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CUPOLA FURNACE COMPUTER PROCESS MODEL

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Final Report

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FINAL REPORT
CUPOLA MODELING PROJECT

▪ **SECTION 1**

▪ **Introduction**

The objective of this program was to bring to commercialization a cupola computer simulation program, CupolaAid, a work that was supported by the DOE since 1989. The model predicts cupola outputs based on given inputs. The model provides the solutions rapidly (~10 seconds) which makes it useful for real time corrections to a cupola's operation as well as for longer term decision making.

The cupola furnace produces about 2/3 of the iron used for castings. The simple construction belies the complex chemical and physical processes that are carried out within. Because of the inherent complexity of the cupola's processes the furnace is difficult to operate efficiently; energy efficiency is poor, valuable chemical elements are destroyed by oxidation and the composition of the end product varies considerably. The basic problem is there are about 50 input variables any of which can affect the six key output variables: %C, %Si, %S, iron temperature, melt rate and cost.

In an effort to improve cupola performance and energy efficiency and to enhance the ability of the foundry to make informed decisions on the cost/benefits for major improvements to the cupola the development of a computer simulation model was undertaken in 1989 with support provided by DOE, American Foundry Society and U.S. foundries. The same entities supported the development of the model until 2001 when S. Katz Associates was contracted by the DOE to bring the model to commercialization.

▪ **SECTION 2**

▪ **Project Goals**

Although the model in 2001 achieved a high level of development it still had shortcomings that needed to be addressed in order to achieve commercialization. These areas included:

1. No ability to model the variety of existing cupola configurations.

2. Shortcomings in the prediction of final iron temperature and the silicon content of iron.
3. Lack of consideration of radiant heat transfer.
4. Inadequately designed graphic user interface.

In the current contract period most of the needed improvements were successfully addressed. Key cupola configurations, rear-slagging and divided-blast (two rows of tuyeres), which were lacking in the earlier versions of the model were added. Modeling of iron temperature was improved and radiant heat transfer was added to the model.

The Graphic User Interface (GUI) was completely revised using a more advanced computer language (C++). Major improvements include (1) the ability to operate the model from a single menu screen (2) the ability to compare data from different runs that are retained in memory. Comparisons can be made by generating data tables or graphs (3) development of a rapid way to generate a series of runs that vary with respect to a single input. As in the previous case, the results can be viewed in the form of tables or graphs.

In connection with the sale of the model; (1) An agreement was reached with the American Foundry Society for S. Katz Associates to gain possession of the rights to the model. (2) A contract is being drawn up with Vlado Associates to prepare a website for the sale of the model. (3) Agreements were reached with individuals who will install the model, give lectures on model operation at foundries. (4) Three foundries will allow S. Katz Associates to optimize their cupola operations, using the model, in exchange for allowing S. Katz Associates to utilize the results of the optimization for sales purposes.

▪ ***Variance from Project Goals***

The predictions of silicon were improved but further improvements are needed before the model can be sold. The shortcomings stem from a failed laboratory research program, conducted at the University of Missouri-Rolla, to provide key silicon data. Cupola performance data generated at the University of Antioquia (Medellin, Columbia) has provided some insight that is aiding the development of suitable algorithms for silicon. Further studies at the University of Antioquia will be conducted to gain needed insight into the important cupola processes, including silicon recovery.

- ***Model description of cupola operation and the need for a model.***

- *General*

The cupola is a tubular furnace which produces cast iron by melting scrap and alloys using the energy generated from the oxidation (combustion) of coke, a coal derivative. Scrap, alloys and coke are introduced at the top of the furnace (see Figure 1). Air, often heated and containing added oxygen, is introduced near the bottom of the furnace. The combustion of coke creates the heat required to melt the scrap. The liquefied iron exits the cupola at the bottom through a taphole. As metal exits the cupola, room is made for more scrap and coke to be added at the top. Although charging is intermittent iron flow is continuous.

In order to make useful castings the liquid iron must have a specific composition. The most important elements are carbon, silicon, and sulfur. Nominal carbon and silicon levels are, respectively, 2.5% - 4.0% and 2.0% - 3.0%. Sulfur levels vary from 0.02% - 0.2%. Steel contains very little carbon and silicon thus creating the need for the separate addition of these elements (alloy additions) to the cupola charge.

Producing a desired composition is not simple as chemical reactions take place in different regions of the cupola where different amounts of elements are removed or added. The extent of reaction depends on a multitude of conditions, not easily anticipated, which is the basis for the need to develop a cupola simulation model.

In addition to the uncertainty related to the production of iron with the correct composition there is a need for the iron temperature to fall in a desired range. Again, many factors control the temperature of iron. These include heat transfer from the hot gases to the solid contents of the cupola and a variety of chemical reactions both exothermic and endothermic.

The size of scrap can vary greatly which affects heat transfer. The size of coke affects the amount of available heat. The oxidation potential and temperature of the heated gas flowing through the cupola affects the gain and loss of alloy elements. A complicating factor is the gain or loss of alloy elements must be anticipated so that appropriate compensating additions can be made to the materials being introduced to the cupola.

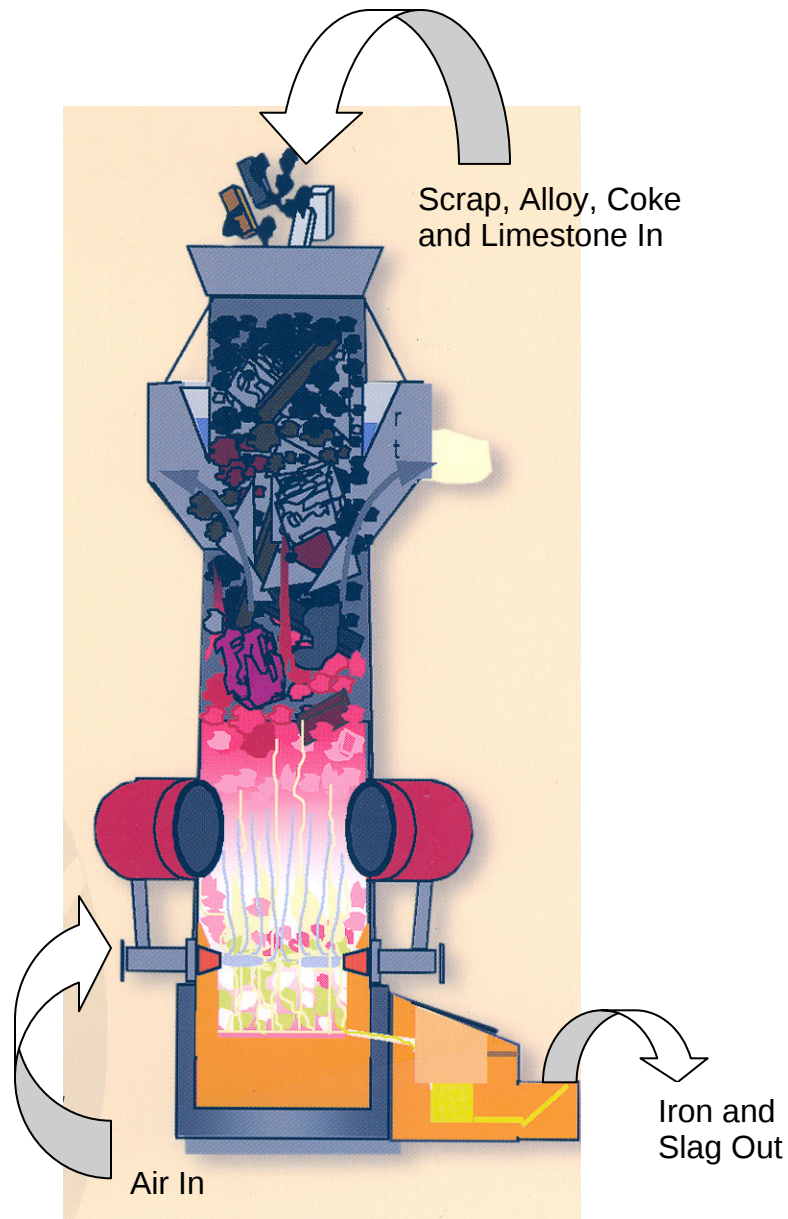


Figure 1. The cupola showing the general inputs and outputs.

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Yet another need is to remove oxides from the cupola. The major sources of oxides are coke ash, alloy oxidized in the cupola, sand adhering to castings and dirt entering with the charge materials. These oxides melt at high temperature and as a result they must be liquefied so they can be conveniently removed from the cupola. To accomplish this task

limestone (CaCO_3) is added with the metallic charge materials. Limestone decomposes in the cupola to form lime (CaO) which in turn combines with oxides to form a liquid (slag) which enables easy removal of the oxides through the taphole (see Figure 1). The amount of limestone added also affects the recovery of carbon, silicon and sulfur.

This general description indicates the complex considerations that are need to produce good castings from cupola produced iron. The effects of all of these sources of change can not be anticipated by the cupola operator hence the desire to develop a simulation model that will aid in the production of high quality iron with a minimum of expended energy and cost.

The table below illustrates the complex nature of cupola operation. Shown are five variables that increase iron temperature. However each creates different changes in other important variables: melt rate, combustion efficiency and % carbon. The model computes the different changes and informs the operator of their magnitude. This permits an intelligent choice to be made as how to increase iron temperature without producing undesirable side effects.

Relative Cupola Response to Increasing Amounts of Given Variables*

Variable	Iron Temperature	Melt Rate	Combustion Efficiency	% Carbon
Blast rate	↑↑↑	↑↑↑	→	↓
Hot blast temp.	↑↑	↑	↓	↑
Oxygen enrichment	↑↑↑	↑↑	↑	→
% Coke	↑↑↑	↓↓	↓↓	↑↑
Metal thickness	↑	↓	↑↑	↑↑

* Based on computer simulation of a 58in diameter lined, cupola,

It would seem natural to inquire why the cupola produces 2/3 of the iron while the much simpler device for melting scrap, the electric induction furnace, only produces 1/3 of the iron. The cupola has three main advantages:

1. Lower cost energy.
2. Ability to melt larger and smaller scrap than the electric furnace. This scrap generally has lower cost.

3. Ability to melt low cost scrap with higher levels of impurities that can not be tolerated in electric induction furnaces. In the cupola many impurities are oxidized and then transferred to the slag.

▪ ***Model fundamentals***

The model is a one dimensional representation of the cupola which means that the composition's of materials, fluid flow conditions and temperatures are assumed to be the same in the radial direction. The model assumes steady-state conditions exist. In general the changes in cupola operation that are made over relatively short time periods are not large enough to invalidate the model's predictions. As a result, although these suppositions are simplistic the model's accuracy validates the simplification.

The model will handle a large number of material inputs: eleven metallic constituents, four alloys, coke and limestone. Each of the materials is tracked individually from the charge door to the tap hole. Unlike other modeling approaches this cupola model considers the cupola as a single system. That is, there are no *a priori* assumptions of the existence, locations, quality and size of any of the major regions (shaft, melt zone, combustion zone, coke bed and slag) within the cupola. The model is formulated as a set of material and heat balances in the form of differential and algebraic equations using kinetic expressions for the rate of underlying reactions and interfacial heat and mass transfer and thermodynamic data for chemical and thermal equilibria.

The differential equations are put into finite difference form and solved numerically at 1,000 levels spanning from the charge door to the taphole. Because of the non-linear character of the underlying equations a complex iterative scheme is employed. A specific feature of the algorithm is that the charging (melting) rate is not known in advance and must be calculated. This is done so that the correct solution can be selected from among the infinite solutions that satisfy the material and heat balance equations. The correct solution satisfies the "no coke tapping condition." That is the solution that guarantees all the carbon present in coke and in alloys is completely consumed exactly when iron reaches the taphole.

▪ ***Chemical reactions considered by the model***

Chemical reactions can be considered to occur in three regions: (1) above the zone of melting, (2) in the zone of melting and (3) below the zone of melting. The zones are not distinct as the reactions take place over finite distances determined by the existing physical and chemical conditions.

▪ *Reactions occurring above the zone of melting*

Three important reactions occur in this zone: (1) calcination of limestone and (2) oxidation of scrap (3) sulfidation of scrap.

Limestone decomposes in the cupola shaft to form lime (equation 1). The reaction is endothermic and its occurrence is determined by chemical equilibrium which is governed by the temperature of limestone and the CO₂ content of the gas phase. The location where decomposition occurs is governed by these factors and in addition by the size of limestone.



In this region iron scrap is partially oxidized to FeO. It is governed by chemical equilibrium for reaction (2) which is endothermic:



The FeO is assumed to create a porous oxide film through which iron diffuses to react with CO₂ at the gas/oxide interface. This reaction takes place a short distance above the melt zone.

In this zone SO₂, produced in the lower regions of the cupola, reacts with iron to form iron sulfide (sulfidation) and iron oxide. The overall reaction is:



The modeling mechanism is based on reaction kinetics. It assumes iron diffuses through the oxide layer to the gas/solid interface where reaction 3 takes place. The amount of SO₂ reacting according to reaction 3 is proportional to the surface to volume ratio of the scrap. Any unreacted SO₂ exits the cupola with the exhausting gases.

▪ *Reactions occurring in the melt zone*

The primary reaction is melting of scrap and alloys which are endothermic processes:





The area in which this reaction takes place depends on the melting point of the scrap or alloy and its thickness. Cast iron and ferrosilicon melt higher in the cupola than steel due to their lower melting points.

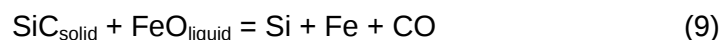
Melting of ferrosilicon is followed by dissolution in the liquefied scrap. The dissolution of ferrosilicon is exothermic. The heat released increases with the silicon content of the alloy. As observed in experimental studies, ferrosilicon primarily dissolves in steel due to the low initial concentrations of silicon and carbon (low silicon activity). The model assumes all the ferrosilicon dissolves in the steel.



Oxidation of alloys by FeO begins in this zone. The available FeO is the amount introduced as rust on the charge material and that produced above the melt zone. Reaction 7 is endothermic while reaction 8 is exothermic:



In recent years, due to cost, silicon carbide has become a popular alloy material. It almost always is produced in briquetted form using impure SiC. The contents of the briquettes include, in addition to SiC, free-carbon, silica and cement. The relative amounts of the ingredients vary. Because of the complex nature of the material it is difficult to model. A complicating factor is SiC does not melt like the metallic materials; it must dissolve in order to be incorporated into the iron. Several algorithms have been tested to describe the performance of SiC. None including the most current one are entirely satisfactory. At present yet another algorithm is being developed. The new algorithm is not considered here as it is not certain that it will be adopted. The model will not be sold until a more suitable algorithm is developed. The current model considers the following sequence of reactions:



If the FeO is exhausted by this reaction the remaining carbon dissolves in iron. If FeO consumes all the carbon and FeO is not exhausted then silicon reacts with FeO by reaction 8. If all the silicon is consumed and some FeO remains it enters the slag layer where further reactions occur. The free-carbon in the briquette is added to the fuel and the silica and cement are added to slag.

Once iron and steel melt they dissolve carbon from the coke. The dissolution process continues to the top of the slag layer. The reaction is endothermic:



The dissolution rate is different for iron or steel as it is determined by reaction kinetics which is governed by the sulfur concentration, temperature and carbon equivalent of the liquid metal, the size of metal drops, the ash content and size of coke and the velocity of the falling drop. The size of iron drops was determined experimentally as they are much smaller than obtained from theoretical predictions.

▪ *Reactions occurring below the zone of melting*

This zone is comprised of four regions. (1) Immediately below the melt zone is the region where air is introduced through water-cooled pipes called tuyeres that extend into the cupola (see Figure 1). (2) Below this region is one comprised of coke through which iron and slag drops fall. There is no gas flow in this region or below. (3) The next zone is a layer of slag, usually less than two feet thick. (4) The bottom layer is a layer of iron which passes out of the cupola through the tap hole. Most cupolas in the US are front-slagging, that is, the bottom of the slag layer is also at the level of the tap hole so it is discharged from the cupola with the iron.

Reactions in the tuyere region

Hot oxygen-enriched air reacts with coke to produce CO₂ (combustion reaction). The reaction rate is governed by the size of the coke, the oxygen content of the gas and gas temperature and velocity. The reaction is exothermic and it is the major heat source in the cupola.



The combustion reaction is actually the sum of two reactions in series. First O₂ diffuses to the coke surface where it reacts to form CO:



As the CO diffuses away from the coke it is oxidized by remaining oxygen.



The rate of reaction depends on, oxygen content and temperature of the air, the size of coke and gas velocity. The overall reaction is exothermic.

Since CO is more stable than CO₂ at the elevated temperatures that exist in the combustion region, CO₂ will react with coke to produce CO once all the oxygen is consumed. This reaction is called the Boudouard or coke gasification reaction. The reaction is endothermic.



The rate of this reaction depends on the concentration of CO₂, gas velocity and the size, porosity and reactivity of coke. Since the main function of the cupola is to melt metal the foundry attempts to minimize this reaction. The principle method used by foundries is the use of large size coke.

This reaction also involves two processes: first the diffusion of CO₂ to the coke surface where it reacts with coke. This is the predominant reaction. Some CO₂ diffuses into the porous coke where it also reacts with carbon. Below about 1000°C the pore reaction becomes rate controlling. However, the rate drops precipitously as the temperature decreases. It effectively appears as if the gasification of coke suddenly stops. This usually occurs near the lower end of the melt zone.

Another reaction that is important, especially in humid climates, is the reaction between coke and water in the incoming blast (reaction 14). The reaction is endothermic and it is controlled by equilibrium with CO and CO₂ (reaction 15).



Coke contains between 0.5% and 0.8% sulfur. As the carbon in coke is consumed the contained sulfur reacts with air to produce SO₂ (reaction 16). This reaction is essentially complete. As indicated earlier some of the SO₂ subsequently reacts with iron; the remaining SO₂ escapes the cupola in the outgoing gas stream.



Because of the high oxidation potential of the gasses in the region of the tuyeres, alloy oxidation takes place. The reactions considered by the model concern oxidation of dissolved carbon and silicon. The assumed reactions are:



These reactions occur in a sequence that is determined by thermodynamic criteria. Carbon reacts at higher temperatures and silicon at lower temperatures. Reaction kinetics is also considered as the rate of reaction considers the diffusion of gases to the surface of iron drop and reaction at the surface. Depending on the concentration of the alloys in the iron and the concentration of CO₂ in the gas phase, the rates of reaction can be governed by diffusion or reaction.

Reactions in the coke bed

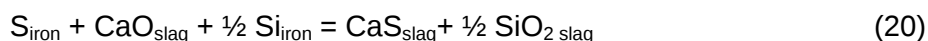
This region is defined by the absence of solid scrap, i.e., it contains only coke and iron and slag drops. It encompasses the area below the melt zone and above the slag layer. The upper boundary is defined by combustion and gasification of coke and the thickness and composition of scrap. The lower boundary is the top of the slag layer whose height is controlled by cupola backpressure and the height of the iron dam outside the cupola. In this region the iron drops contact coke and dissolve carbon by reaction 10. The controlling processes for carbon dissolution are the same as indicated above. In this region silicon from FeSi continues to combine with steel drops as indicated by reaction 6.

Reactions occurring in the slag layer

The model assumes any FeO that does not react in the melt zone descends and dissolves homogeneously. The uniformity of the dispersion of FeO is based on experimental data. Carbon and silicon in the iron drops passing through the slag layer react with FeO via reactions 7 and 8 in proportion to their “normality” (molar concentrations divided by valence). This is based on limited evidence. Complete reaction of FeO is assumed. A more accurate model based on available kinetic data may be implemented in the future.

Another reaction considered by the model is the partition of sulfur between iron and slag (reaction 19). Partition is based on an empirical relationship which works well. It also can be calculated based on the equilibrium expressed by reaction 20.

$$(x+y)S_{\text{iron}} = xS_{\text{iron}} + yS_{\text{slag}} \quad (19)$$



Reactions occurring in the iron layer

No reactions are assumed to take place in the slag layer.

- ***Heat transfer and fluid flow modeling***

- *Heat transfer and fluid flow*

One dimensional convective- and radiant-heat transfer is considered along the height of the cupola. Heat transfer dispersion is considered in the combustion region which serves to spread the heat energy above and below the combustion zone. Radial heat-transfer to the cupola wall is considered in the combustion region which serves to more accurately model heat losses through the wall. Convective heat loss to the water cooled tuyeres is also modeled.

The cupola is divided into three regions which can employ different refractory materials (or none). The regions are (1) the cupola well, (2) the combustion zone and (3) the region above the combustion zone. Heat loss between the taphole and the iron dam is also treated. In the cupola-well conductive heat-transfer to the cupola wall is considered for the region occupied by slag. Radiant- and convective heat-transfer are considered as the mechanisms for heat loss above the slag layer. As expected the greatest heat loss takes place in the region of the tuyeres where temperatures are the highest. This zone generally extends about 1m above the tuyeres. In this region considerable heat may be absorbed by copper water-cooled tuyeres. The amount absorbed increases with increasing extension of the tuyeres into the cupola.

Each charge material is designated as a separate stream and heat is transferred in proportional to its effective surface area. The effective area depends on the fraction of area that is exposed to the gas stream. The model also provides a parameter to describe channeling of the gas stream. Often cupolas charge very large or very fine materials that cause the gas flow to channel.

- ***Model features developed during this contract period (Dr. Vladimir Stanek).***

- *Radiant heat-transfer in the axial directions.*

Radiant heat-transfer constitutes certainly an important contribution to overall heat transfer in the cupola, particularly in the region of the tuyeres and the melt zone. In the model representation the gas and molten metal pass through a bed of solid particles as a pseudo-homogenous system that has an effective axial thermal conductivity defined as the

radiant heat flux in the axial direction divided by corresponding axial temperature gradient in the gas and coke phase. Thus the effective radiant axial conductivity is defined as:

$$k_{\text{radiant axial conductivity}} = 4\sigma d \epsilon_{\text{emissivity}} \frac{T^3}{2 - \epsilon_{\text{emissivity}}} \quad (21)$$

where σ designates Stefan-Boltzman constant and d solid particle diameter. For the particle diameter the model uses the computed local size of coke particles which dominate the high temperature region where radiation is strong. For the same reason the emissivity, $\epsilon_{\text{emissivity}}$, used in the above formula is that of coke.

Implementation of the axial radiant heat-transfer required modification of the coke and gas phase heat balances which in the presence of axial radiant heat-transfer became second-order partial differential equations. Also additional boundary conditions were formulated for the gas and coke temperature at the outlet ends of the respective streams. A new algorithm was developed to solve the equations. The algorithm works reliably while the typical computer time for a single run virtually has not changed.

The role of axial radiant heat flux is that it generally smoothes out the sharp temperature peaks and steep temperature gradients. Probably the most important practical impact of the modification is that the heat from the hot combustion zone penetrates below the level of tuyere not only by convection with the moving metal and coke streams but also by radiation. Furthermore, the following heat flux is radiated from the coke bed into the slag and metal pool in the cupola well.:

$$Q_{\text{coke-pool}}^{\text{radiative flux}} = - \left[(1 - \epsilon(z)) k_{\text{radiant axial conductivity}} \frac{dt_{\text{coke}}}{dz} \right]_{z=z_{\text{coke-pool}}} \quad (22)$$

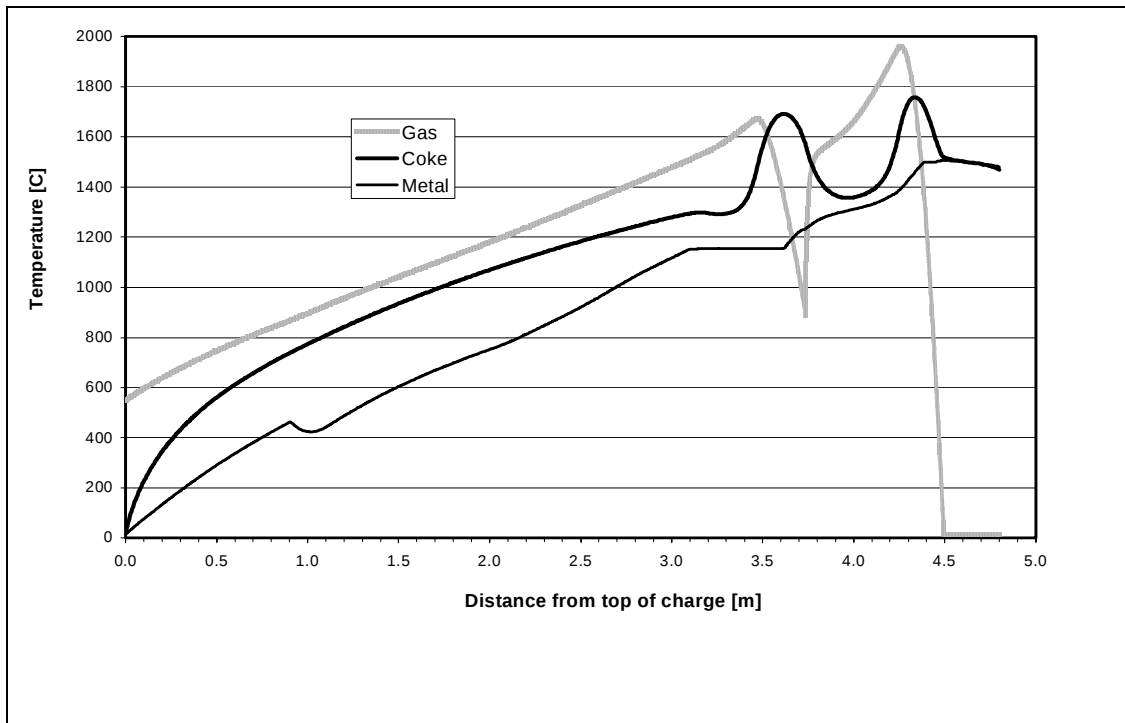


Figure 2. Gas, coke and metal profiles in a cupola showing the effect of radiant heat transfer on iron temperatures.

Profiles of gas, coke and metal temperature that are plotted in Figure 2 were computed for the case of a divided-blast, cold-blast cupola. In this figure the coke temperature profile smoothly transitions below the level of the tuyeres (4.5m) due to the radiation of the heat from the hot zone.

Below the tuyeres the coke and metal temperatures rapidly equalize with that of metal due to intimate mutual coke/metal contact. Near the surface of slag layer in the cupola-well the coke and metal temperature exhibit a sharp gradient due radiant heat absorbed by the slag and metal pools.

▪ *Front/Rear-slagging option*

The model has been expanded to handle the case of rear-slagging cupolas (see differences between Figures 3a and 3b). For the rear slagging mode the user must provide additional inputs related to the second taphole.

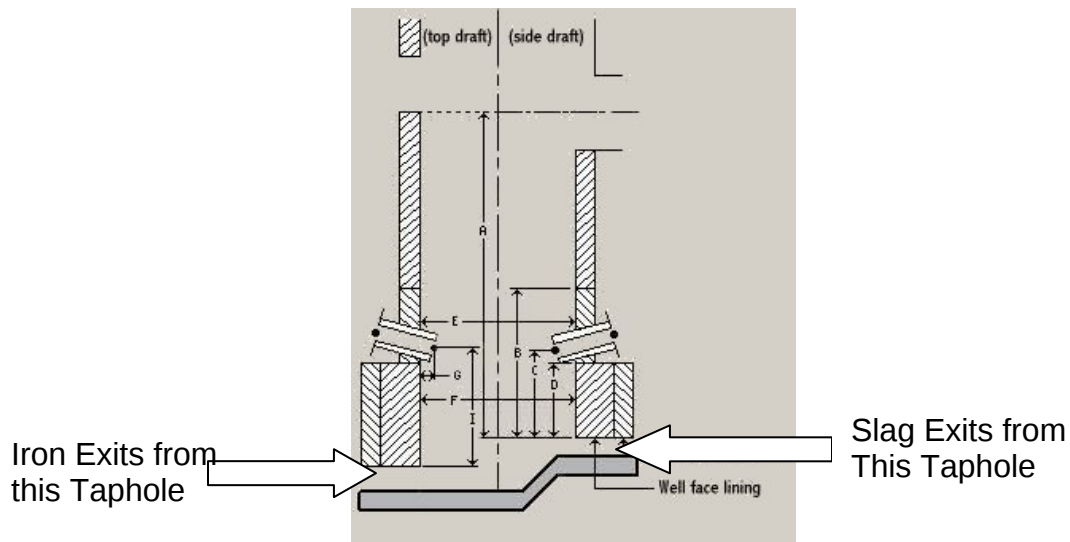


Figure 3a. Diagram of a rear-slagging cupola

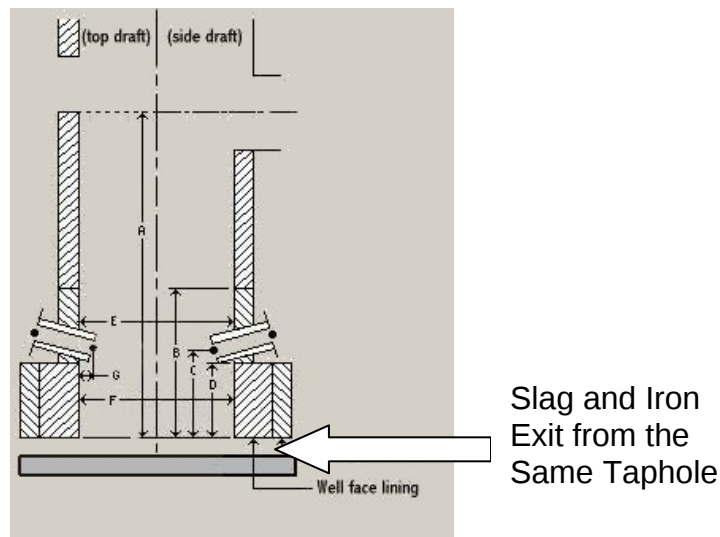


Figure 3b. Diagram of a Front-Slagging Cupola

The inputs pertaining to metal and slag trough dimensions and cupola backpressure need to satisfy certain constraints that are checked by the model: For both front- and rear-slagging cupolas, if the pressure in the cupola-well is sufficient to allow blast air to escape through the taphole it is reported on the screen and the run is aborted. For rear-slagging cupolas if the iron dam height relative to the slag dam height is low enough to allow slag to exit with the metal, the situation is reported on screen but it is not considered a fatal error and the model calculation is allowed to continue.

For the rear-slugging mode the model also evaluates the heat balances in the slag trough and predicts the slag temperature and the temperature drop in the slag.

▪ *Divided-blast cupola*

The model now handles the case of divided-blast cupolas (two rows of tuyeres). In this case the user is required to provide additional data inputs about the second row of tuyeres such as the number of tuyeres, inner/outer tuyere diameter and the distance between the two rows of tuyeres. The user also has the option to specify the air the blast rate, oxygen enrichment and temperature of the blast individually for the two rows of tuyeres.

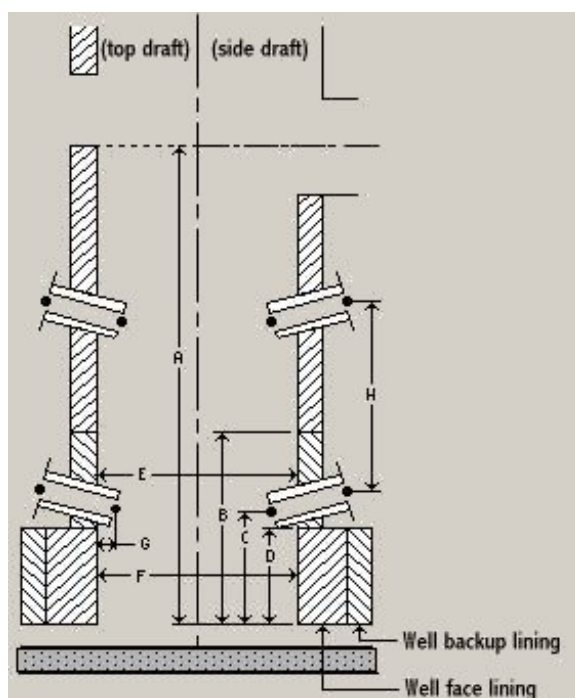


Figure 4. Diagram of a split-blast cupola showing the measurements required by the model.

The profiles of temperatures shown in Figure 2 were computed for the case of a divided-blast cupola with the two rows of tuyere spaced 0.76 meters apart and with the cold blast divided equally between the two rows. The rate of coke combustion at the upper row is computed by the model using the blast properties specified for the upper row before mixing with the gas within the cupola. However, the computed gas-related properties written into the output files are those after mixing with the gas within the cupola. Thus the plotted predicted gas temperature at the level of upper row does not equal the temperature of the cold blast but still it is lower than that of the coke.

The model accounts for the cooling of both rows of tuyeres. However, carbon monoxide that is already present in the gas stream at the level of the upper row of tuyere is not subject to oxidation. The oxygen of the blast at the upper row is assumed to burn only coke.

The results plotted in Figure 2 indicate that the coke temperature at the level of upper row of tuyeres is lower than that at the level of the lower tuyere row. The reason is that in the analyzed case the blast is cold at both levels. In reality, of course, the situation at both tuyere levels is clearly three dimensional and, consequently, the temperatures at these levels significantly vary in radial direction.

In spite of the simplification of the model by its one-dimensionality the predicted conditions do indicate the advantages of the split blast operation showing the wider zone of hot coke formed under the split blast compared to conventional single-row configuration. Also the tests of the trends of the major outputs as a function of the distance between the two rows of tuyeres or with the ratio of splitting the blast between the two rows showed the model predictions to be correct.

▪ *Sulfur partition in slag*

The handling of sulfur by the model has been expanded. To the existing combustion of sulfur in coke to sulfur dioxide and subsequent pickup of sulfur by metals the partition of sulfur between metal and slag has been added.

Based on the analysis of several hundred real cupola experimental data the sulfur partition coefficient, $S_{partition}$, has been found to be the following function of slag basicity, $S_{basicity}$:

$$S_{partition} = 9.552 \times 10^{-3} \exp \left[13.393 \frac{S_{basicity}}{1 + S_{basicity}} \right] \quad (23)$$

together with the condition:

$$S_{partition} = \text{MAX}(S_{partition}, 1.5) \quad (24)$$

that stipulates that the partition coefficient does not drop below 1.5.

The sulfur concentration in metal after partition in slag is computed from the following formula:

$$[\%S]_{Fe}^{after} = [\%S]_{Fe}^{prior} \frac{\frac{G_{Fe}}{G_{slag}}}{S_{partition} + \frac{G_{Fe}}{G_{slag}}} = [\%S]_{Fe}^{prior} \frac{1}{S_{partition} \frac{G_{slag}}{G_{Fe}} + 1} \quad (25)$$

The superscripts “after” and “prior” in the above formula distinguish between sulfur concentrations in metal after and prior to partition in slag. The values of the slag rate, G_{slag} , and the metal rate, G_{Fe} , used in the calculation are those predicted by the model.

Figure 5 compares the experimental and predicted final sulfur concentrations in molten metal for a number of melts in conventional cupolas operated with a single row of tuyeres using experimental data published in reports by BCIRA. The plotted data cover a large variety of melting conditions such as blast velocity and blast temperature, water cooled cupola shell, slag basicity, tuyere size and projection, oxygen enrichment, slag depth, fraction of steel in charge, depth of the well, size and type of coke, including formed coke.

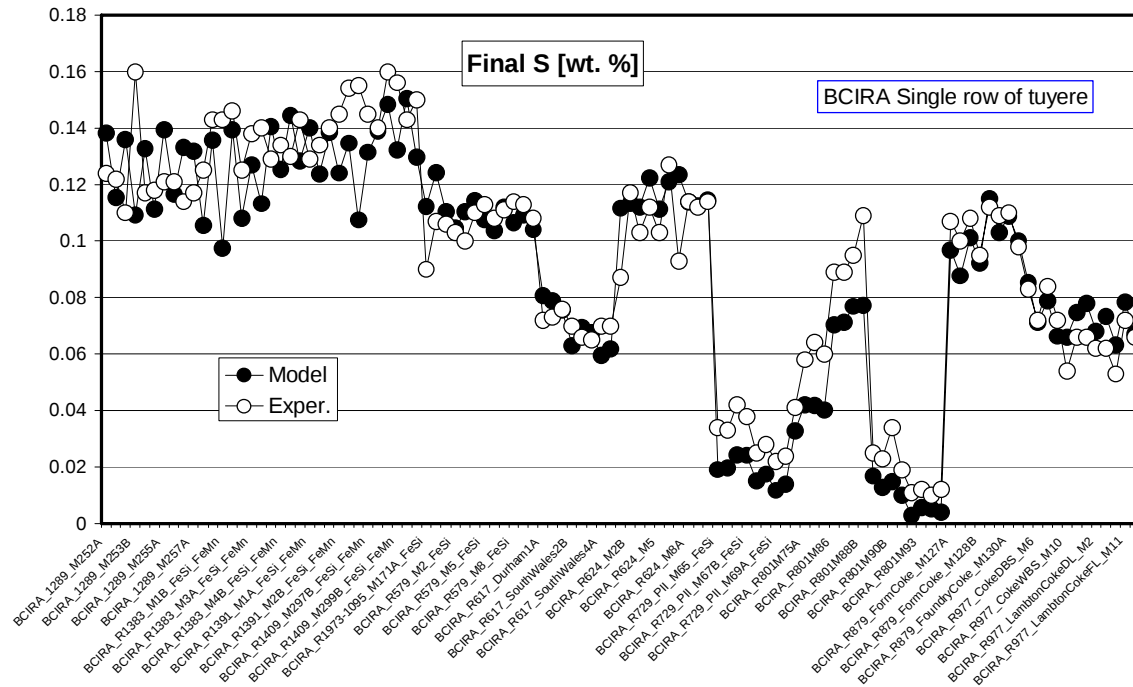


Figure 5. Comparison of experimental and model data for output sulfur.

The figure shows that model predictions, covering a wide range of sulfur charge concentrations, cope with the variable melting conditions very well. The mean standard error of sulfur prediction is about 0.01% and the accuracy appears quite satisfactory.

The affect of sulfur dissolved in iron on carbon pickup is not considered by the model but it will be added at a later date as a model upgrade.

▪ ***Tuning capabilities***

The GUI provides eight “tuning” coefficients to make the model predictions more precise. These permit changes to be made to kinetic parameters to affect rates of reaction. As is often stated in the foundry, “No two cupolas behave the same.” There are small differences between cupolas that are not captured by the required inputs to the model. The tuning coefficients permit altering the rates to correspond more closely to the observed outputs.

Two examples are provided to explain the need for tuning capabilities. (1) Scrap composition and thickness cannot be defined exactly thus changing from one type of scrap to another can change unmeasured properties such as the porosity of the scrap charge or the nominal thickness of the scrap. The porosity of a charge cannot be measured. Although measuring the thickness of scrap is possible, it is a tedious job. Thus, it is necessary to provide the means to modify the model to suite the conditions. The problem created by not knowing scrap thickness can be compensated using Coefficient 8 below. There is an input for porosity, not listed here, that can correct for bed porosity. The indication for the need to change the value for porosity is cupola backpressure.

(2) The quality of coke is worsening due to extremely high demand. This is changing the performance of coke (the rate of carbon dissolution and energy efficiency). The model does take into account the two most likely properties that cause these changes: the reactivity and the graphitic nature of the coke, however the information is not available to foundries. The changes in performance can be compensated by altering the rates of reaction that are affected by the changes in the intrinsic properties; in this case altering Coefficients 1 and 5 below.

1. Coefficient to multiply rate of carbon pickup
2. Coefficient to multiply rate of carbon oxidation in molten metal by CO_2
3. Coefficient to multiply rate of silicon oxidation in molten metal by CO_2
4. Coefficient to multiply rate of manganese oxidation in molten metal by CO_2
5. Coefficient to multiply rate of Boudouard reaction
6. Coefficient to multiply rate of solid iron oxidation by CO_2
7. Coefficient to multiply holdup of molten metal

8. Choice of metal particle diameter (0) or size of cluster of particles (1) as length scale for gas/solid heat transfer (HTAEF)

The first six of these coefficients simply multiply the rates of given reactions. Another tuning coefficient is needed to control the rate of reaction between SO_2 and iron (reaction 3).

The seventh coefficient multiplies the holdup of molten metal as it was evaluated from the employed correlation. Holdup compensates for the fact that iron drops fall more slowly through a bed of coke than in free fall. With high holdup iron drops spend more time in the various zones which increase the amount of reaction that can take place.

The last coefficient requires a choice of one of two quantities. Both quantities determine the available surface for gas/solid heat transfer. The option of the “cluster” of particles is suitable for highly non-uniform charges prone to strong gas flow maldistribution and channeling. In those cases the efficiency of gas-solid heat transfer becomes extremely low and it is preferable to use cluster size rather than extremely low values of effective area for heat transfer (HTAEF). The choice of HTAEF is for fine tuning heat transfer for non-channel flow. HTAEF values are also model inputs associated with each metallic charge. The use of HTAEF in the tuning parameters section provides fine tuning capability.

▪ **Model Predictions**

▪ Prediction of trends

To achieve good predictions it is critical that the blast rate is accurately known. This is critical because the blast rate is the only rate that the model receives. In turn it governs the melt rate and indirectly all other outputs. This can present a problem because there is blast leakage in most cupolas, especially hot-blast cupolas. Because of the critical importance of an accurate blast rate, the model provides a routine to determine blast leakage.

The BCIRA reports provided an extensive experimental data base for testing the model's ability to predict the trends of the major outputs (final metal composition: C, Si, Mn and S, melting rate, metal temperature, off-gas composition: CO_2 , CO and SO_2 and off gas temperature with the change of the following quantities:

- Coke rate
- Blast rate
- Blast temperature
- Oxygen enrichment
- Coke particle diameter
- Steel/cast iron charge makeup
- Type of coke
- Tuyere projection
- Tuyere diameter
- Ratio of blast between two rows of tuyeres
- Distance between two rows of tuyeres
- Slag basicity

▪ *Prediction of Values*

Predictive capabilities of the model are demonstrated on two experimental data sets: The data measured on a 1.4m inner diameter cupola by a General Motors research team and The BCIRA experiments published in a series of reports on a 0.76m inner diameter cupola. The BCIRA cupola was extensively modified and reconstructed in the course of time as various aspects of cupola operation and cupola geometry were studied. These BCIRA experimental data sets were divided into two sub-sets: Divided-blast and single row tuyere cupola.

It should be noted in the examination of the following charts that it cannot be assumed that the deviations were entirely due to model errors. In a number of cases where the experimental studies were duplicated, there was considerable difference in some of the output variables.

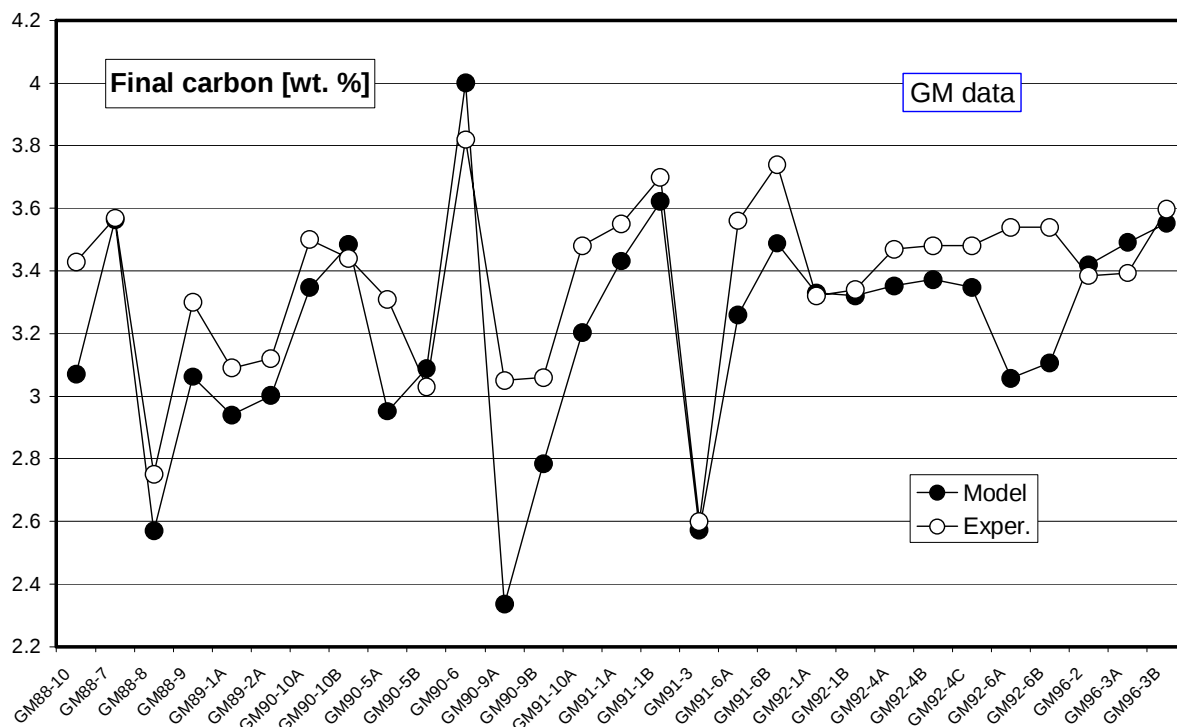
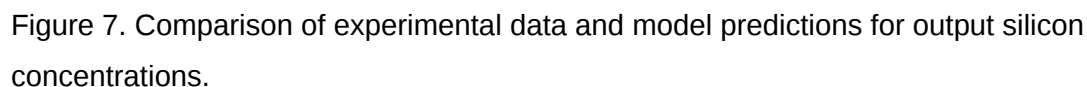


Figure 6. A comparison of experimental data with model predictions for output carbon.

Figures 6 and 7 compare the predicted and experimental final carbon and silicon concentrations of the metal for the GM and the BCIRA divided blast data. In Figure 6 we note the good prediction of the final carbon for the runs designated as GM90-6 which melted a 100% cast iron charge and GM91-3 which melted a 100% shredded steel charge. This observation is quite important as it demonstrates the ability of the model to make accurate predictions over the entire scrap composition range.

Figure 7 provides the comparison of experimental data and model predictions for output Si concentrations. This is poorest of the correlations. However even in the cases where predicted Si concentrations deviate more strongly from the experimental values, the zigzag pattern of the predicted curve copies that of the experimental curve indicating correctly prediction of trends.

Figure 8 compares predictions of melting rate for the BCIRA single row tuyere data. The predictions follow the pattern of the experimental data very well and accuracy is quite satisfactory. Overall the experimental data were slightly higher than the model predictions.





Figures 11 and 12 plots the predicted and experimental values of metal and off-gas temperature. The off-gas temperature predictions are good, especially considering the difficulties of obtaining representative samples.

It is fair to say that a good prediction of the metal temperature may sometimes be a problem. The reason is that the metal superheat constitutes only a small fraction of the heat generated in the cupola. For example 1% of the total energy is sufficient to change the iron temperature 100°C. Thus for an accurate metal temperature prediction it is necessary to provide very accurate inputs even for variables that at first may not appear as being important. That being said, agreement between experimental data and the model predicted data is generally within 25°C. A very important point is that in production when there is a 25°C change in iron temperature it reasonably affects all other variables. As seen in the various plots, the discrepancies in metal temperature do not have a significant affect on the other key output variables.

A description of the overall heat balances of the cupola operation is an output of the cupola model. It specifies the heat losses from each of the following portions of the cupola: upper and lower shaft, the well, the slagging trough and water cooled tuyeres. These losses can account for over 10% of the total heat generated within the cupola. The values are not measured in commercial cupola operation and may account for as much as several hundred degrees of metal superheat. The knowledge of the extent of these heat losses will indicate to foundries where cost and energy savings can be made. For example it would provide an accurate assessment of the energy and cost savings from the installation of a lining in a liningless cupola or changing the refractory thickness in a lined cupola. With respect to model accuracy, this points to the importance of providing accurate inputs such as the quality and thickness of cupola linings.

▪ *A final word on model accuracy*

Most outputs are linear over relatively large ranges of a particular variable. This has two important advantages for cupola operation in real time. If as often happens, a change takes place in cupola outputs due to some change in the inputs (such as a change in coke size or scrap thickness) that the operator is not aware of, the operator must take corrective action. Using the model, the operator examines a range of options. However because the

cause has not been identified the resulting model outputs will not be the same as the actual cupola outputs. A plot of the cupola and model outputs (see Figure 13) generally will be parallel. For the case shown, an increase in blast temperature needed to obtain a given increase in metal temperature determined from the model data is valid for application to the real cupola operation. The same applies to cases where the experimental data and model predictions in Figures 5 - 12 do not coincide well.

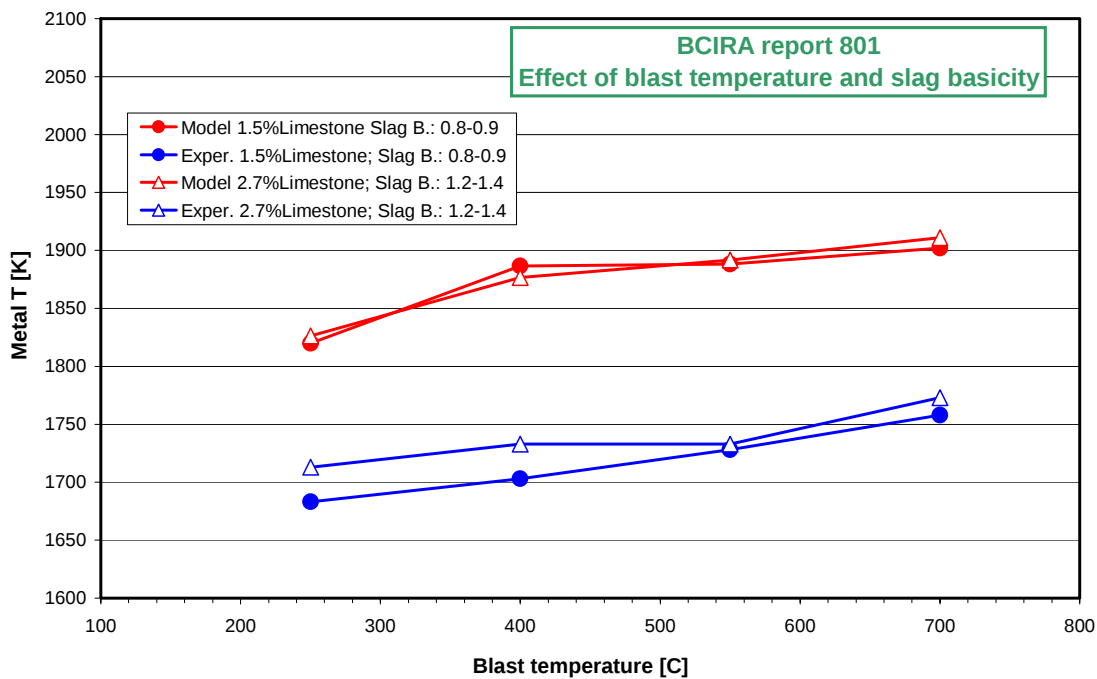


Figure 13. Data showing parallel nature of experimental and model data.

▪ **Graphic user interface (Adam Landefeld)**

▪ **General**

A major goal of this program was to modify the Graphic User Interface (GUI) to make it as user-friendly as possible. There are two general aspects to this effort: improving the ability to run the model in an easy and logical way and to make inputting of data simple.

In order to operate the model successfully it is necessary to provide it with cupola input operating data. Some of the data, such as the physical dimensions of the cupola are invariant and are installed permanently in the model's memory; other data varies from run to run. Examples of the latter are the number and amounts of metallic materials being charged or the air and oxygen injection rates. The need for this information is rather obvious however the model also uses more subtle variables such as the humidity of the blast air or

the level of rust and dirt contained in the charge materials. As seen from the table below, the total number of variables examined by the model is generally on the order of fifty if only one cast iron, steel and alloy material is charged. Each additional material in the cupola charge increases the number of variables by ten.

KEY INPUT VARIABLES

Steel – Charge weight, size, thickness, surface area, cost, %C, %Si, %Mn, %S, % rust.

Cast Iron - Charge weight, size, thickness, surface area, cost, %C, %Si, %Mn, %S, % rust.

Alloys – Charge weight, size, % alloy, composition, % binder and other materials, binder composition.

Coke – Charge weight, size, % carbon, % ash, % sulfur, reactivity, apparent density, cost.

Limestone – Charge weight, size, % CaO.

Blast Air – Rate, temperature, humidity.

Oxygen – Rate, Cost.

Based on the information provided, the model generates 26 output files that contain both the obviously needed outputs such as iron composition and temperature but also more detailed information such as an assessment of the sources of heat losses or data for plotting temperature and composition profiles. The files contain even more esoteric information for use by advanced users of the model. To handle this large amount of information and yet to provide it in an easily accessible manner required a complete revision of the GUI with which the cupola operator or the foundry engineer communicates with the model.

▪ *Input screens*

The philosophy adopted was to be able to operate the many options that the model afforded from a single master screen, the “Quick” screen, shown in Figure 14. The screen is divided into two essential parts. The first is the windows that contain the names, amounts and costs of the input scrap and alloys and also the blast conditions for a given run. Above this section are a series of tabs labeled, Metals, Cupola, Trough, etc. that store detailed information about cupola dimensions and each of the charge materials employed by the foundry. The window on the lower left contains the names of all the metallic charge materials employed by the foundry which include scrap and alloy. The model operator sets up the desired metallic charge by highlighting the desired materials and pressing the add button on the bottom. This transfers the names to the next window to the right. Following

this, the weight and cost of each charge material is entered into the two columns of windows to the right including the weight and cost of coke and limestone. Next the desired blast conditions are entered in the appropriate boxes above. Once this operation is complete, clicking on the “Run” button starts the computation which is completed in 10 to 15 seconds.

Cupola Model - E:\CBuilder5\Projects\Cupola2\Input\default5.ids

File Units Help Tools

Quick Multiple Runs Iterative Runs Metals Cupola Trough Wall Heat Losses Blast Coke Limestone Model Parameters Output >>

4.20 Indicated Air Blast Rate (m^3/s @ 0C) 25.00 Temperature of Ambient Air (C) **Run**

260.00 Temperature of Blast Air (C) 50.00 Relative Humidity of Ambient Air (%)

0.0536 Pure Oxygen Addition Rate (m^3/s @ 0C) 0.1101 Oxygen Cost/ m^3

	Weight (kg)	Cost/tonne
Coke	219.99	200.00
Limestone	61.60	40.0029

Metal Database: Default

Metallic Charge

	Steel	Iron	Briquettes	FeCr	FeMn	FeSi
SGI-1						
Cyl Briq 2.18C						
Cl Pillow Briq						
Low-C FeCr						
Medium-C FeMn lump						
50% FeSi lump 1x0.25						
'20-40' FeSi briq						

Add >>

<< Move << Copy

	Metal Weight	Metal Cost
	947.98	106.8599
Total Charge Cost		150.858

Figure 14. The master screen for operating the model.

It should be noted that the units in Figure 14 are metric. The model operates with either metric or English units. To select the desired units the cursor clicks on the “Units” box located above the “Quick” and “Multiple Runs” tabs and then clicks again to choose the desired type of metric.

▪ Output screens

When the computation is complete an output screen is automatically displayed (Figure 15). The tab at the top of the screen identifies this as the “Metal, Gas and Alloy” screen. The most important output variables for the operation of the cupola are provided in the boxes on the left. They provide the input and output concentrations for the important alloys and the differences which indicate the changes that took place inside the cupola. The

lower boxes contain the computed iron temperatures at two locations and the melt rate. The upper middle box provides the cost of metallic ingredients and the total cost of molten metal.

Cupola Model - E:\CBuilder5\Projects\Cupola2\Input\Presentation.IDS

File Units Help Tools

Metal, Gas & Alloy | Reactions & Heats | Compare Table | Graph | Input >>

Chemical Composition			
	Charge	Iron Dam	Difference
% C	1.9699	4.0561	2.0862
% Si	2.2408	1.6064	-0.6344
% Mn	1.127	1.026	-0.101
% S	0.07	0.1389	0.0689
% Coke	23.875		
% Coke C	22.184		
% C from SiC	0.00		

Cost of Molten Metal	
Metallics (per tonne)	102.79
SiC (per tonne)	0.00
Ferroalloys (per tonne)	13.477
Coke (per tonne)	47.759
Oxygen (per tonne)	0.0019
Limestone (per tonne)	2.6748
Total (per tonne)	166.70

Off Gas Properties	
% CO	26.072
% CO ₂	7.3753
% H ₂	1.3065
CO ₂ /(CO ₂ +CO)	0.2205
Temperature (C)	544.05

Iron Temperature	
At Taphole (C)	1376.90
At Dam (C)	1350.90

Alloy Recovery - Gain (+), Loss (-)		
	% final - % initial	% final / % initial
C	2.0862	2.059
Si	-0.6344	0.7169
Mn	-0.101	0.9104

Melt Rate (ton/h) 11.062

Open

Figure 15. Output screen for compositions, temperatures, melt rate, off-gas composition.

The values in the box to the far right are for variables that are rarely measured by foundries but are extremely useful. The top three boxes contain the concentration of CO, CO₂ and H₂. The term labeled CO₂/[CO₂+CO] is the combustion efficiency. Increasing this value decreases the amount of fuel required which has both the advantages of lowering costs as well as lowering the level of carbon monoxide discharged from the cupola. The latter is important from the environmental standpoint as high CO taxes the emission system. Soon to be added is the SO₂ concentration in the discharged gases which also has emissions implications. This is particularly useful information as the levels of SO₂ emissions are rather easily controlled by the manner in which the cupola is operated.

Referring to the tabs at the top of the screen, the next tab "Reactions & Heats" provides a table indicating the amount of heat gained or lost due to the important chemical reactions

described above. The values for the reactions provide clues as to what needs to be done to improve energy efficiency and costs.

The next two tabs serve the same overall function that is to compare the outputs of several sets in tables ("Compare Table" tab) or graphs ("Graph" tab). The "Compare Table" function is illustrated in Figure 16. If a large number of files are to be compared a table is the most convenient way to view the data. In this example the input variables were a set of blast rates

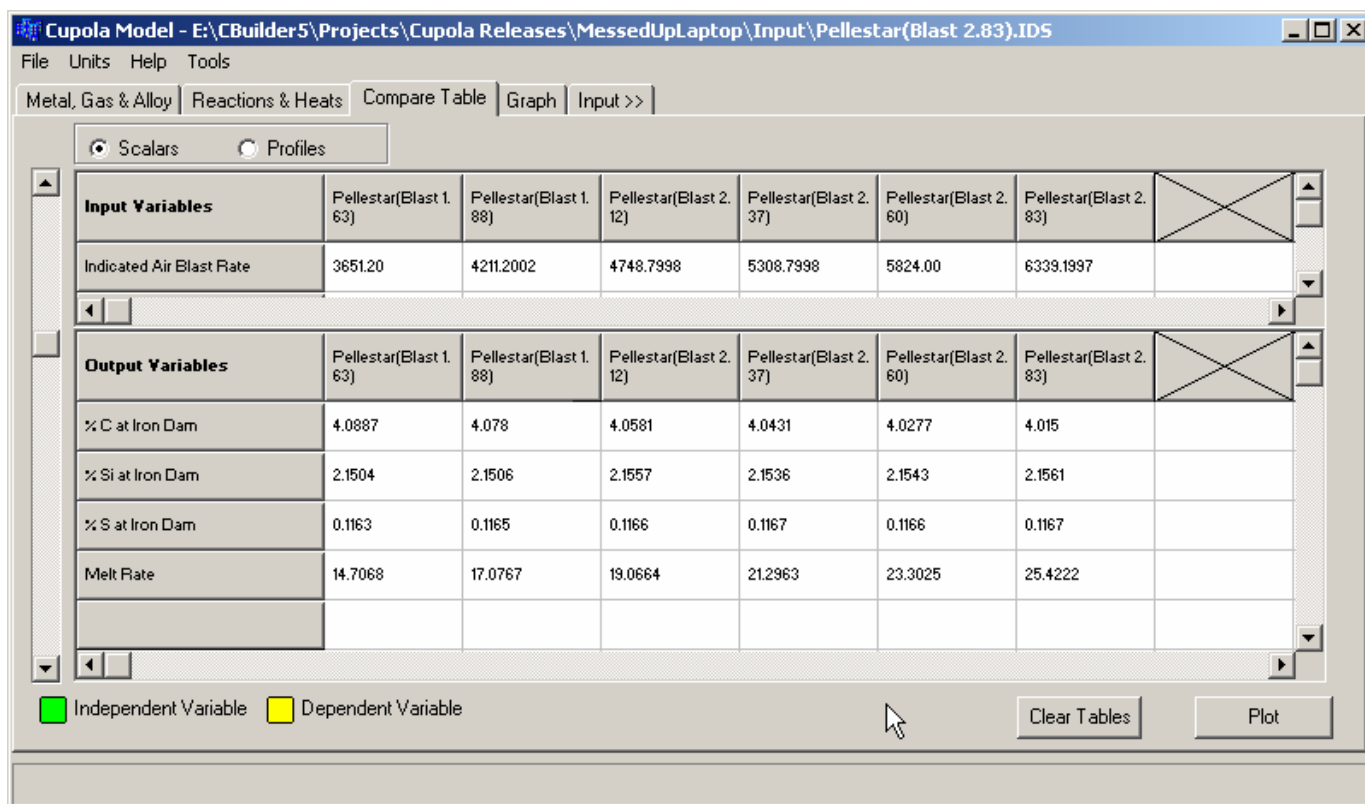


Figure 16. Example of the use of the Compare Table.

The "Plot" function is most useful to observe trends although quantitative data can also be secured with a little extra effort. Figure 17 provides an example of the graphing capability. Unlike the "Compare Table", the "Graph" function can track the performance of more than one variable. In Figure 17 both silicon concentrations and the melt rates for different levels of coke are plotted. The coke levels increase in increments of 50kg. It is clear to see the trends for increasing silicon recovery (less oxidation) and decreasing melt rates with the increase in coke.

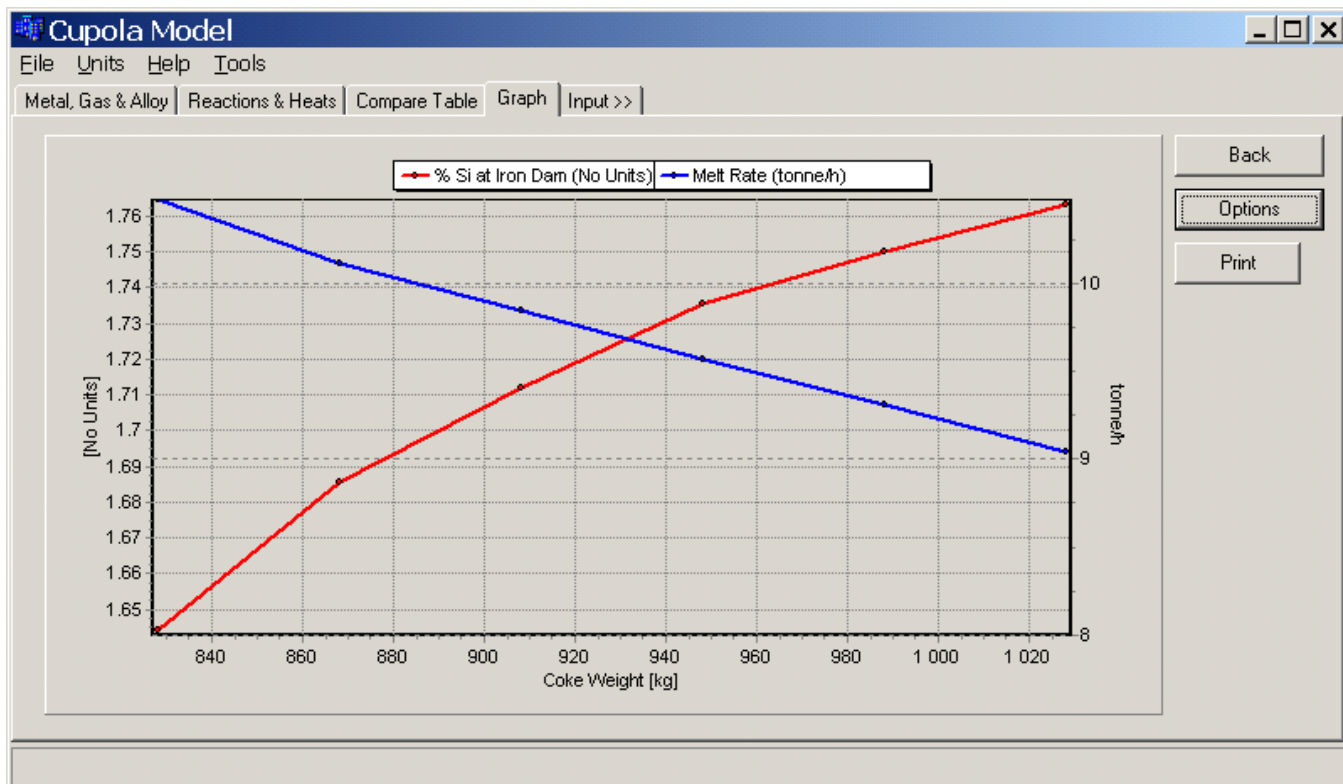


Figure 17. A demonstration of graphing using the Graph function.

Another very important function of the “Graph” function is to plot the profiles of variables along the length of the cupola. A wide selection of variables is available for plotting. This is illustrated in Figure 18 which plots the temperature profiles of scrap melted in the same cupola operating in one case (lower line) with one row of tuyeres and in the second case (upper line) with two rows of tuyeres. Clearly when this cupola operated with two rows of tuyeres it produced higher iron temperatures for the same amount of coke. The charge door was at the zero level and the tuyeres were located about 14.5 feet below the charge door.

It is believed that the use of the model in this capacity will serve as a powerful learning tool for those connected with cupola operation. This figure shows not only what worked the best but also why it worked the best. It is clear the metallic charge heated up faster in the case with two rows of tuyeres. It was due to the two tuyere configuration producing a larger high temperature zone by spreading the blast over a wider area in the tuyere region. The figure also shows where important processes took place. The inflection of the line in the region 5 to 8 feet below the charge door represents the endothermic calcination of limestone. The horizontal portion of the lines represents the region where the metallic charge was melting.

The line (red) representing the operation with two tuyeres indicates melting occurred higher in the cupola than the case for the one tuyere operation (blue). If the carbon data was plotted it would be found that the amount of carbon dissolved was also greater for the two tuyere configuration. With two tuyeres the iron drops produced in the melt zone passed through a deeper bed of coke which allowed a greater amount of carbon to dissolve. A similar examination of the corresponding gas composition profiles would indicate the area where silicon oxidation occurred. The importance of the learning function of the model cannot be overstated. In foundries in general the level of understanding of what governs the qualities of the iron being produced is low. The result is poor efficiency.

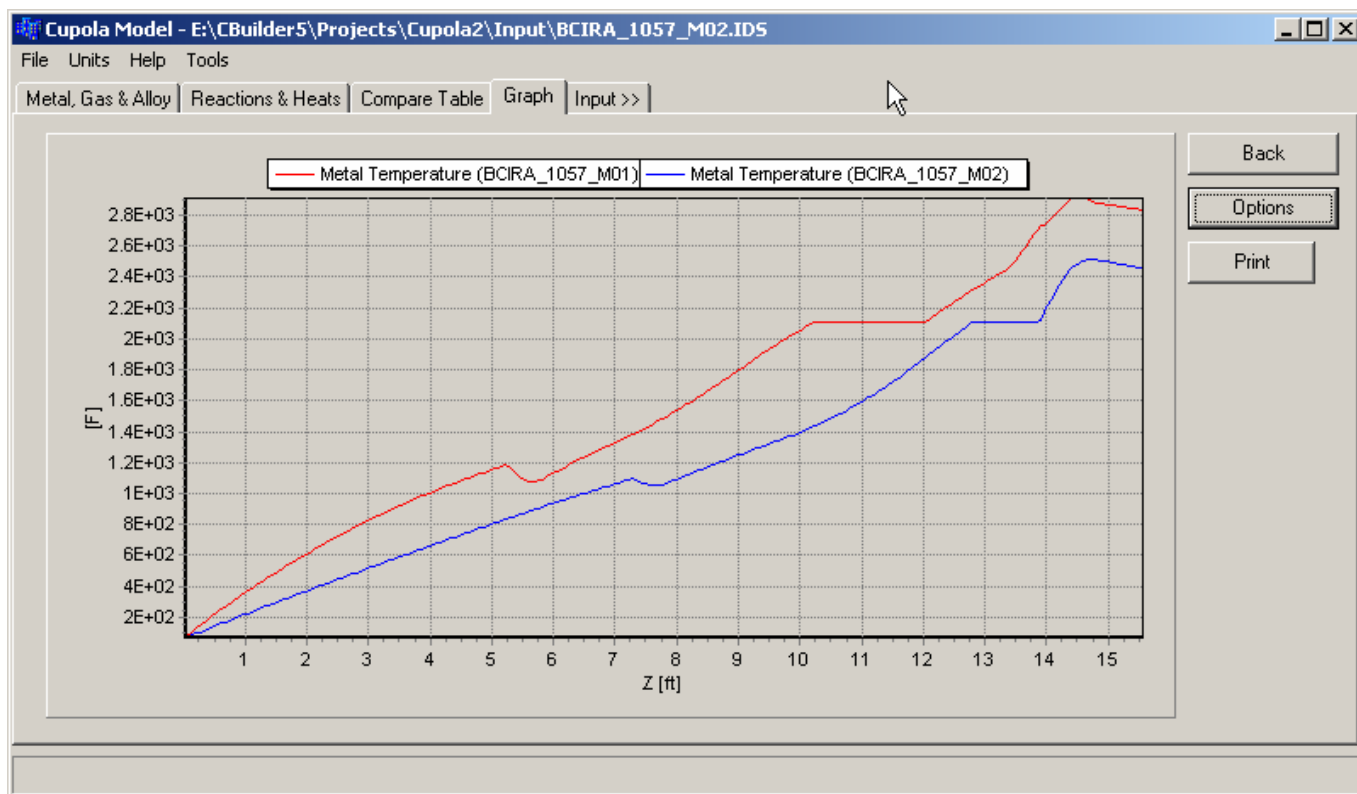


Figure 18. Graphs showing the differences in metal temperatures produced by a cupola operating with one and two tuyeres.

Up to this point the description concerns the possible options that are available starting with the "Quick" menu. The second and third tabs on the "Quick" menu screen are labeled "Multiple Runs" and "Iterative Runs". These functions are designed to allow the operator to carry out more than one run in a single operation. With the "Multiple Runs" tab a

series of input data can be inserted and by pressing the “Run” button each of the runs will be carried out in succession. The results of each run are provided on separate screens as illustrated in Figure 15.

Alternatively, one can use the “Iterative Runs” tab screen (Figure 19) to carry out several runs based on the same selected input data file and varying the input variable over a given number of iterations. The initial input file is selected from the window on the left, labeled “Datasets”. The “Datasets” window shows that data set “default 5” was selected (see highlighted line at the bottom of the window). The middle section of the screen indicates that the selected “Input Variable,” was the Air Blast Rate which was taken from a “drop down” menu. Also selected were the “Initial” and “Final” values of the blast rate and the “Number of Increments”. If the variable for iteration is a charge material the screen on the right is used to select the variable, the limits of the iteration and the number of increments. Pressing the “Output” tab on the far right displays the results, which can be viewed on separate screens or displayed collectively in a table or in a graph. Figure 17 is a typical graph. As seen, the “Coke Weight” is plotted in increments of 50kg.

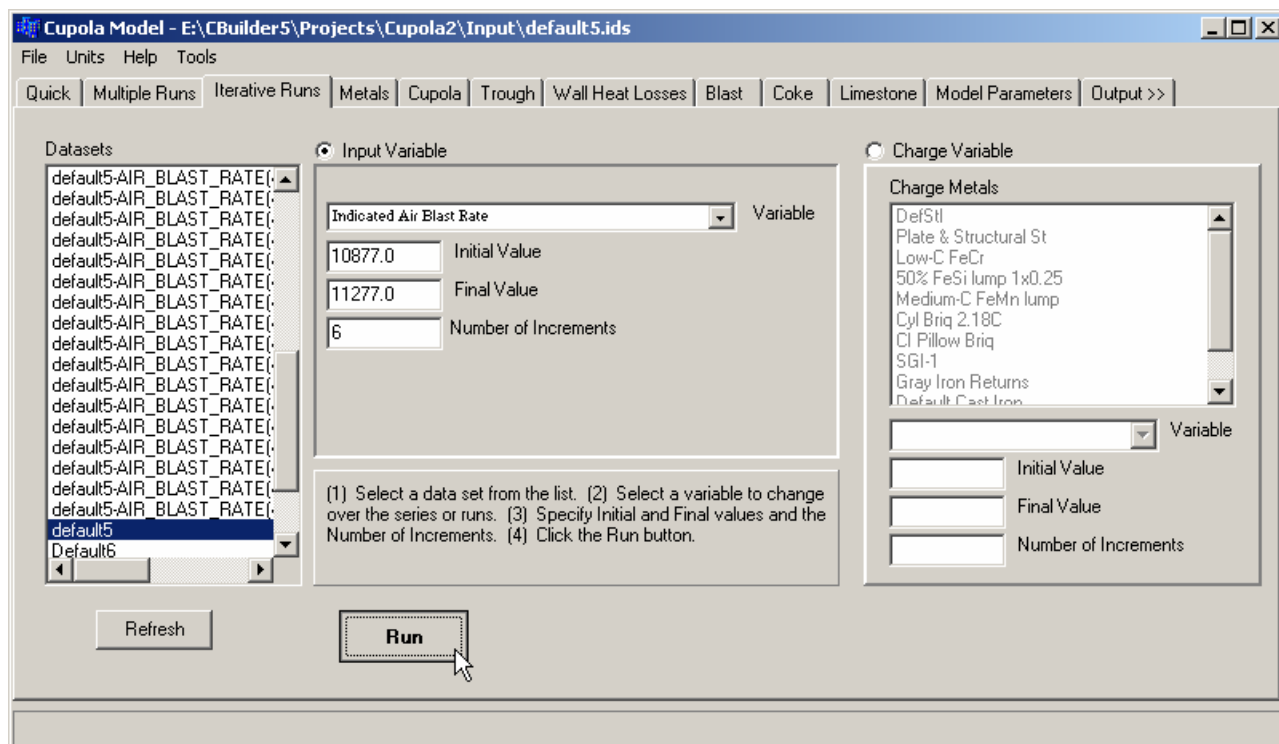


Figure 19. “Iterative Runs” screen.

- *Data storage*

Most of the remaining tabs on the “Quick” screen store the data related to the physical dimensions of the cupola and the properties of the charge materials. A few examples will be examined here.

The screenshot shows the 'Cupola Model' software window. The title bar indicates the file path: 'E:\CBuilder5\Projects\Cupola2\Input\BCIRA_1057_M01.ID5'. The menu bar includes 'File', 'Units', 'Help', and 'Tools'. The tab bar at the top contains: 'Quick', 'Multiple Runs', 'Iterative Runs', 'Metals', 'Cupola' (selected), 'Trough', 'Wall Heat Losses', 'Blast', 'Coke', 'Limestone', 'Model Parameters', and 'Output >>'. The main area is divided into two panels. The left panel, titled 'Tueres', contains input fields for: 'Number of Tueres' (4.00), 'Outer Diameter of Tueres (ft)' (0.4068), 'Inner Diameter of Tueres (ft)' (0.3346), and 'Tueres Protrusion Beyond Refractory (ft)' (G: 0.4593). There is a checkbox for 'Split Blast Cupola' which is currently unchecked. The right panel, titled 'Geometry', contains input fields for: 'A' (16.25) - Distance: Top of Tap Hole to Effective Top of Charge (ft), 'B' (16.25) - Distance: Top of Tap Hole to Start of Upper Lining (ft), 'D' (1.1713) - Distance: Top of Tap Hole to Top of Well (ft), 'E' (2.50) - Inner Diameter of Cupola at the Tueres (ft), and 'F' (2.50) - Inner Diameter of Cupola in Well (ft). Below these are radio buttons for 'Front Slagging' (selected) and 'Rear Slagging'. Further down are input fields for 'C' (1.4993) - Distance: Top of Slag Tap Hole to Tueres Center (ft) and 'Slag Dam Height From Top of Slag Taphole (ft)' (0.397). At the bottom of the window are four buttons: 'Load Cupola', 'Save Cupola', 'Delete Cupola', and 'Picture'.

Figure 20. Cupola dimensions screen.

Figure 20 shows contents of the “Cupola” screen. The box on the left is concerned with the cupola tuyeres. If the cupola in question has two rows of tuyeres, clicking on the “Split Blast Cupola” box opens another window containing the additional measurements that are needed. The box on the right contains dimensions in the vertical direction. If the cupola is rear-slagger then other needed dimensions appear if the “Rear Slagging” circle is checked.

If there is a problem understanding the meanings of the various distances called for by the menu. Pressing the button at the bottom of the screen labeled “Picture” brings up a diagram of the cupola where all the required dimensions are illustrated. The drawings are

provided in Figures 3a, 3b and 4. The distances are labeled with letters A-G which correspond to the letters found to the left of the appropriate boxes in the “Cupola” screen.

Figure 21 shows a typical charge material screen. It asks for the common parameters connected with charge materials, i.e., charge weight, composition and cost. It also asks for less common and relatively poorly understood properties such as thickness, amount of dirt and a value for HTAEF. The model only requires approximate values for these latter variables. For the variable, “dirt”, default values are provided. The thickness of some scrap is known. For purchased scrap, the specifications used to purchase scrap usually contain the limits for thickness. Using an average is usually adequate. Inspection is better. HTAEF is the fraction of area exposed to the blast air. For bars the values is close to unity. For pipe the value is 0.5. For engine blocks, for example, less than half of the casting surface is exposed to the blast so an appropriate value might be 0.3 or 0.4.

Material Description	
Cast Iron #1	

Property	Value
Weight (lb)	521.96
Section Thickness (in)	32.0092
Heat Transfer Area Effective Fraction (HTAEF)	33.80
Cost per ton	234.3844

Composition			
3.40	% Carbon	1.00	% Silica
2.50	% Silicon	7.50	% Al ₂ O ₃
0.40	% Manganese	7.50	% CaO
0.11	% Sulfur	35.00	% FeO
		50.00	% SiO ₂

Typical Dirt Values

OK Cancel

Figure 21. A typical screen used to specify the properties of a metallic charge material.

▪ ***Experimental studies***

Two types of experimental studies were contracted. The first was for experimental studies of the chemical and physical properties of silicon carbide briquettes. The contract for this study was given to Professor Von Richards at the University of Missouri-Rolla.

The second contract was for cupola studies relating to the performance of silicon carbide. The contract for this study was given to Professor Daniel Mejia at the University of Antioquia, Medellin, Colombia. This laboratory was chosen because the charges for the best cupola facility, the DOE laboratory in Albany, OR, were impossibly high. The University of Antioquia charged less for seven experiments than the DOE Albany facility charged for a single experiment.

▪ ***Laboratory studies at the University of Missouri-Rolla***

Studies were conducted at the University of Missouri-Rolla from February to August 2002. The program was divided into three main sub-projects: (1) Qualitative understanding of how briquettes of SiC break up in the cupola. (2) Qualitative understanding of how SiC is wetted by iron and slag. (3) Kinetics of SiC dissolution in iron with different compositions. The outline of studies is included in the appendixes that follow. Also Included in the appendixes are the monthly reports for February through July 2002. No further reports were made.

At the end of August 2002 the project spent 60% of the contracted cost for the project. Experimental data was available for only the first sub-program and indications were that it shed little light on the objective (see S. Katz' comments in a letter dated July 11, 2002, entitled; Thoughts re: University of Missouri Rolla Monthly Report for July 2002"). After investigating the problems in September the program was cancelled on October 14, 2002. The letter of cancellation sent to the Vice-Provost for Research, Dr. Wayne Huebner is included in the appendixes.

The failure of this program was a blow to the overall modeling program as the information was necessary for developing algorithms characterizing the behavior of silicon carbide in the cupola. This failure is responsible in large measure to the difficulties still being experienced in the computer modeling of silicon performance.

▪ *Cupola studies at the University of Antioquia.*

The objectives of the program with the University of Antioquia were to obtain an understanding of the chemical and physical process that silicon carbide undergoes in the cupola and to understand where it happens. The specific goals were: (1) Determine the location in the cupola where silicon carbide dissolves in iron. (2) Determine the importance of the binder used for silicon carbide briquettes with respect to the dissolution of silicon carbide in iron. (3) Determine the differences in the dissolution of silicon carbide in iron and steel. (4) Determine the fate of free carbon and silica that are contained in silicon carbide briquettes. It was planned that the needed information would be obtained in a series of seven experiments. The document outlining the planned experiments is provided in the appendixes.

To obtain data from inside the cupola the project paid for the design, fabrication and installation of six specialized gate valves that were attached to the cupola wall at intervals of 4", starting at tuyere level. In addition, steel probes were fabricated that were introduced through the gate valves to secure samples of the materials in the interior of the cupola.

This program also had its difficulties. Although the staff in this case was very competent the cupola presented serious problems preventing the achievement of steady state conditions which requires 4-5 hrs of operation. Good data was obtained from the last two experiments carried out on December 13, 2003 and September 18, 2004 which showed there were differences in the performance of different types of commercial silicon carbide materials used by foundries (see Figure 22). However the final experiment which would tie all the information together failed. The failed experiment is described below as well as the actions currently being taken to repeat the experiment. The last two reports are provided in the appendixes.

Figure 22 shows cupola data that illustrates there are differences in the performance of different commercial silicon carbide materials. Two commercial alloys were added together to the cupola charges. The relevant details are seen between hours 1 and 5. Between hour 1 and 2 there was a rapid rise in silicon and a second rise occurred at hour 3.75 each was caused by a different commercial material. The first rise occurs very shortly after the both alloys entered the melt zone. Clearly one material dissolved much faster than

the other. For modeling purposes it is necessary to understand the differences and also what processes made the materials perform differently.

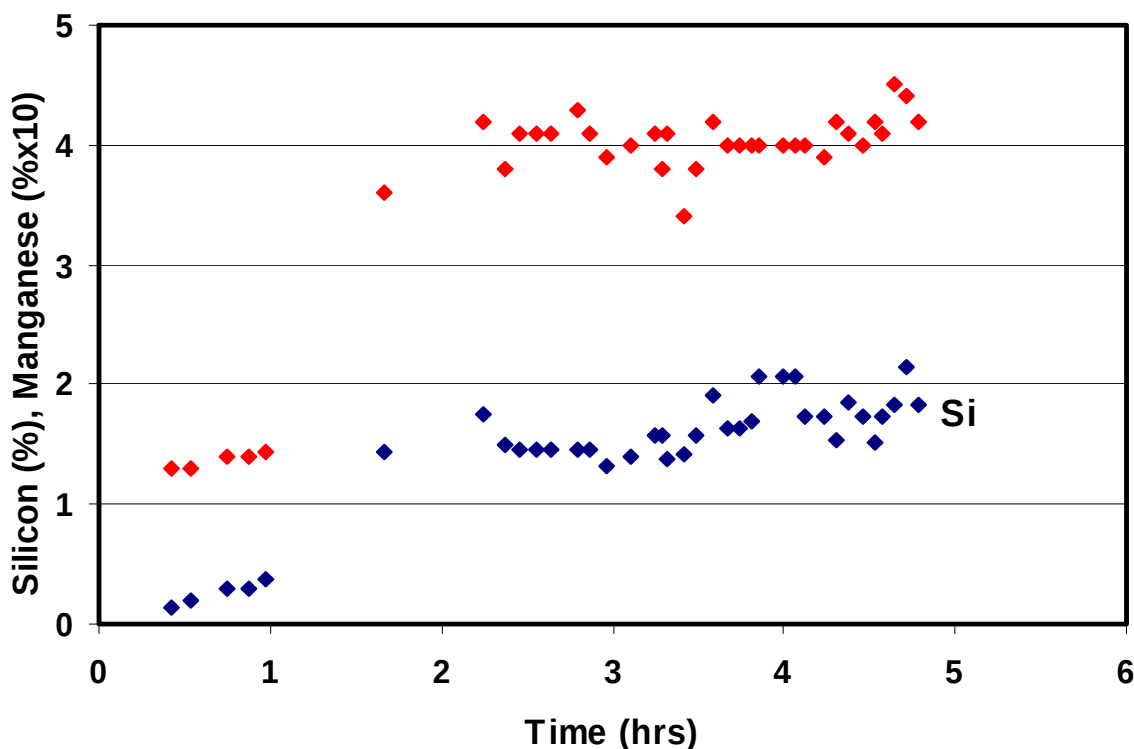


Figure 22. Cupola data on the performance of two commercial SiC materials.

As indicated, the experiment carried out in September, 2004 had another major objective that unfortunately failed. After operating for five hours, air blast to the cupola was discontinued and liquid nitrogen was injected through the tuyeres in order to quench the cupola. After cooling to room temperature the cupola contents were to be analyzed, using archeological techniques, in order to get first hand information about the reactions and changes in materials throughout the cupola. Unfortunately all the metallic materials in the cupola melted so there was nothing to analyze.

After the fact, a theoretical analysis of the effect of the high flow rate of nitrogen on the temperature conditions in the cupola indicated a high temperature wave progressively passed through the cupola which melted the metallic ingredients. Since the problem was never conceived to happen it could not have been avoided. The analysis suggested a better procedure. Since all of the current contract funds are exhausted, S. Katz and Associates

has undertaken to obtain funding for another attempt at quenching the cupola. Records indicate that cupolas have only been quenched twice. These events took place in 1945 and the early 1950s. Very few analyses were performed as a result very little of importance was uncovered. A proper analysis of a quenched cupola will not only provide the insight needed to properly model silicon carbide behavior but will uncover many important aspects of cupola operation that will vastly improve our understanding of how cupola work. Reports relating to the quenching experiment and the heat analysis conducted afterward are given in the appendixes.

▪ **Marketing**

The marketing of the model is covered in two sections. The first section is concerned with an assessment of the marketing climate. The second section gives anticipated model costs and services.

▪ *Marketing climate*

In 2001 New Horizon Technologies conducted a study assessing the marketing climate that the model faces. In general the assessment is still valid. Their study forms the basis for this discussion. New developments will be discussed within the structure provided by the study.

Technology overview – “Currently, cupola furnace control relies on the intuition of the operator, as there is no automation involved. The quality of output, energy requirements, and environmental impacts are all dependant on the skill and experience of the operator.” These problems are more severe today as foundries have lowered operating expenses by retiring older, more experienced operators and employing younger workers without the years of foundry experience. In this environment the model can be used as a substitute for the lost operating experience to serve as a real time guide to cost and energy efficient operation.

Marketing overview – The cupola produces 2/3 of the iron used for castings. Severe competition from overseas foundries has damaged the US iron foundry industry, leading to foundry closing and bankruptcies. In 1999 there were an estimated 175 foundries operating about 250 cupolas. It would not be surprising that these numbers have been reduced by

15%. Although the market has shrunk, competition has increased making it more important for the remaining foundries to operate more efficiently.

It is safe to say that cost reduction has become an almost overriding goal of foundries. Significant inefficiencies exist in almost every cupola operation. Since charge materials represent a very large fraction of the cost of a casting, large cost savings are possible with relatively small increases in efficiency. The table below illustrates this. As shown small reductions in coke or alloy usage can save foundries of up to millions of dollars/year. With such high potential savings it would seem the prospect for model sales would be good.

Tons Iron/hr	Reduce Coke 1%	Reduce Si 0.25%
100	1,100,000	1,160,000
80	880,000	928,000
60	660,000	699,000
40	440,000	464,000
20	220,000	232,000
10	110,000	116,000

Another indicator for the need of the model is the very large increases in the cost of scrap, alloys and coke. The severity of the cost increases over the last 2.5 years is indicated in the following table.

Yet another factor that favors the sale of the model is the degradation of the quality of many the charge materials due to increasing demand. Coke quality has been seriously diminished and poorer grades of scrap are increasingly used. The return to earlier quality seems remote. The model is the best hope for providing the direction to minimize the difficulties presented by these changes.

Some experts that were interviewed by New Horizon Technology indicated cupola furnace operators would also benefit from the training tools provide by the model.

Scrap and Alloy Prices: January 2002 vs. June 2004

Scrap Material	Cost 2004 \$/ton	Cost 2002 \$/ton	Ratio \$/t 2004/2002
<u>Steel</u>			
Plate & Structural	240	140	1.71
Busheling	240	140	1.71
Foundry Steel	185	112	1.65
<u>Cast Iron</u>			
Basic Pig Iron	340	150	2.27
Clean Auto-Cast	187	92	2.03
Briquetted Borings	182	112	1.63
Loose Borings	155	84	1.84
<u>Alloys</u>			
36% Silicon Carbide (24% Si)	250	200	1.25
50% Ferrosilicon Briquettes (50%Si)	480	330	1.45
50% Ferrosilicon Lump	700	420	1.67

Although there are significant number of reasons for the sale of the model there are also significant barriers to its sale. From our estimates items 1 and 2 are the most serious.

1. With the financial difficulties facing foundries today, demanded payback periods have shrunk drastically. At present the model has no history of cost savings and reductions in emissions on which to base the payback period.
2. The majority of foundries employing cupola melting are small companies that may not be able to afford the investment in a model. They could also lack the expertise or the desire to utilize new computer technology.
3. The market survey conducted by New Horizon Technology indicated there is the perception that the model might not be user-friendly and too difficult to run. We estimate that a certain degree of skill is necessary to effectively operate the model. It probably requires the abilities of someone with some college education.
4. The industry may be hesitant to adopt new software without assurances of adequate training and ongoing customer support.

Marketing features and sales structure. Many of the issues raised in the New Horizons Technologies survey have been addressed and are listed below.

1. Model operation has been simplified with all operations conducted from a single screen.
2. Although the model is easy to operate it still requires some understanding of cupola performance characteristics in order to intelligently question the model. In many foundries the cupola operator does not have this ability. In order to make the model useful to the majority of cupola operators the model may be adapted to work in concert with an expert-systems program. In this respect, contact has been made with Professor M. Abdulrahman⁴⁴, Tennessee Tech University who has developed such a program. Another method for achieving this result is to develop a Neural Network Model where the inputs and outputs of many thousands of cupola runs are assembled and can be retrieved in extremely short times. Such a system has been developed for the cupola model by Dr. Denis Clark, INEEL⁴³. The INEEL work did not cover a sufficient number of variables and therefore further work is necessary to achieve the level of required complexity.
3. The most time consuming aspects of the model are the initial entering of needed cupola and charge material data and fine tuning the model to more exactly match the unique operational characteristics of the cupola.
4. The model will be offered for about \$5,000. This is \$3,000 less than the price charged by Process Metallurgy International, Inc. the entity that sold an early version. This price includes a Users Guide and six months of telephone and e-mail support. Beyond the six month period support and upgrades will be available at \$1,500/year.
5. There are two levels of customization. The first includes the installation of required input data which includes cupola geometry, other furnace parameters, blast and charge materials variables and model computational factors (cost: \$1,500). The second level of customization is fine tuning the model to match the specific performance of the cupola (cost \$3,000).
6. In-plant training: includes two days of in-plant training and includes the first level of customization (cost: \$3,500 + travel expenses).
7. A consulting service will be provided where customized studies are performed. This is aimed at foundries that would like to address a single issue but do not have the interest to perform the modeling (cost \$1,000/day).

8. A website will be posted that explains the company the products and the services
9. Currently, several foundries have been approached and have shown their willingness to trade a cupola optimization study of their operation, which includes items 2 and 3 above, for their permission to use the savings ascribed to the model for advertising purposes. This would include posting the information on our website without identifying the foundry. They agree to pay \$4,500 for this \$10,000+ package.

▪ **Conclusions**

Major advances and improvements in both the predictive accuracy and capabilities of the model have been made. New features include modeling of divided-blast and rear-slagging cupola modes. Extensive improvements have been made to the capabilities and user-friendliness of the graphic user interface. Model tuning tools have been provided to further customize the model for the user. The model thus creates a powerful tool for the improvement of cupola performance and cost. As part of the sales effort S. Katz Associates will also offer aside from the model, a Users Guide, telephone and e-mail technical support, customization of the model at two levels, in-plant training and consulting services.

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GOLDEN FIELD OFFICE
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Solicitation Number: DE-PS36-00G010787
Grant/Proposal Number: 01G011034
GANTT CHART

Month Starting August 2001	A	S	O	N	D	J 02	F	M	A	M	J	J	A	S	O	N	D	J 03	F	M	A	M	J	J	A	S	O	N	D	J 04	F	M	A	M	J
Tasks																																			
Cupola Modeling																																			
Radiant Heat Transfer																																	Completed		
Divided Blast																																	Completed		
Rear Slagging																																	Completed		
Model Corrections																																	Complete		
Graphic User Interface																																			
User Friendly GUI																																	Completed		
Range Restrictions																																	Completed		
New Algorithms																																	Completed		
Marketing Efforts																																			
TEES Market Survey																																	Completed		
Marketing Plans																																	Cmpl		

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Task																																				
SiC Cupola Studies																																				
Design/Build Install Probes																															Completed					
Prepare/Ship SiC Brix																															Completed					
Cupola Studies																																				
SiC Lab Studies																																				
Construct Facility																															Completed					
Prepare Slags & Irons																															Completed					
Strength Tests SiC Brix																															Project Cancelled					
SiC Wetting Iron & Steel																															Project Transferred to SiC Cupola Studies					
Kinetics SiC Dissolution																															Project Cancelled					
Reaction SiC +FeO																															Project Transferred to SiC Cupola Studies					
Kinetics SiC+FeO																															Project Cancelled					
Indirect Costs																																				
Reports																																				
Meetings																																				

	Milestone/Task Title	Original Planned Completion Date	Revised Planned Completion Date	Actual Completion Date	Responsible Organization	Original Projected Cost (Fed/ Non-Fed)	Revised Projected Cost (Fed/ Non-Fed)	Actual Completed Cost (Fed/ Non-Fed)	Milestone Notes
1	Radiant Heat Transfer	August 15, 2001	November 30, 2001	December 31, 2001	Stanek	26,813/ 28,613	19,000/ 33,000	18,327/ 32,798	Completed prior to this reporting period
2	Two Rows Tuyeres + Rear Slagging	November 15, 2001	May 30, 2002	May 30, 2002	Stanek	8,688/ 9,844	9,000/ 10,000	8,688/ 562	Completed prior to this reporting period
3	Testing Model & Corrections	June 15, 2002	September 30, 2003	May 31, 2004	Stanek	6,023/ 6,740	50,000/ 68,000	60,586/ 99,026	See Milestone Notes
4	SiC Cupola Studies	June 15, 2002	December 31, 2003	June 30, 2004	Mejia/Katz	52,880/ 35,350	85,000/ 90,000	82,802/ 86,330	Completed prior to this reporting period
5	SiC Laboratory Studies	April 15, 2002	September 30, 2003	September 30, 2003	Katz	62,807/ 47,675	36,500/ 35,000	36,528/ 34,706	Program cancelled before completion
6	Enhanced GUI	January 15, 2002	September 30, 2003	May 31, 2004	Landefeld	15,789/ 4,725	26,500/ 12,000	26,229/ 13,866	See Milestone Notes
7	Marketing Efforts	July 15, 2002	May 30, 2003	June 15, 2004	Katz	8,100/ 4,500	12,000/ 12,000	10,104/ 39,557	See Milestone Notes
8	Indirect Costs			June 31, 2004	Katz	18,900/ 62,056	20,000/ 36,000	17,798/ 35,372	
9	Semi Annual Report May 31, 2003	April 30, 2004	April 30, 2004	May 1, 2004	Katz	Included in Indirect Costs			
10	Final Technical and Financial Status Reports	June 30, 2004	June 30, 2004	December 31, 2004	Katz	Included in Indirect Costs			
Total						200,000/ 199,503	258,000/ 296,000	258,000/ 342,342	

Attachment C

Energy, Environmental, and Economic Savings for I&I

The installed unit for the *I&I project* technology is a computer model of a cupola furnace.

The installed unit for the *comparable competing* technology as presented in the original proposal is : **there is no comparable competing technology.**

Energy Savings

Provide the energy savings for the project technology versus the comparable competing technology. **The conservative, potential, energy savings are 1.59×10^{10} MJ/yr (1.50×10^{13} Btu/yr). See Table 1 below.**

The *projected* energy consumption for the *project* unit in Btu/yr/unit was (at the beginning of the project) _____.

The energy consumption for the *I&I project* unit in Btu/yr/unit is _____.

Provide assumptions and references for the derivation of your values. (Refer to Attachment H for energy conversion factors)

- A. F. Neumann and E. Baake, "Reduction of energy consumption and environmental pollution during melting in iron foundries – Part2. Crucible induction furnaces," Casting Plant +Technology International, #4 (1997) 8-12.
- B. K.H. Kirgin, "Looking Forward: Ductile Iron's 'Roar' into the 21st Century," Modern Casting, October 1998, pg. 64.
- C. F. Neumann and E. Baake, "Reduction of energy consumption and environmental pollution during melting in iron foundries – Part1. Cupolas," Casting Plant +Technology International, #3 (1997) 18-27.

The energy consumption for the *comparable competing* unit in Btu/yr/unit is _____.

Provide assumptions and references for the derivation of your values. (Refer to Attachment H for energy conversion factors) **See calculations below.**

Environmental Savings

Provide the environmental savings for the project technology versus the comparable competing technology. **The conservative, potential, reduction in CO₂ emissions is 4.80×10^6 metric-tons/yr (5.28×10^6 tons/yr). See Table 1 below. For references see References A and C above.**

Economic Savings

Provide the economic savings for the project technology versus the comparable competing technology.

The *projected* unit cost for the *I&I project* technology (at the beginning of the project) was **There was no available technology.**

Define the unit cost for the *I&I project* technology **The base price for the computer program is \$6,000.**

Define the unit cost for the *comparable competing* technology **There is no comparable technology.**

Provide assumptions to allow the reviewers to understand the derivation of the stated values.

CRITERION 3. ENERGY SAVINGS AND ASSOCIATED ENVIRONMENTAL BENEFITS

The cupola model can provide the needed impetus for speeding the transformation of the cupola to a more energy efficient process with the additional benefit of lower greenhouse gas emissions. The benefits will mainly derive from saving energy and greenhouse gases by:

- Adding refractory linings to cupolas.
- Converting cold blast operations to hot blast.
- Recovery of heat from the exiting hot gasses.
- Reduction of silicon oxidation losses.
- Reduction of in-plant scrapped iron.
- New innovations using the model.

Although the benefits of refractory linings and heating of blast air are known to be beneficial, the cost/benefit relationship is different for each operation. It is the ability of the model to demonstrate the site-specific benefits that is expected to drive the more rapid introduction of these enhancements.

Greenhouse gas emission regulations could be the demise of the cupola, despite the fact that electric induction furnaces produce higher CO₂-emissions (when emissions from electric generation are included) [A,B]. The reduction in emissions enabled by the improvements treated here will provide half the amount required by the 1998 Kyoto Protocol. Further reduction in CO levels will be made possible by process improvements made possible by the cupola model, e.g., the safe conversion of CO to CO₂ in the cupola stack.

Table A summarizes the potential savings in energy and greenhouse gas generation to be obtained from accelerated improvements to cupola operations and the savings from not forcing cupola conversion to electric melting. The total energy savings are 1.59x10¹⁰ MJ/yr (1.50x10¹³ Btu/yr). The total reductions in CO₂ emissions are 4.80x10⁶ metric-tons/yr (5.28 x10⁶ tons/yr). The calculations are based on data from commercial operations [4,5]. Supporting calculations are provided below.

Cupola iron production in the U.S.

Metric tons of cupola iron melted in 2003 in the U.S was 7.4x10⁶ tonnes/yr. (down 36% since 1999)

$$7.4 \times 10^6 \frac{t \text{ UScastings}}{yr} \times 0.60 \frac{t \text{ cupolacastings}}{t \text{ UScastings}} \times 2.0 \frac{t \text{ melted}}{t \text{ cupolacastings}} = 8.9 \times 10^6 \frac{t \text{ cupolamelt}}{yr}$$

There are three basic arrangements of cupola melting and two arrangements of electric induction melting; each has different energy metrics. Table 2 [5,6] provides all of the metrics used to generate the data in Table 1. Estimates for the fraction of each cupola and electric furnace type were obtained, respectively, from manufacturers: Modern Equipment Co. and Inductotherm, Inc. Abbreviations used in Table 4 are: HB = Hot Blast; CB = Cold Blast; L = Refractory lined; W = water-cooled shell.

The equations below only calculate the energy savings. Savings of CO₂ were obtained by substituting tonnes CO₂/tonne Fe, from Table 2, for the corresponding energy values (MJ/tonne) in the equations below.

Extra energy required if cupola operations were converted to electric melting.

$$\text{Extra Energy} = 8.9 \times 10^6 \frac{t \text{ melted}}{yr} \left[6,650 \left[\frac{MJ}{tonne} \right]_{electric} - 5,772 \left[\frac{MJ}{tonne} \right]_{cupola} \right] = 0.78 \times 10^{10} \frac{MJ}{yr}$$

Energy saved by adding linings to cupolas without linings.

$$\text{Energy Saved} = 8.9 \times 10^6 \frac{t \text{ melted}}{yr} \times 0.45 \frac{\text{cupolas w/o linings}}{\text{total number cupolas}} \left[5,921 \frac{MJ}{tonne} - 4,932 \frac{MJ}{tonne} \right] = 0.42 \times 10^{10} \frac{MJ}{yr}$$

Energy saved by adding hot blast to cold blast cupolas.

$$\text{Energy Saved} = 8.90 \times 10^6 \frac{t \text{ melted}}{yr} \times 0.20 \frac{\text{cold blast cupolas}}{\text{total number cupolas}} \left[6,908 \frac{MJ}{tonne} - 5,921 \frac{MJ}{tonne} \right] = 0.185 \times 10^{10} \frac{MJ}{yr}$$

Energy saved by reducing silicon oxidation losses.

Average cupola silicon loss is 0.6% of the charge weight. It is estimated the model will reduce the losses by 0.2%. The energy required to produce silicon was taken as 21,600 MJ/tonne (data from Elkem Corp.). The CO₂ savings were calculated from the equation: SiO₂ + C = Si + CO₂.

$$\text{Energy Saved} = 8.9 \times 10^6 \frac{t \text{ melted}}{yr} \times 0.002 \frac{\text{tonne Si saved}}{\text{tonne melt}} \times 21,6200 \frac{MJ}{tonne} = 0.041 \times 10^{10} \frac{MJ}{yr}$$

$$\text{Reduced CO}_2 = 8.9 \times 10^6 \frac{t \text{ melted}}{yr} \times 0.002 \frac{\text{tonne Si saved}}{\text{tonne melt}} \times 1.57 \frac{\text{tonne CO}_2}{\text{tonne Si}} = 0.028 \times 10^6 \frac{\text{tonnes}}{yr}$$

Energy saved by reducing in-plant scrapped iron.

Assumed 3% in-plant scrapped iron.

$$\text{Energy Saved} = 8.9 \times 10^6 \frac{\text{t melted}}{\text{yr}} \times 0.03 \frac{\text{tonne iron saved}}{\text{tonne scrap}} \times 5,772 \frac{\text{MJ}}{\text{tonne}} = 0.162 \times 10^{10} \frac{\text{MJ}}{\text{yr}}$$

Table A. Summary of potential energy savings and CO₂ emission reduction

Operation	Energy Savings	Reduced CO ₂ Emissions
	MJ/yr	Metric tons/yr
Prevent conversion to electric	0.78x10 ¹⁰	2.79x10 ⁶
Add refractory linings	0.42x10 ¹⁰	1.28x10 ⁶
Add hot blast	0.19x10 ¹⁰	0.62x10 ⁶
Reduce silicon loss	0.04x10 ¹⁰	0.03x10 ⁶
Reduce melting scrap	0.16x10 ¹⁰	0.08x10 ⁶
	Total: 1.59x10 ¹⁰	4.80x10 ⁶

Table B Energy and emission metrics for cupola and electric furnaces.

Type Operation	U.S. Melting (%)	Total Energy Requirement (MJ/tonne Fe)	CO ₂ Emissions (tonnes CO ₂ /tonne Fe)	Coke Usage (% scrap wt)
<u>Cupola</u>				
HB, L, W	35	4,932	0.285	9-11
HB, W	45	5,921	0.320	11.5-12.5
CB, L	20	6,908	0.350	13-15
		Avg. 5,772	Avg. 0.314	
<u>Electric</u>				
Mains	30	6,900	0.400	
Med. Freq.	70	6,400	0.370	
		Avg. 6,650	Avg. 0.385	

Table C. Savings for small improvements in operation

Tons Iron/hr (Ton Iron/yr)	Reduce Coke 1% of iron wt	Reduce Si 0.25% of iron wt
	(\$/yr)	(\$/yr)
100 (400,000)	1,100,000	1,160,000
80	880,000	928,000
60	660,000	699,000
40	440,000	464,000
20	220,000	232,000
10	110,000	116,000
4.44x10 ⁶ tons Iron/yr	13.3x10 ⁶	14.0x10 ⁶

Attachment E

Commercialization Table
(I&I Category 2 Projects Only)

<i>Category</i>	U. S. Market				
	Project Completion Year 2004	5 Years after Completion	10 Years after Completion	15 Years after Completion	20 Years after Completion
(A) Total Number of Units in U.S. Market (Addressable Market)	150	130	120		
(B) Total Number Installed Units Using Your Technology (Capturable Market)	10	75	100		
(C) Market Penetration = $B/A \times 100\%$	6.7%	57%	83%		

- **Your technology** - Total number of units employing the technology developed with the I&I grant. This number includes, but is not limited by the number of units that the industrial partner will sell or operate.
- **Addressable Market** is that fraction of the entire market to which your technology is truly applicable. Remember to project the number of installed units by first considering limiting factors related to technology and market fit. For instance, the proposed technology may only fit a certain size range of equipment, i.e., a proposed glass furnace burner technology can only be constructed is sizes smaller than 5 MMBtu/hr, or the proposed burner can only be applied to recuperated furnaces, not regenerative furnaces.
- **Capturable Market** is that fraction of the Addressable Market willing to accept your new technology. Remember that the rate at which industrial technologies capture the market depends on technology characteristics (new vs. retrofit), industry characteristics (industry growth, competition), and external factors (government regulations and trade restrictions). Consider these limiting factors related to rates of market acceptance before projecting the number of installed units in the Capturable Market.

General Scope of Marketing Efforts -

Estimated Market – Given above.

Commercialization Strategy –

1. The product will be accurate and easy to use. The model has utility at two levels (1) guidance for optimum performance in real time and (2) Longer decision making such as making decisions as to the best materials to use for least cost charging or making cost/benefit judgments for major modifications to the cupola. At present the model is accurate and it is relatively simple to use by someone with a two year attendance at a college this covers the second level of utility. It is not at all certain that the cupola operator, which at many foundries may not even have a high school education could make use of the model. Efforts will be made in the near future to simplify certain aspects to make it really attractive for real time decision making.
 - a. For improving the real time use of the model discussions are being held with Professor Mohamed Abdelrahman, Tennessee Technical University⁴⁴, concerning the combination of the current model with an expert system model which he has developed
 - b. We will also investigate improving the user-friendliness of the model.
2. The model will be sold with the following options:
 - a. The basic model with a well written users guide. Also included in the price is six months of support by telephone or email. Support is renewable at a cost.
 - b. Many data entries must be made as the model considers over 100 variables. Based on supplied information all the user's data will be inputted by S. Katz Associates. The user will supply the information before receiving the CD.
 - c. There are always small differences between cupolas that are not captured by the entered data. A service will be provided at extra cost to tune the model to the performance of a particular cupola.
 - d. The final option is to have the model installed by our people. Also included with this option is two days of lectures and teaching. We have located three very capable people who are anxious to carry out teaching efforts at the foundries.
 - e. It is hoped that a special version which includes the expert system will prove to be viable.
 - f. Another down-the –road option is to use Neural Networks to memorize many sets of modeling data so that optimum suggestions for operation can be obtained in extremely short time.
3. An attractive website is in the planning stages. A very capable company has been engaged to prepare the website and we are considering link-ups with other sites.

4. In order to instill confidence in the product. We are working with three foundries to optimize their cupola process. The price has been reduced in exchange for their permission for S. Katz Associates to publicize the cost and process improvements on our website and in other advertisements.
5. We have negotiated with the American Foundry Society to trade a commission for sales for free advertisement in the monthly foundry journal, Modern Casting.
6. We have presented the model at numerous foundry meetings.

Attachment F

Final Cost Sharing

#	Company Name	Company Type*	In-Kind Contribution	Cash Contribution	Total
1	V. Stanek	Small business	105,532		105,532
2	D. Mejia	University	36,225		36,225
3	C. Landefeld	Small business	9,896		9,896
4	S. Katz	Small business	114,409		114,409
5	Exolon	Business	30,328		30,328
6	V. Richards	University	10,360		10,360
7	A. Landefeld	Small Business	1,000		1,000
8	Bosch Foundry	Business	2,540		2,540
9	Auburn Analytical	Small Business	4,110		4,110
10	General Motors	Business	12,250		12,250
11	G. Kruger	Small Business	1,000		1,000
12	American Foundry Society	Non Profit	20,000		20,000
	DOE			258,000	258,000
	Total		347,650	258,000	605,650

Only Include Cost-sharing Partners

* small business, business, non-profit, university, state agency, or utility

Attachment G

Partners and Contractors

#	Company Contact	Address	City	ST	Zip	Phone / Fax / e:mail
1	V. Stanek	343 Vysocanska	Prague	Czech Republic		
2	Adam Landefeld	14619 43 rd Place Apt. 1504	Bellevue	WA	98007	
3	Prof. D. Mejia	University of Antioquia	Medellin	Columbia		
4	Prof. V. Richards	University of Missouri-Rolla	Rolla	Missouri	65409	
5	T. Mutton	52367 42 nd Ave.,	Lawrence	MI	49064	
6	Dr. J.Santner	American Foundry Society 1695 Penny Lane	Schaumburg	IL	60173	

List all companies involved in the project (equipment vendors, consultants, subcontractors, customers

- 1) Dr. Vladimir Stanek – Contractor – Carried out the cupola modeling program
- 2) Adam Landefeld – Contractor – Produced the Graphic User Interface for the cupola model.
- 3) Professor Dan Mejia – Contractor – Performed cupola studies at the University of Antioquia to characterize the performance of silicon carbide in the cupola.
- 4) Professor Von Richards – Contractor – Performed laboratory studies to develop mechanisms for the behavior of silicon carbide in the cupola.
- 5) Tom Mutton - Exolon Corp. – Consultant on the behavior and material properties of silicon carbide.
- 6) Dr. Joseph Santner - American Foundry Society – Consultant – Advised on tactics for marketing. Provided facilities for meetings.