURE

APPENDIX A NOMENCLATURE

A = area

C = specific heat

D = fluid depth

Ec = Eckert number = $\frac{v^2}{C\Delta T}$

Ga = Galileo number = $\frac{gL^3}{v^2}$

Gr = Grashof number = $\frac{g\beta\Delta TL^3}{v^2}$

H = volumetric heat generation rate

L = a length or dimension

Nu = Nusselt number = $\frac{hL}{\lambda}$

P = pressure

Pe = Peclet number = $RePr = \frac{VL}{\alpha}$

Pr = Prandtl number = $\frac{\nu}{\alpha} = \frac{\mu C}{\lambda}$

Q = heat transfer rate

Re = Reynolds number = $\frac{VL}{\nu}$

Ra = Raleigh number = $GrPr = \frac{g\beta\Delta TL^3}{\nu\alpha}$

T = temperature

T_0 = reference temperature

$\vec{U}$ = dimensionless velocity = $\frac{\vec{v}}{U_0}$

U_0 = reference velocity

V = velocity, general; applied voltage

X = horizontal coordinate perpendicular to electrodes

X^* = dimensionless X coordinate = $\frac{X}{X_{\max}}$

Y = horizontal coordinate parallel to electrodes

$Y^* = \text{dimensionless } Y \text{ coordinate} = \frac{Y}{Y_{\max}}$

Z = vertical coordinate

$Z^* = \text{dimensionless } Z \text{ coordinate} = \frac{Z}{Z_{\max}}$

f = friction factor

$\vec{g} = \text{gravitation vector} = g\hat{n}$

g = gravitation constant

h = convective heat transfer coefficient

$\hat{n} = \text{unit vector}$

q = heat transfer rate per unit area

t = time

$\Delta t_0 = \text{reference time increment}$

u = velocity, X component

v = velocity, Y component

w = velocity, Z component

Greek Symbols

$\alpha = \text{thermal diffusivity} = \frac{\lambda}{\rho C}$

$\beta = \text{volume expansion coefficient}$

$\delta_i = \text{fraction of total heat loss through surface "i"}$

$\Delta = \text{denotes the difference in successive values of a variable}$

$\epsilon_i = \text{scale factor for "i" parameter (see Table 3-4)}$

$\epsilon_L = \text{scale factor for length}$

$\epsilon L' = \text{apparent scale factor} = \frac{(\nu_m \alpha_m)^{1/3}}{(\nu_p \alpha_p)^{1/3}}$

$\theta = \text{dimensionless temperature difference} = \frac{\Delta T}{\Delta T_0}$

$\lambda = \text{thermal conductivity}$

$\mu = \text{dynamic viscosity}$

$\nu = \text{kinematic viscosity} = \mu/\rho$

$\pi = \text{Pi} = 3.1416$

$\rho = \text{density}$

σ = electrical resistivity

τ = dimensionless time

γ_ϕ = dimensionless source, power number = $\frac{\phi_s L^2}{\lambda \Delta T}$

ϕ_s = volumetric heat source due to chemical reaction/nuclear decay/
electrical dissipation

γ_{ϕ_v} = dimensionless heat source due to viscous dissipation

∇ = gradient operator

γ_{∇} = dimensionless gradient operator

Subscripts

i = element "i" of a set

L = length (scale)

m = model property

o = reference condition

p = prototype property

sp = source term in the prototype

s = heat source

v = viscous source

x = horizontal coordinate perpendicular to electrodes

y = horizontal coordinate parallel to electrodes

z = vertical coordinate

APPENDIX B

DIMENSIONAL ANALYSIS

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DIMENSIONAL ANALYSIS

The characteristic dimensionless parameters that govern the flow and heat transfer processes in the model and in the prototype may be deduced by nondimensionalizing the governing differential equations and boundary conditions. As a starting point, we accept the generalized Navier-Stokes equations, which are specialized for application to the systems of interest in this analysis. The equations are then nondimensionalized by division with characteristic parameters derived from the geometry of the system. A similar process is followed with applicable boundary conditions. We begin with the governing equations for flow and heat transfer.

The generalized form of the Navier-Stokes equations⁽¹⁾ for variable properties may be given as

Conservation of Mass:

$$\frac{D\rho}{Dt} = -\rho(\nabla \cdot \vec{V}) \quad (B-1)$$

Conservation of Momentum:

$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \rho \vec{g} - \nabla \cdot \vec{\tau} \quad (B-2)$$

Conservation of Energy:

$$\rho \frac{Du}{Dt} = -\nabla \cdot \vec{q} - p(\nabla \cdot \vec{V}) - \vec{\tau} : \vec{V} + \phi_s \quad (B-3)$$

The terminology is defined in Appendix A.

The substantial derivative is denoted by

$$\frac{D(\quad)}{Dt} = \frac{\partial(\quad)}{\partial t} + \vec{v} \cdot \nabla(\quad). \quad (B-4)$$

From this point on in the analysis, we will neglect time derivative terms because we are not concerned with nonsteady processes.

The fluid in this case is a liquid and may thus be assumed incompressible. The left-hand side of Equation B-1 may thus be neglected. However, the variation of density with temperature is the driving force for flow and thus cannot be entirely neglected. For the momentum equation we employ the classic Boussinesq approximation,⁽¹⁾

$$-\nabla P + \rho \vec{g} \simeq -\vec{g} \bar{\beta} \bar{\rho} (T - \bar{T}) \quad (B-5)$$

where the overbar denotes properties evaluated at the average temperature $\bar{T}$. The gradients of P in the horizontal plane are neglected.

For variable properties, the term containing the stress tensor is complex. For dimensional analysis we may use the approximate result for constant properties,

$$-\nabla \cdot \vec{\tau} \simeq \bar{\mu} \nabla^2 \vec{v}. \quad (B-6)$$

The conduction term may be given by Fourier's Law:

$$\vec{q} = -\lambda \nabla T \quad (B-7)$$

$$-\nabla \cdot \vec{q} \simeq \bar{\lambda} \nabla^2 T. \quad (B-8)$$

The term $\rho(\vec{v} \cdot \vec{\nabla})$ may be neglected by continuity of mass assuming incompressible flow.

The viscous dissipation term is very complex. For the present case it may be given approximately as:

$$-\vec{T}:\vec{v} = \mu \phi_v \simeq \frac{\mu}{2} \sum_i \sum_j \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)^2 \quad (B-9)$$

where i and j take on values x , y and z .

The quantity ϕ_s is the internal heat generation per unit volume due to electrical dissipation, chemical reaction or radioactive decay of constituents in the fluid. In the glass melter, all of these heat sources may contribute to some degree. It will not be necessary to define ϕ_s explicitly at this point because the ultimate source of the internal heat is not relevant to the analysis.

The internal energy of the fluid may be given with respect to a reference at T_0 by

$$u = \int_{T_0}^T C_v dT \quad (B-10)$$

$$\simeq \bar{C}(T - T_0). \quad (B-11)$$

For a liquid, the specific heats at constant volume and constant pressure are equivalent. We have assumed constant specific heat evaluated at the mean temperature.

The simplified form of the Navier-Stokes equations may now be given as

$$\nabla \cdot \vec{v} \simeq 0 \quad (B-12)$$

$$\vec{\rho} \cdot \nabla \vec{v} - \vec{g} \beta \rho (T - \bar{T}) + \nabla^2 \vec{v} \quad (\text{B-13})$$

$$\rho C \vec{v} \cdot \nabla T \simeq \lambda \nabla^2 \bar{T} + \frac{\mu}{2} \sum_i \sum_j \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)^2 + \phi_s. \quad (\text{B-14})$$

In all the above equations, properties are to be evaluated at the average temperature $\bar{T}$. However, the overbar notation used earlier has been dropped from this point on.

We now proceed to reduce all these equations to dimensionless form. To do so we define reference values for length, velocity, temperature and heat sources. The characteristic length, L , is usually a hydraulic diameter of the flow enclosure. The characteristic velocity, V , may be that due to throughput or the velocity in the eddies created by free convection; however, we need not be specific at this point. The characteristic temperature, ∇T , for this model is taken as a temperature difference representative of the extremes in the flow. The temperature level is not relevant to the analysis.

The heat source term is nondimensionalized by a characteristic heat flux,

$$\phi_s = \frac{\phi_s \Delta V}{\lambda A \frac{\Delta T}{X}} = \frac{\phi_s L^2}{\lambda \Delta T} \quad (\text{B-15})$$

This term should be of order one since conduction is dominant in high Prandtl number flows of the type in this study.

The nondimensional variables may now be summarized by

$$x_i = X_i/L \quad (\text{B-16})$$

$$u_i = v_i/V \quad (\text{B-17})$$

$$\tilde{\nabla}_i = \frac{\partial}{\partial x_i} \quad (B-18)$$

$$\vec{\theta} = \left(\frac{T - \bar{T}}{\Delta T} \right) \quad (B-19)$$

$$\tilde{\phi}_v = \frac{1}{2} \sum_i \sum_j \left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right]^2 \quad (B-20)$$

$$\tilde{\phi}_s = \phi_s L^2 / \lambda \Delta T \quad (B-21)$$

Substitution of the above into Equations B-12, 13 and 14 upon rearrangement will then yield the following dimensionless equations:

$$\tilde{\nabla} \cdot \vec{U} = 0 \quad (B-22)$$

$$\left(\frac{\rho V L}{\mu} \right) \vec{U} \cdot \tilde{\nabla} \vec{U} = - \left(\frac{g \rho \beta \nabla T L^2}{V \mu} \right) \frac{g}{g} \theta + \tilde{\nabla}^2 U \quad (B-23)$$

$$\left(\frac{\rho C V L}{\lambda} \right) \vec{U} \cdot \tilde{\nabla} \theta = \tilde{\nabla}^2 \theta + \left(\frac{\mu V^2}{\lambda \nabla T} \right) \tilde{\phi}_v + \tilde{\phi}_s \quad (B-24)$$

The dimensionless groups have been arranged to form the standard characteristic similarity variables.

We see that the continuity equation contributes nothing. The coefficient of the first term on the right in Equation B-23 may be given by

$$\frac{g\rho\beta\Delta TL^2}{\mu V} = GrRe^{-1} \quad (B-25)$$

$$= RaPe^{-1} \quad (B-26)$$

where the last of these is adopted for reasons discussed below. The coefficient of the term on the left in Equation B-23 is the Reynolds number.

The coefficient of the term on the left in Equation B-24 is the Peclet number. The coefficient of the second term on the right is

$$\frac{\mu V^2}{\lambda \Delta T} = \frac{V^2}{C \Delta T} \left(\frac{\mu C}{\lambda} \right) = EcPr \quad (B-27)$$

where the Eckert number Ec is the ratio of the fluid kinetic energy to the mean internal energy difference in the system.

With the above substitution, the dimensionless Navier-Stokes equations may be given as follows:

$$\vec{\nabla} \cdot \vec{U} = 0 \quad (B-28)$$

$$Re \vec{U} \cdot \vec{\nabla} \vec{U} = -RaPe^{-1} \frac{\vec{g}}{g} + \vec{\nabla}^2 \vec{U} \quad (B-29)$$

$$Pe \vec{U} \cdot \vec{\nabla} \theta = \vec{\nabla}^2 \theta + EcPr \phi_V + \phi_S \quad (B-30)$$

We now consider which of the terms in these equations are dominant and thereby define the parameters to be matched in the modeling criteria. We note first that the viscosities are large and the velocities are small such that

$Re \ll 1$. Therefore, the inertial terms on the left in Equation B-29 may be neglected. We thus deduce that Ra and Pe are the appropriate modeling criteria that arise from the momentum equation.

In Equation B-30 for conservation of energy, the viscous dissipation term $\tilde{\phi}_v$ is multiplied by the product $EcPr$. The ratio of kinetic energy to internal energy in the system must be very small, $Ec \ll 1$, since the velocities are very small. Thus, even though $Pr > 1$, the product must be negligible ($EcPr \ll 1$) so that energy flux due to viscous dissipation may be neglected. Thus, the only dimensionless variables which arise from the energy equation are Pe and $\tilde{\phi}_s$.

The total dimensionless parameters arising from the Navier-Stokes equations are thus Ra , Pe and $\tilde{\phi}_s$. It is significant to note that Re and Pr appear in these equations only as products and not individually. Thus, Re and Pr do not have to be individually matched in the model and prototype so long as the products $Ra = GrPr$ and $Pe = RePr$ are maintained in proper proportion. This simplifies the choice of the model fluid and allows more freedom in selecting an appropriate model scale.

Finally, we proceed to analyze the heat transfer boundary conditions. We note that it is necessary to match the relative heat flows through respective surfaces in the model and prototype. For a given surface, the boundary condition in the fluid can be given by the classical equation for convective heat transfer,

$$q_w = hA(T_w - T_\infty). \quad (B-31)$$

For similarity, the heat out of this wall must be some fraction δ_i of the total power dissipated from the fluid $P_o = \phi_s \Delta V$. Thus, we may write

$$\delta_i \phi_s \Delta V = hA(T_w - T_\infty). \quad (B-32)$$

We now nondimensionalize this equation in a manner analogous to that used above. The result is

$$\delta_i \tilde{\phi}_s \left(\frac{\lambda \Delta T \Delta V}{L^2} \right) = (hA\Delta T)\theta_b \quad (\text{B-33})$$

$$\theta = \frac{\delta_w \tilde{\phi}_s}{\left(\frac{hL}{\lambda} \right)} = \delta_i \tilde{\phi}_s \text{Nu}^{-1} \quad (\text{B-34})$$

The heat transfer boundary conditions thus introduce one more parameter, the Nusselt number. Our list of dimensionless parameters for the modeling criteria is now given by Ra, Pe, Nu and $\tilde{\phi}_s$. In addition, we must maintain the correct proportional heat loadings at the boundaries, as specified by δ_i .

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APPENDIX C

UNCERTAINTY ANALYSIS

APPENDIX C

UNCERTAINTY ANALYSIS

Accuracies of the physical modeling study results were estimated using the uncertainty method presented by Schenck.⁽¹¹⁾ Consider the general case of a result R , which is a function of the two measured variables X_m and Y_m :

$$R + r = F(X_m + x, Y_m + y).$$

If this function is continuous and differentiable, it can be shown with 95 percent confidence that the result R lies within the uncertainty interval W such that

$$W_r^2 = \left(\frac{\partial R}{\partial X_m} \right)^2 W_x^2 + \left(\frac{\partial R}{\partial Y_m} \right)^2 W_y^2.$$

WATER JACKET FLOW RATE

For the water jackets surrounding the model melter, the flow rate $\dot{Q}$ is directly related to the analog voltage output of the flowmeter electronics by the relationship

$$\dot{Q} = CV/K$$

$$W_{\dot{Q}}^2 = \left(\frac{\partial \dot{Q}}{\partial K} \right)^2 W_K^2 + \left(\frac{\partial \dot{Q}}{\partial C} \right)^2 W_C^2 + \left(\frac{\partial \dot{Q}}{\partial V} \right)^2 W_V^2$$

The flowmeter constant K was specified accurate to $\pm 0.5\%$ and the frequency to voltage conversion C was specified to $\pm 0.5\%$. The accuracy of the analog voltage V recorded by the data logger was $\pm 0.04\%$.

For nominal conditions $K = 5019 \text{ pulses/} \pm 25.1$

$$C = 400 \text{ Hz/V} \pm 2.0$$

$$V = 2.5 \text{ VDC} \pm 0.001$$

$$\dot{Q} = \frac{400 \times 2.5}{5019} \times 60 = 11.95 \text{ l/min}$$

$$\begin{aligned} w_{\dot{Q}}^2 &= \left(-\frac{CV}{K^2} \right)^2 w_K^2 + \left(\frac{V}{K} \right)^2 w_C^2 + \left(\frac{C}{K} \right)^2 w_V^2 \\ &= \left[-\frac{400 \times 2.5 \times 60}{(5019)^2} \right]^2 (25.1)^2 + \left(\frac{2.5}{5019} \right)^2 (2.0 \times 60)^2 \\ &\quad + \left(\frac{400 \times 60}{5019} \right)^2 (0.001)^2 \\ &= 3.574(10^{-3}) + 3.573(10^{-3}) + 2.287(10^{-5}) \\ &= 7.170 (10^{-3}) \\ w_{\dot{Q}} &= 8.468 (10^{-2}) \text{ l/min} \\ w_{\dot{Q}/\dot{Q}} &= \frac{0.085}{11.95} = 0.71\%. \end{aligned}$$

STROBOSCOPIC VELOCITY MEASUREMENT

The velocity u of a light-scattering particle suspended in the modeling fluid was calculated from the relationship

$$u = \frac{\ell}{M_p M_c} \Delta t$$

where

ℓ = length of the image string on the photograph

M_c = camera magnification

M_p = photograph enlargement

Δt = total exposure time

$$W_u^2 = \left(\frac{\partial u}{\partial \ell} \right)^2 W_\ell^2 + \left(\frac{\partial u}{\partial M_p} \right)^2 W_{M_p}^2 + \left(\frac{\partial u}{\partial M_c} \right)^2 W_{M_c}^2 + \left(\frac{\partial u}{\partial \Delta t} \right)^2 W_{\Delta t}^2$$

The photograph enlargement was known to within $\pm 0.1\%$ and the magnification of the camera could be determined consistently to $\pm 0.8\%$. The exposure time was assumed to be at least as accurate as 1 part in 60 or ± 0.017 sec. The image string length was measured with a dial micrometer to within ± 0.25 mm. Nominal values for this study were:

$$u = 0.42 \text{ mm/sec}$$

$$\ell = 12.7 \text{ mm} \pm 0.025$$

$$M_p = 2.0 \pm 0.002$$

$$M_c = 0.5 \pm 0.004$$

$$\Delta t = 30.0 \text{ sec} \pm 0.017$$

$$\begin{aligned}
W_u^2 &= \left(\frac{1}{M_p M_c \Delta t} \right)^2 W^2 + \left(\frac{-\ell}{M_p^2 M_c \Delta t} \right)^2 W_{M_p}^2 + \left(\frac{-\ell}{M_p M_c^2 \Delta t} \right)^2 W_{M_c}^2 \\
&\quad + \left(\frac{-\ell}{M_p M_c \Delta t^2} \right)^2 W_{\Delta t}^2 \\
&= \left(\frac{1}{2.0 \times 0.5 \times 30} \right)^2 (0.25)^2 + \left(\frac{-12.7}{4.0 \times 0.5 \times 30} \right)^2 (0.002)^2 \\
&\quad + \left(\frac{-12.7}{2.0 \times 0.25 \times 30} \right)^2 (0.004)^2 + \left(\frac{-12.7}{2.0 \times 0.5 \times 900} \right)^2 (0.017)^2 \\
&= 6.944(10^{-5}) + 1.792(10^{-7}) + 1.147(10^{-5}) + 5.755(10^{-8}) \\
&= 8.091(10^{-5})
\end{aligned}$$

$$W_u = \pm 0.009 \text{ mm/sec}$$

$$W_u/u = \pm 2.13\%$$

POWER SUPPLY VOLTAGE

The accuracy of the true rms voltage recorded by the data logger system was dependent on the sensing transformer ratio TR, the power transducer analog voltage output V, and the power transducer conversion ratio TD according to the relationship

$$V_r = V \times TR \times TD$$

Nominal values were: $V_r = 120 \text{ VAC}$
 $TR = 1.80 \pm 0.036$
 $TD = 24.0 \pm 0.24$
 $V = 2.75 \text{ VDC } 0.10$

$$\begin{aligned}
 W_{V_r}^2 &= \left(\frac{\partial V_r}{\partial V} \right)^2 W_V^2 + \left(\frac{\partial V_r}{\partial TR} \right)^2 W_{TR}^2 + \left(\frac{\partial V_r}{\partial TD} \right)^2 W_{TD}^2 \\
 &= (TR \times TD)^2 W_V^2 + (V \times TD)^2 W_{TR}^2 + (V \times TR)^2 W_{TD}^2 \\
 &= (1.80 \times 24)^2 (0.10)^2 + (2.75 \times 24)^2 (0.036)^2 \\
 &\quad + (2.75 \times 1.80)^2 (0.24)^2 \\
 &= 18.66 + 5.65 + 1.41 \\
 &= 25.72 \\
 W_{V_r} &= \pm 5.07 \text{ VAC} \\
 W_{V_r} / V_r &= \pm 4.23\%.
 \end{aligned}$$

POWER SUPPLY CURRENT

The relationship used to calculate the power supply current from the transducer analog voltage, V , power transducer conversion ratio, TD , and the sensing transformer ratio TR was

$$I_r = V \times TR \times TD$$

Nominal values for this study were: $I_r = 3.0 \text{ A}$
 $TR = 2.0 \pm 0.006$
 $TD = 1.0 \pm 0.01$
 $V = 1.5 \text{ VDC} \pm 0.05.$

Substituting these values into the uncertainty formula for power supply voltage above

$$W_{I_r} = 0.137 \text{ A}$$

$$W_{I_r} / I_r = 4.57\%.$$

POWER SUPPLY POWER

In a fashion similar to the power supply voltage and current, the accuracy of the power measurement was based on the relationship

$$P = V \times TR_V \times TR_I \times TD$$

Nominal values were: $P = 300 \text{ W}$
 $V = 0.69 \text{ VDC} \pm 0.024$
 $TR_V = 1.80 \pm 0.036$
 $TR_I = 2.0 \pm 0.060$
 $TD = 120.0 \pm 1.20$

The resulting uncertainty in power measurement was

$$W_p = \pm 14.94 \text{ W}$$

$$W_p / p = \pm 5.0\%.$$

APPENDIX D

MODEL FLUID TEMPERATURE DATA

TABLE D-1. Determination of Temperature Correspondence for Model Fluids
at $T_{po} = 1100^{\circ}\text{C}$

Fluid	T(°C)	$(\nu\alpha)^{1/3}$	$\epsilon_L' = \frac{(\nu\alpha)_m^{1/3}}{(\nu\alpha)_p^{1/3}}$	Equivalent $T_p(^{\circ}\text{C})$		$T_{mo} (^{\circ}\text{C})$	
				$\epsilon_L =$ 0.33	0.27	$\epsilon_L =$ 0.33	0.27
BNW 72-68	1100	0.367	1.000				
MF-1	30	0.226	0.616	936	866	57.0	68.5
	40	0.178	0.485	997	927		
	50	0.141	0.384	1058	988		
	60	0.115	0.313	1118	1049		
	70	0.096	0.262	1178	1110		
	80	0.081	0.221	1239	1171		
MF-2	30	0.208	0.567	977	913	52.0	63.5
	40	0.160	0.436	1033	969		
	50	0.127	0.346	1088	1025		
	60	0.104	0.283	1144	1080		
	70	0.087	0.237	1200	1136		
	80	0.074	0.202	1256	1192		
MF-3	30	0.228	0.621	959	899	55.0	65.5
	40	0.174	0.474	1015	955		
	50	0.137	0.373	1072	1012		
	60	0.111	0.302	1128	1068		
	70	0.091	0.248	1185	1125		
	80	0.079	0.215	1241	1182		

TABLE D-2. Determination of Temperature Correspondence for Model Fluids
at $T_{po} = 950^\circ\text{C}$

Fluid	T(°C)	$(\nu\alpha)^{1/3}$	$\epsilon_L' = \frac{(\nu\alpha)_m^{1/3}}{(\nu\alpha)_p^{1/3}}$	Equivalent T_p (°C)		T_{mo} (°C)	
				$\epsilon_L =$ 0.33	0.27	$\epsilon_L =$ 0.33	0.27
BNW 72-68	950	0.684	1.000				
MF-1	30	0.226	0.330	953	898	29.5	38.5
	40	0.178	0.260	1014	959		
	50	0.141	0.206	1074	1020		
	60	0.115	0.168	1135	1081		
	70	0.096	0.140	1195	1142		
	80	0.081	0.118	1256	1203		
MF-2	30	0.208	0.304	960	927	28.3	34.0
	40	0.160	0.234	1016	983		
	50	0.127	0.186	1071	1039		
	60	0.104	0.152	1127	1095		
	70	0.087	0.127	1183	1151		
	80	0.074	0.108	1239	1207		
MF-3	30	0.228	0.333	950	908	30.0	37.5
	40	0.174	0.254	1006	964		
	50	0.137	0.200	1063	1021		
	60	0.111	0.162	1119	1077		
	70	0.091	0.133	1176	1134		
	80	0.079	0.115	1232	1190		

TABLE D-3. Scale Factor Summary for MF-1, MF-2, MF-3

$$\epsilon_L = 0.33 \quad \epsilon = \frac{\text{Model Value}}{\text{Prototype Value}}$$

Parameter	Scale Factor	Value, $T_{po} = 1100^\circ\text{C}$			Value, $T_{po} = 950^\circ\text{C}$			Scale Factor
		MF-1 $T_{mo}=57.0^\circ\text{C}$	MF-2 $T_{mo}=52.0^\circ\text{C}$	MF-3 $T_{mo}=55.0^\circ\text{C}$	MF-1 $T_{mo}=29.5^\circ\text{C}$	MF-2 $T_{mo}=28.3^\circ\text{C}$	MF-3 $T_{mo}=30.0^\circ\text{C}$	
Thermal Expansion	ϵ_β	6.057	5.590	5.661	6.057	5.590	5.661	ϵ_β
Thermal Conductivity	ϵ_λ	0.093	0.093	0.093	0.116	0.116	0.116	ϵ_λ
Thermal Diffusivity	ϵ_α	0.088	0.089	0.089	0.118	0.119	0.118	ϵ_α
Thermal Capacity	ϵ_c	1.060	1.043	1.062	0.981	0.979	0.980	ϵ_c
Dynamic Viscosity	ϵ_ν	0.420	0.411	0.419	0.303	0.267	0.313	ϵ_ν
Prandtl Number	ϵ_{Pr}	4.961	4.744	4.750	2.564	2.332	2.651	ϵ_{Pr}
Electrical Resistivity	ϵ_σ	47.32	50.00	55.36	43.71	35.84	44.58	ϵ_σ
Temperature	ϵ_T	0.165	0.179	0.177	0.165	0.179	0.177	ϵ_T
Length	ϵ_L	0.33	0.33	0.33	0.33	0.33	0.33	ϵ_L
Velocity	ϵ_u	0.264	0.268	0.266	0.358	0.376	0.354	ϵ_u
Time	ϵ_τ	1.261	1.238	1.256	0.921	0.844	0.941	ϵ_τ
Power Density	ϵ_ϕ	0.138	0.151	0.148	0.176	0.187	0.185	ϵ_ϕ
Power	ϵ_p	0.0051	0.0055	0.0055	0.0063	0.0066	0.0068	ϵ_p
Voltage	ϵ_V	0.851	0.914	0.954	0.919	0.863	0.957	ϵ_V
Throughput	$\epsilon_{\dot{Q}}$	0.0293	0.0290	0.0297	0.0390	0.0426	0.0392	$\epsilon_{\dot{Q}}$

TABLE D-4. Scale Factor Summary for MF-1, MF-2, MF-3

$$\epsilon_L = 0.27 \quad \epsilon = \frac{\text{Model Value}}{\text{Prototype Value}}$$

Parameter	Scale Factor	Value, $T_{po} = 1100^\circ\text{C}$			Value, $T_{po} = 950^\circ\text{C}$			Scale Factor
		MF-1 $T_{mo} = 68.5^\circ\text{C}$	MF-2 $T_{mo} = 63.5^\circ\text{C}$	MF-3 $T_{mo} = 65.5^\circ\text{C}$	MF-1 $T_{mo} = 38.5^\circ\text{C}$	MF-2 $T_{mo} = 34.0^\circ\text{C}$	MF-3 $T_{mo} = 37.5^\circ\text{C}$	
Thermal Expansion	ϵ_β	6.057	5.590	5.661	6.057	5.590	5.661	ϵ_β
Thermal Conductivity	ϵ_χ	0.093	0.093	0.093	0.115	0.116	0.116	ϵ_χ
Thermal Diffusivity	ϵ_α	0.087	0.087	0.086	0.116	0.118	0.116	ϵ_α
Thermal Capacity	ϵ_C	1.072	1.056	1.075	0.977	0.977	0.995	ϵ_C
Dynamic Viscosity	ϵ_ν	0.222	0.214	0.234	0.169	0.173	0.169	ϵ_ν
Prandtl Number	ϵ_{Pr}	2.635	2.526	2.714	1.487	1.581	1.452	ϵ_{Pr}
Electrical Resistivity	ϵ_σ	26.54	29.02	33.04	25.35	26.22	28.85	ϵ_σ
Temperature	ϵ_T	0.165	0.179	0.177	0.165	0.179	0.177	ϵ_T
Length	ϵ_L	0.27	0.27	0.27	0.27	0.27	0.27	ϵ_L
Velocity	ϵ_u	0.324	0.322	0.316	0.430	0.437	0.430	ϵ_u
Time	ϵ_τ	0.827	0.813	0.860	0.628	0.618	0.628	ϵ_τ
Power Density	ϵ_ϕ	0.214	0.228	0.222	0.261	0.285	0.282	ϵ_ϕ
Power	ϵ_P	0.0041	0.0045	0.0045	0.0051	0.0056	0.0055	ϵ_P
Voltage	ϵ_V	0.641	0.694	0.734	0.694	0.738	0.770	ϵ_V
Throughput	$\epsilon_{\dot{Q}}$	0.0233	0.0242	0.0234	0.0313	0.0318	0.0313	$\epsilon_{\dot{Q}}$

TABLE D-5. Model Data Run 003, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 58.3^{\circ}\text{C}$

Walls $T = 62.0^{\circ}\text{C}$

Top $T = 18.8^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
12.70	42.3	38.2	43.5	39.6	44.2	45.0	0.976
10.16	73.5	71.5	72.2	71.7	73.3	73.3	0.780
7.62	73.2	73.0	73.5	72.2	70.5	72.9	0.585
5.08	72.7	71.7	72.6	71.2	72.6	73.0	0.390
2.54	72.0	71.8	72.2	72.0	72.0	72.1	0.195
0.00	68.4	68.9	68.6	68.5	68.8	68.4	0.000
-0.08	61.2	61.7	61.3	61.3	61.3	60.7	-0.006
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-6. Model Data Run 004, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 58.0^{\circ}\text{C}$

Walls $T = 62.0^{\circ}\text{C}$

Top $T = 19.1^{\circ}\text{C}$

X (cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z (cm)							Z*
13.03	36.7	37.0	37.0	39.4	39.1	38.4	1.000
12.07	56.9	56.1	59.6	57.8	60.3	61.3	0.927
10.16	65.3	63.0	65.0	64.7	65.2	65.2	0.780
7.62	64.8	64.4	63.6	62.6	65.0	65.3	0.585
5.08	66.0	63.1	63.6	64.3	64.6	65.9	0.390
2.54	68.1	64.0	63.6	63.5	63.9	67.6	0.195
0.00	66.0	61.8	61.7	61.8	61.8	65.0	0.000
-0.08	55.8	55.6	55.3	55.6	55.1	54.8	-0.006
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-7. Model Data Run 005, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 58.1^{\circ}\text{C}$

Walls $T = 62.0^{\circ}\text{C}$

Top $T = 21.5^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
13.03	40.4	37.3	36.7	37.3	39.7	41.4	1.000
12.70	51.6	48.8	49.3	50.9	53.5	56.0	0.976
12.07	64.0	62.5	63.0	63.4	64.0	64.5	0.927
11.43	69.1	68.3	68.3	64.9	68.6	63.9	0.878
8.89	68.8	69.4	70.5	69.3	70.4	70.1	0.683
6.35	70.7	70.4	69.7	70.3	70.3	70.7	0.488
3.81	72.2	70.1	70.0	69.1	70.2	72.5	0.293
1.27	73.9	69.5	69.3	69.3	69.5	74.7	0.098
0.00	71.3	68.1	67.6	67.4	67.7	72.1	0.000
-0.08	62.2	61.4	60.6	60.6	60.7	60.9	-0.006
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-8. Model Data Run 006, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 60.8^{\circ}\text{C}$

Walls $T = 63.5^{\circ}\text{C}$

Top $T = 19.4^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z★
13.18	36.5	22.8	22.7	22.5	22.5	34.3	1.012
11.43	66.5	43.2	23.8	23.2	42.5	67.3	0.878
10.16	70.9	61.8	60.6	59.6	64.6	70.5	0.780
7.62	70.5	70.1	68.9	69.7	69.4	71.0	0.585
5.08	70.8	69.7	70.3	70.3	69.0	70.7	0.390
2.54	70.3	70.1	70.4	70.2	69.4	70.4	0.195
0.00	67.8	68.0	67.9	68.0	67.9	67.8	0.000
-0.08	60.8	61.3	60.9	61.1	61.0	60.4	-0.006
X★ =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-9. Model Data Run 012, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 41.2^{\circ}\text{C}$

Walls $T = 45.5^{\circ}\text{C}$

Top $T = 12.3^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
10.32	33.5	29.4	28.4	28.5	30.3	33.5	1.016
9.05	62.2	59.9	59.5	59.3	60.0	60.3	0.891
8.42	64.4	64.2	63.6	63.4	61.8	64.3	0.828
7.15	66.4	66.7	66.0	66.6	65.3	66.8	0.703
4.61	66.0	65.8	65.7	65.7	65.8	65.0	0.453
2.07	62.6	62.1	61.5	60.8	61.1	61.5	0.203
0.00	52.4	54.8	56.5	56.6	54.7	52.3	0.000
-0.08	46.5	48.8	50.2	51.0	49.0	46.7	-0.008
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-10. Model Data Run 012, $Y^* = 0.257$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 41.2^{\circ}\text{C}$

Walls $T = 45.5^{\circ}\text{C}$

Top $T = 12.3^{\circ}\text{C}$

$X(\text{cm})$	5.240	10.190	15.138	20.089	25.037	29.987	
$Z(\text{cm})$							Z^*
10.32	24.8	26.3	25.7	26.0	29.2	27.5	1.016
7.46	66.2	65.4	65.7	65.3	65.8	66.4	0.734
4.92	66.4	66.3	66.3	65.8	66.3	66.2	0.484
2.38	62.8	62.3	61.9	61.3	61.3	62.0	0.234
0.00	51.8	54.0	55.7	55.7	54.1	52.0	0.000
-0.08	45.8	47.6	49.4	49.6	48.7	46.4	-0.008
$X^* =$	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-11. Model Data Run 014, $Y^* = 0.257$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 46.3^{\circ}\text{C}$

Walls $T = 50.2^{\circ}\text{C}$

Top $T = 17.5^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
10.32	40.9	34.1	35.6	38.0	36.9	41.8	1.016
8.89	67.1	66.8	68.5	69.7	69.0	71.9	0.875
7.62	75.9	73.4	76.0	75.1	74.2	76.0	0.750
5.08	75.9	75.3	76.0	76.2	75.6	76.0	0.500
2.54	71.3	70.5	70.2	69.9	70.0	70.5	0.250
0.00	57.5	59.8	61.3	61.2	59.9	57.7	0.000
-0.08	49.8	51.5	53.3	53.1	52.1	49.9	-0.008
<hr/>							
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-12. Model Data Run 014, $Y^* = 0.257$
 Fluid Temperatures ($^{\circ}\text{C}$)
 (During simulated calcine feeding)

Electrodes $T = 46.3^{\circ}\text{C}$

Walls $T = 50.2^{\circ}\text{C}$

Top $T = 17.5^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
10.32	40.6	32.7	33.4	34.3	34.9	39.9	1.016
8.89	67.5	64.1	65.6	65.1	64.8	69.5	0.875
7.62	74.4	72.0	72.4	72.6	72.2	75.0	0.750
5.08	74.2	73.3	74.1	74.5	73.8	74.5	0.500
2.54	71.0	70.4	70.4	70.4	70.6	70.7	0.250
0.00	58.8	60.7	62.9	62.9	60.8	58.5	0.000
-0.08	51.0	52.3	55.1	55.4	53.8	51.4	-0.008
<hr/>							
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

TABLE D-13. Model Data Run 015, $Y^* = 0.500$
Fluid Temperatures ($^{\circ}\text{C}$)

Electrodes $T = 25.2^{\circ}\text{C}$

Walls $T = 28.3^{\circ}\text{C}$

Top $T = 15.0^{\circ}\text{C}$

X(cm)	5.240	10.190	15.138	20.089	25.037	29.987	
Z(cm)							Z*
10.16	27.3	26.0	25.3	26.7	27.6	27.3	1.000
8.89	52.1	50.8	52.0	51.5	51.4	52.3	0.875
7.62	56.2	56.1	55.9	56.5	54.6	56.6	0.750
5.08	56.1	56.0	56.2	56.2	56.0	56.2	0.500
2.54	50.0	49.7	49.3	49.1	49.4	50.1	0.250
0.00	38.7	41.4	43.4	43.7	41.5	38.5	0.000
-0.08	34.4	37.1	38.7	39.6	37.5	34.8	-0.008
X* =	0.149	0.289	0.430	0.570	0.710	0.851	

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A. A. Churm
DOE Chicago Patent Division
9800 South Cass Avenue
Argonne, IL 60439

R. E. Cunningham
Deputy Director for Fuels
and Materials
Nuclear Regulatory Commission
Silver Springs, MD 20910

Assistant Director for Radioactive
Waste Management Branch
NRC Division of Materials and Fuel
Cycle Facility Licensing
Washington, DC 20545

W. G. Belter
DOE Division of Biomedical
and Environmental Research
Earth Sciences Branch
Washington, DC 20545

W. A. Brobst
DOE Division of Environmental Control
Technology
Washington, DC 20545

W. E. Mott
DOE Division of Environmental Control
Technology
Washington, DC 20545

R. B. Chitwood
DOE Division of Nuclear
Power Development
Washington, DC 20545

T. C. Chee
DOE Office of Nuclear Waste
Management
Washington, DC 20545

C. R. Cooley
DOE Office of Nuclear Waste
Management
Washington, DC 20545

Sheldon Meyer
DOE Office of Nuclear Waste
Management
Washington, DC 20545

R. G. Romatowski
DOE Office of Nuclear Waste
Management
Washington, DC 20545

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DOE Office of Nuclear Waste
Management
Washington, DC 20545

C. A. Heath
DOE Office of Nuclear Waste
Management
Washington, DC 20545

G. Oertel
DOE Office of Nuclear Waste
Management
Washington, DC 20545

A. F. Perge
DOE Office of Nuclear Waste
Management
Washington, DC 20545

D. L. Vieth
DOE Office of Nuclear Waste
Management
Washington, DC 20545

R. D. Walton
DOE Office of Nuclear Waste
Management
Washington, DC 20545

J. Neff, Program Manager
Department of Energy
Columbus Program Office
505 King Avenue
Columbus, OH 43201

J. B. Whitsett
DOE Idaho Operations Office
P.O. Box 2108
Idaho Falls, ID 83401

DOE Oak Ridge Operations
Office
P.O. Box X
Oak Ridge, TN 37830

John Van Cleve
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