CONTROL AND OPTIMIZATION
OF FLASH SMELTING

BY

© ERIC PARTELPOEG

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If golde ruste,
what shal iren do?

Chaucer: Prologue to
The Canterbury Tales

ABSTRACT

A computer model is developed to simulate the steady-state operation of flash furnaces. The model can be used as the core of a real-time furnace control system, or as in this thesis, as a tool to aid in comparing different flash smelting operating modes.

The model shows that the optimum flash smelting mode is autogenous, i.e. with no hydrocarbon fuel additions. Furthermore, flash furnaces should operate with oxygen-enriched air, and should endeavour to carry out as much oxidation as possible in the furnace itself, and thus minimize the amount of converting required. This mode of operation minimizes the volume of off-gases generated in the smelter in all cases and minimizes the energy requirements in most cases.

RESUME

Un modèle mathématique est developpé dans cette thèse pour simuler le fonctionnement des fours flash à l'état de régime. On peut utiliser ce modèle comme l'élément fondamental du système de contrôle du four en temps réel ou, ainsi que dans cette thèse, comme un outil servant à comparer les différents modes opératoires de ces fours.

Ce modèle démontre que le fonctionnement optimal des fours flash est autogène, c'est-à-dire sans addition de carburant.

De plus, ces fours devraient être utilisés avec de l'air riche en oxygène et devraient permettre la plus grande oxydation possible pour minimiser ainsi les transformations requises par la suite pour la production de cuire brut. Cette façon d'opérer minimise les volumes de gas rejetés de la fonderie dans tous les cas, et minimise la quantité d'énergie nécessaire dans la plupart des cas.

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CHAPTER 1

OBJECTIVES

Flash smelting emerged in the 1970's as the most significant ~~copper~~ smelting process in terms of new installed smelting capacity. It did so because, compared to alternative copper smelting processes, flash smelting reduces energy consumption and facilitates handling and treatment of effluent off-gases.

The objectives of this thesis are to present a fundamental model of steady-state flash smelting. The model developed in this thesis is based upon element mass balance equations and heat balance equations. These equations are solved simultaneously to determine the steady-state operating mode of a flash furnace.

The model is used (i) to demonstrate the principles of flash smelting control and optimization and (ii) to determine the optimum smelting mode based on energy and SO2 recovery considerations.

CHAPTER 2

FLASH SMELTING

2.0 INTRODUCTION

Flash smelting consists of injecting fine, dry sulphide concentrate with a source of gaseous oxygen into a hot furnace. Concentrate reacts with oxygen exothermically under these conditions to produce: (i) a liquid sulphide 'matte' phase, (ii) a liquid oxide 'slag' phase and (iii) a gas phase with a high concentration of SO2.

The matte contains most of the primary metal values (copper, nickel, cobalt) while the slag is dilute in these. This concentration of primary metal values into the matte is the main objective of all smelting processes.

Flash smelting is most commonly used for smelting copper concentrates and as a result, this work deals with copper flash smelting exclusively. This chapter introduces and describes:

(a) the raw materials, products, and chemistry of copper flash smelting;

(b) the history and development of copper flash smelting;

(c) the emergence of copper flash smelting as a significant process;

(d) the importance of steady-state furnace operation.

2.1 RAW MATERIALS, PRODUCTS, AND CHEMISTRY OF COPPER FLASH SMELTING

2.1.1 RAW MATERIALS

The principal raw materials required for copper flash smelting are (i) dry sulphide concentrate, (ii) silica flux and (iii) a source of gaseous oxygen. Hydrocarbon fuel may also be necessary to provide supplemental heat.

2.1.2 COPPER CONCENTRATES AND SILICA FLUX

Approximately 90% of the copper in the earth's crust occurs as sulphide minerals of which the most common is chalcopyrite ($CuFeS2$). Chalcopyrite is easily flash smelted since the oxidation of the iron and sulphur is exothermic (page 5). Chalcocite ($Cu2S$) and bornite ($Cu5FeS4$) may also occur to limited extents in orebodies along with chalcopyrite.

These minerals are suitable for flash smelting also but their oxidation reactions, per unit mass of copper, are less exothermic than that of chalcopyrite.

Copper ores are virtually always concentrated by froth flotation resulting in typical concentrate grades for chalcopyrite concentrates of about 20-30 % Cu. One fortunate aspect of this concentration process is that the particle size required for efficient beneficiation (~50 μm) is also very suitable for rapid oxidation during flash smelting.

Concentrates must be dried prior to flash smelting to ensure good dispersion in the oxidant as they enter the furnace. This mixing is necessary for the reactions to occur quickly and efficiently.

Silica flux (typically 90% SiO_2, 10% Al_2O_3, CaO, etc) is usually mixed with the concentrate prior to drying and smelting. Its purpose is to combine with the 'rock' in the concentrate and the iron oxide produced during combustion of the concentrate, to form a liquid slag phase which is immiscible with the sulphide matte phase.

2.1.3 THE OXIDANT

The gaseous oxygen with which the concentrates react in a flash furnace may be in the form of air, air mixed with commercially pure oxygen, or commercially pure oxygen itself. Oxidant temperature varies from 298 K for oxygen-rich oxidants to 1300 K for air. The effects of oxidant composition on furnace and smelter operation are discussed extensively in Chapters 6 and 7.

2.1.4 FLASH SMELTING REACTIONS AND PRODUCTS

The principal reactions which take place during the smelting of chalcopyrite concentrate in a flash furnace can be represented by:

$$CuFeS_2 + 1/2\ O_2 = 1/2\ Cu_2S + FeS + 1/2\ SO_2 \qquad (2.1)$$

$$\Delta H^0_{298} = -100\ MJ/kg\text{-}mol\ CuFeS_2$$

$$FeS + 3/2\ O_2 = FeO + SO_2 \qquad (2.2)$$

$$\Delta H^0_{298} = -460\ MJ/kg\text{-}mol\ FeS$$

(enthalpy data presented in Appendix 2)

As can be seen, the reactions are highly exothermic. They provide much or all of the thermal energy required to heat, melt and superheat the smelting furnace products.

Cu_2S and FeS are completely miscible above ∿1375 K, forming a liquid sulphide matte phase which settles in the hearth of the flash furnace. Cu_2S does not oxidize appreciably in flash furnaces because FeS oxidizes preferentially (Reaction 2.2). Cu_2O which does form is reduced by FeS back to Cu_2S, except for a small fraction which remains as a component of the total copper losses to the slag. The extent to which Reaction 2.2 proceeds is limited only by the amount of oxygen fed to the furnace, i.e. under the well mixed conditions in the flash furnace all of the oxygen fed will react with concentrate.

FeO formed in the flash furnace by Reaction 2.2 is fluxed with silica by reactions such as:

$$2FeO + SiO2 = 2FeO.SiO2 \qquad (2.3)$$

$$\Delta H^{0}298 = -11 \text{ MJ/kg-mol SiO2}$$

The product is a liquid slag phase which is immiscible with the matte and which, being less dense, floats on top of the matte. Flash furnace slags typically contain 26-36 wt % SiO2, depending upon desired slag characteristics (1).

Flash furnace off-gases consist of SO2 produced by Reactions 2.1 and 2.2 and N2 from the oxidant. If supplementary fuel is burnt, the combustion products of the fuel (CO2 and H2O) are also constituents of the off-gas. Off-gas SO2 concentration is determined by the extent of oxygen enrichment of the oxidant and by the amount of hydrocarbon fuel. Industrial SO2 concentrations range from 12-80%, considerably greater than those produced by reverberatory (0.5-3% SO2) and electric (4-8% SO2) smelting furnaces (1).

The temperature of flash smelting products is usually around 1500 K. The slag is typically 25 K cooler than the off-gas and the matte is typically 25-50 K cooler than the slag.

The operating parameter most significant to flash furnace operators is the matte grade (i.e. wt% Cu in matte), which quantifies the extent of concentrate oxidation. The industrial range of matte grade for flash furnace smelting is 40-65% Cu with the recent trend being towards higher matte grades (2).

2.2 HISTORY AND DEVELOPMENT OF FLASH SMELTING

Two processes for flash smelting were developed in the late 1940's. Inco developed the oxygen flash smelting process in Canada and Outokumpu developed the air flash smelting process in Finland.

2.2.1 THE INCO OXYGEN FLASH SMELTING PROCESS

The principle of the Inco oxygen flash smelting process has remained the same since its conception (3-10). Dry sulphide concentrate and commercially pure (95%+) oxygen are injected horizontally into a rectangular furnace (Figure 2.1). The concentrate reacts with the oxygen (Reactions 2.1-2.2) to form a flame above the hearth. The resultant SO2 leaves via a central uptake while the liquid products shower onto the bath of slag and matte. Slag-forming reactions (like Reaction 2.3) take place in the slag phase while the unoxidized sulphides settle through the slag and into the matte phase.

The Inco oxygen flash smelting process is significant in two important aspects:

(a) the furnace operates autogenously; no hydrocarbon fuel is required because the exothermic oxidation reactions provide sufficient heat to melt the products and maintain furnace temperature;
(b) the SO2 content of the off-gas is approximately 80% which facilitates highly efficient fixing of the SO2 as liquid SO2 or sulphuric acid.

2.2.2 THE OUTOKUMPU FLASH SMELTING PROCESS

Outokumpu flash smelting consists of injecting dry concentrate and a combination of preheated air and/or oxygen-enriched air downwards into a furnace (11-17). Feed enters through the top of a reaction shaft located at one end of the Outokumpu furnace (Figure 2.2). Here it combusts with the blast oxygen, reacting as in the Inco furnace. Off-gases leave via a vertical uptake shaft at the other end of the furnace.

The original Outokumpu flash furnace in Harjavalta operated using air preheated to 775 K (14). Hydrocarbon fuel was required as a supplemental source of heat. Oxygen enrichment (~40 volume % O_2 in the oxidant) and increased oxidation of the concentrate have eliminated the need for fuel in this furnace and it is now operating autogenously (1). However, most Outokumpu-type flash furnaces operate with preheated air or moderately enriched air (23-25 volume % O_2) and as a result supplementary fuel is required.

The Outokumpu flash smelting process is significant in that:

(a) there is a zero or low hydrocarbon fuel requirement;

(b) operation is possible within a wide range of oxygen enrichment, oxidant preheat, and hydrocarbon fuel combustion levels;

(c) the SO_2 from the off-gas can be efficiently fixed to sulphuric acid.

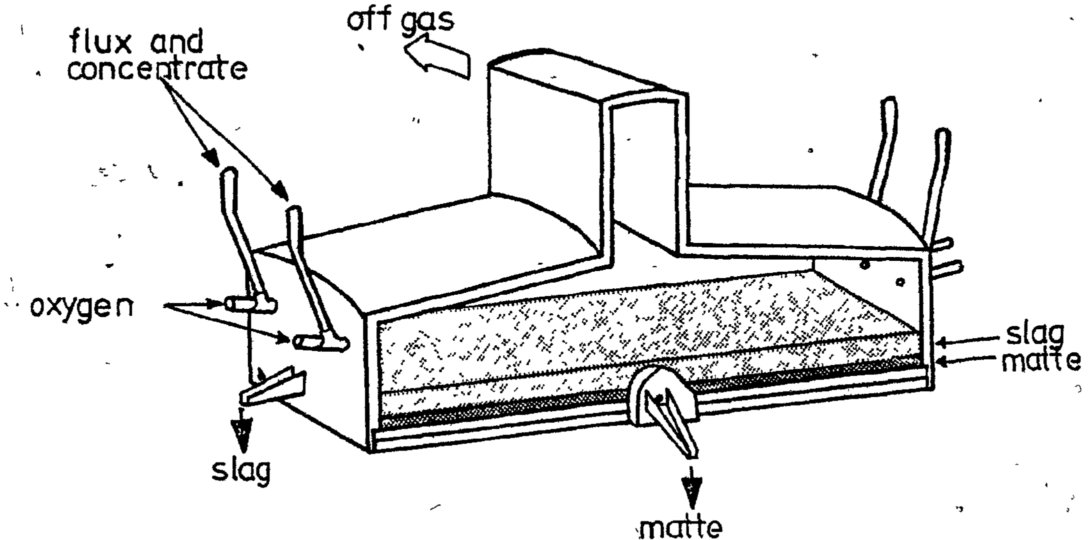

Figure 2.1 The Inco oxygen flash furnace. Oxygen, and dried concentrate and flux are injected horizontally through four burners. The resultant off-gas, about 80% SO2, leaves via the central uptake. Dimensions are about 24m in length, 7m in width, and 6m in height.

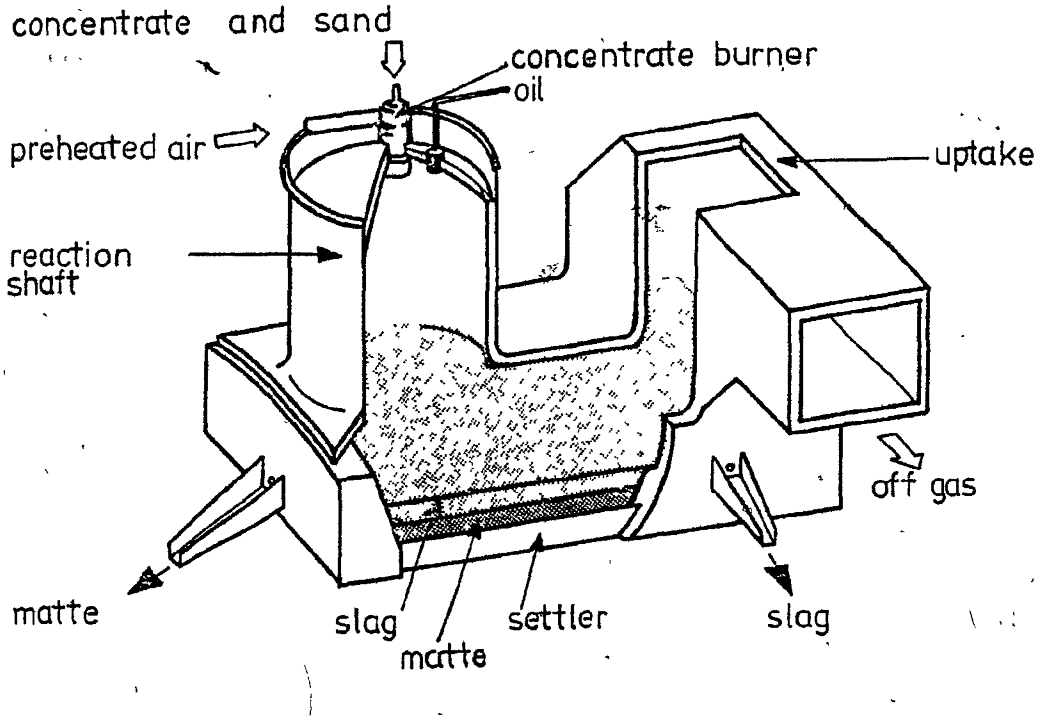

Figure 2.2 The Outokumpu flash furnace. Preheated or oxygen-enriched air and dried feed is injected into the reaction shaft. Typical dimensions are 20m in length, 7m in width, the reaction is about 6m in diameter and 8m in height.

2.3 EMERGENCE OF FLASH SMELTING AS A SIGNIFICANT PROCESS

The early 1970's saw an increased concern for protecting the environment and for minimizing energy consumption. Flash smelting is advantageous in both these regards and hence it emerged as a major smelting method in this period. This is substantiated by the fact that 75% of new copper smelting capacity commissioned in the 1970's employed flash smelting (2).

2.3.1 ENERGY CONSUMPTION IN FLASH SMELTING

As noted in Section 2.2, energy consumption has been reduced in flash smelting to the extent that flash furnaces can operate autogenously, i.e. without hydrocarbon fuel addition. This compares favourably to reverberatory furnace smelting where only about 50% of the energy requirement is generated from the smelting reactions; the balance being provided by hydrocarbon fuel (1).

2.3.2 SO2 GENERATION IN FLASH SMELTING

Government legislation has imposed strict limits regarding sulphur dioxide emissions from non-ferrous smelters (18). Consequently, the SO2 must be collected and fixed. Sulphur dioxide is fixed mainly as sulphuric acid, with minor amounts being fixed as elemental sulphur, liquid SO2, and gypsum. Regardless of the fixation process, overall cost of sulphur fixation is minimized if smelters generate steady, concentrated streams of SO2.

Flash furnaces inherently produce such steady streams of gas with high SO2 concentration due to their:

(a) low fuel consumption; little or no hydrocarbon fuel is consumed in flash smelting and consequently dilution of the off-gas by hydrocarbon combustion products is minimized or eliminated.

(b) use of oxygen enrichment; oxygen enrichment leads to a more concentrated stream of SO2 in off-gases because there is less dilution by nitrogen.

(c) design as sealed smelting units; SO2 generated in the furnace can be delivered to the sulphur fixation plant with little or no air dilution.

2.4 IMPORTANCE OF STEADY-STATE FURNACE OPERATION

Steady-state operation of a furnace is attained when product compositions and temperatures are maintained at prescribed set points. The benefits obtained by such steady-state operation include smooth overall smelter operation, low costs, and long furnace life. Specific advantages of operating at steady-state are discussed in

Chapter 5.

The basis by which flash furnaces can be maintained at steady-state can be described by a model based principally on heat and mass balances. Application of the model to computer assisted furnace control can aid in obtaining and maintaining steady-state operation of flash furnaces.

The model and its application to furnace control are discussed in Chapter 3 and Chapter 6 respectively.

2.5 PREVIOUS FLASH FURNACE MODELS

Previous models of steady-state flash smelting have for the most part been developed as tools which are used to study or control a particular furnace or a particular type of furnace (19-20). Other, more general models have also been developed for the purpose of comparing different smelting processes (21-22). These models, however, have remained black boxes since their authors have been primarily concerned with the results of the overall comparisons. For these reasons, a detailed review of previous work cannot be presented in this study.

The model developed here is general and can be applied to study all modes of flash smelting. This thesis describes the basis of the model and how it can be modified to suit particular applications.

CHAPTER 3

THE STEADY-STATE FLASH SMELTING MODEL

3.0 INTRODUCTION

In this chapter a fundamental model is developed to describe the steady-state operation of a flash furnace. Based principally on mass and heat balances, the model can be employed as a control tool which indicates or makes the required changes to flash furnace control parameters. It can also be used as an aid in process design and optimization, by simulating various smelting alternatives which can then be compared and analyzed.

3.1 FUNDAMENTAL EQUATIONS: MASS AND HEAT BALANCES

The fundamental equations used to develop the model are:

(a) steady-state mass balances for elements entering and leaving the furnace;

(b) an overall steady-state enthalpy balance for the furnace.

3.1.1 MASS BALANCES

The steady-state mass balance stipulates that the mass of inputs entering the furnace must equal the mass of the products leaving the furnace:

$$\text{mass in} = \text{mass out} \qquad (3.1)$$

This equation is a summation of the element mass balance equations which stipulate that the mass of each element entering the system must be equal to the mass leaving the system. The element mass balance equations for copper flash smelting are:

mass Cu in = mass Cu out (3.2)

mass Fe in = mass Fe out (3.3)

mass S in = mass S out (3.4)

mass O in = mass O out (3.5)

mass N in = mass N out (3.6)

mass SiO2 in = mass SiO2 out * (3.7)

3.1.2 HEAT BALANCES

The steady-state enthalpy balance stipulates that the enthalpy entering the system must be the same as that leaving the system:

enthalpy in = enthalpy out (3.8)

Equation 3.8 can be expressed conveniently in a modified form:

Heat supply to the process = Heat demand of the process (3.9)

---

* SiO2 is assumed to behave as an element in the sense that the silicon-oxygen bond is not broken during smelting.

In Equation 3.9 heat supply is defined as:

$$\text{Heat supply} = H298(\text{reactants}) - H298(\text{products}) + HT(\text{reactants}) - H298(\text{reactants}) \quad (3.10)$$

The first two terms of Equation 3.10 represent the heat generated from the oxidation of the concentrate. This is the main source of heat in the system. The last two terms represent the sensible heat of the incoming charge. Sensible heat is significant when the oxidant is preheated or in particular situations where a hot revert material (such as molten converter slag) is returned to the furnace. Sensible heats of the concentrate and flux are not normally significant.

Heat demand is defined in the following manner so as to be compatible with the above definition of heat supply:

$$\text{Heat demand} = HT(\text{products}) - H298(\text{products}) + \begin{bmatrix}\text{Radiative and convective}\\ \text{furnace heat losses}\end{bmatrix} \quad (3.11)$$

The first two terms of Equation 3.11 represent the sensible heat of the products and they account for 70-80% of the total heat demand. Radiative and convective furnace heat losses account for the remainder. These losses depend upon (i) furnace size and shape, (ii) operating temperatures, and (iii) concentrate throughput rate (Chapter 6). They are usually known quite closely for individual operating furnaces.

3.2 FEED AND PRODUCT SPECIFICATIONS

In addition to mass and heat balances, considerable information regarding the constitution and temperatures of feed and products is usually known or specified. This information in conjunction with mass and heat balances forms the core of the steady-state model.

3.2.1 FEED COMPOSITIONS AND TEMPERATURES

Feed (concentrate, flux, and oxidant) composition and temperature data are usually known for a particular operating furnace or they can be expressly specified if the model is to be used for optimization purposes.

3.2.2 PRODUCT CONSTITUTION AND TEMPERATURES

The constitution of flash furnace products is well established on the basis of industrial copper smelting information and thermodynamic principles. The data and information used to define product constitution in the model are as follows:

(a) The matte is described in terms of a liquid solution of Cu2S and FeS. Oxygen solubility in matte is represented as Fe3O4 and is quantified as a percentage of matte mass.

(b) The slag phase is described in terms of a liquid solution of FeO, SiO_2, Fe_3O_4, and minor amounts of CaO and Al_2O_3. The solubilities of copper and sulphur are assumed to be negligible. SiO_2 and Fe_3O_4 concentration in the slag are quantified as a percentage of slag mass.

(c) The product gas is SO_2 and N_2. Quantities of SO_3, S_2, and O_2 leaving industrial furnaces are negligible.

Product temperatures are dependent variables in that they are determined by the furnace heat balance. Industrial data show however, that matte, slag and off-gas temperatures are similar for all flash furnace operations (1450, 1500, and 1550 K +/-50K respectively), and consequently, these values can be specified as target temperatures for control/optimization purposes. Of course, target temperatures can subsequently be altered as required.

It should be noted that furnace or operating temperature are terms which in this thesis and in most smelters are synonymous with slag temperature. Since matte and off-gas temperatures are related to slag temperature (page 6), changing the furnace temperature invariably implies changing all of the product temperatures.

3.3 RESULTS OBTAINABLE FROM THE MODEL

The model incorporates (i) mass and heat balances, (ii) specified concentrate and flux feed compositions and (iii) product temperature specifications with the above-described product constitution assumptions. In this manner it determines:

(a) possible combinations of oxidant temperature, oxidant O_2/N_2 ratio and O_2/concentrate feed ratio with which a furnace can be operated autogenously, i.e. without requiring hydrocarbon fuel additions;

or

(b) quantities of hydrocarbon fuel necessary if a furnace is not operating autogenously;

or

(c) possible combinations of oxidant temperature, oxidant O_2/N_2 ratio and hydrocarbon fuel with which a furnace will produce a matte with a specified concentration of copper.

Additional information obtained includes:

(a) mass of SiO_2 required to flux the slag;
(b) product masses (matte, slag, and off-gas);
(c) concentration of copper in the matte and of SO_2 in the off-gas.

The central calculations required to determine these are the solving of the mass and heat balances simultaneously. An interactive computer program was written which reads the required data, generates mass and heat balance equations, and solves the equations. This computer program was used to solve the example calculations which are presented in the following chapter. In addition, graphs appearing throughout this work (unless specifically referenced) are based on data generated by the computer program.

CHAPTER 4

EXAMPLE APPLICATIONS OF THE STEADY-STATE MODEL

4.0 INTRODUCTION

Three example calculations pertaining to different autogenous operating modes of flash furnaces are presented in this chapter. They demonstrate the method by which the model describes general flash smelting situations. The operating parameters predicted by the model are then compared to their industrial equivalents.

4.1 EXAMPLE I, SIMPLIFIED OXYGEN FLASH SMELTING

The first example calculates the operating parameters of an oxygen flash furnace.

"A CONCENTRATE IS SMELTED IN AN INCO TYPE (OXYGEN) FLASH FURNACE. WHAT ARE THE OXYGEN AND FLUX REQUIREMENTS WHICH WILL PERMIT THE FURNACE TO OPERATE AUTOGENOUSLY WITH THE FOLLOWING FEED AND PRODUCT SPECIFICATIONS?"

concentrate:	chalcopyrite ($CuFeS_2$), 298 K
flux:	silica (SiO_2), 298 K
matte:	Cu_2S-FeS, 1475 K
slag:	70% FeO, 30 wt% SiO_2, 1500 K
oxidant:	100% O_2, 298 K
off-gas:	SO_2, 1525 K
throughput:	50 tonnes/hour of concentrate
radiative and convective heat loss rate :	25000 MJ/hour

The data for this example are simplified, but they demonstrate procedures used in solving such problems.

Solution: Mass and heat balance equations

Five mass balance equations which must be satisfied in this example are as follows (all variables represent masses, kg per 1000 kg of concentrate feed, and all percentages are mass %):

$$\text{mass Cu in} = \text{mass Cu out} \tag{3.2}$$

$$1000 \cdot \frac{\text{\% Cu in concentrate}}{100} = \text{mass } \text{Cu}_2\text{S} \text{ in matte} \cdot \frac{\text{\% Cu in } \text{Cu}_2\text{S}}{100}$$

$$\text{mass Fe in} = \text{mass Fe out} \tag{3.3}$$

$$\begin{aligned} 1000 \cdot \frac{\text{\% Fe in concentrate}}{100} = {} & \text{mass FeS in matte} \cdot \frac{\text{\% Fe in FeS}}{100} \\ & + \text{mass FeO in slag} \cdot \frac{\text{\% Fe in FeO}}{100} \end{aligned}$$

$$\text{mass S in} = \text{mass S out} \tag{3.4}$$

$$\begin{aligned} 1000 \cdot \frac{\text{\% S in concentrate}}{100} = {} & \text{mass } \text{SO}_2 \text{ in offgas} \cdot \frac{\text{\% S in } \text{SO}_2}{100} \\ & + \text{mass FeS in matte} \cdot \frac{\text{\% S in FeS}}{100} \\ & + \text{mass } \text{Cu}_2\text{S} \text{ in matte} \cdot \frac{\text{\% S in } \text{Cu}_2\text{S}}{100} \end{aligned}$$

$$\text{mass O in} = \text{mass O out} \qquad (3.5)$$

$$\text{mass O in oxidant} = \text{mass SO2 in offgas} \cdot \frac{\text{\%O in SO2}}{100} + \text{mass FeO in slag} \cdot \frac{\text{\%O in FeO}}{100}$$

$$\text{mass SiO2 in} = \text{mass SiO2 out} \qquad (3.7)$$

$$\text{mass SiO2 in flux} = \text{mass slag} \cdot \frac{\text{\% SiO2 in slag}}{100}$$

$$= (\text{mass FeO} + \text{mass SiO2}) \cdot \frac{\text{\% SiO2 in slag}}{100}$$

In addition to the mass balance equations, there are three heat balance equations (Section 3.1.2):

(a) the overall heat balance equation is:

$$\text{heat supply} = \text{heat demand} \qquad (3.9)$$

(b) the heat supply equation is:

$$\text{heat supply} = \text{H298(reactants)} - \text{H298(products)} + \text{HT(reactants)} - \text{H298(reactants)} \qquad (3.10)$$

In this example the last two terms of Equation 3.10 cancel since the inputs to the furnace are at 298 K, and heat supply is:

$$
\begin{array}{rll}
\text{heat supply} = & H^0 298(\text{CuFeS2}) & \cdot \text{ kg-moles CuFeS2} \\
 & + H^0 298(\text{SiO2}) & \cdot \text{ kg-moles SiO2} \\
 & + H^0 298(\text{O2}) & \cdot \text{ kg-moles O2} \\
 & - \left[\begin{array}{ll} H^0 298(\text{Cu2S}) & \cdot \text{ kg-moles Cu2S} \\ + H^0 298(\text{FeS}) & \cdot \text{ kg-moles FeS} \\ + H^0 298(\text{SO2}) & \cdot \text{ kg-moles SO2} \\ + H^0 298(\text{FeO}) & \cdot \text{ kg-moles FeO} \\ + H^0 298(\text{SiO2}) & \cdot \text{ kg-moles SiO2} \end{array} \right]^{*} & *
\end{array}
$$

(c) The heat demand equation:

$$
\begin{array}{rl}
\text{heat demand} = & \text{HT(products)} - \text{H298(products)} \\
 & + \text{Radiative and convective furnace heat losses}
\end{array}
\tag{3.11}
$$

---

* $H^0(T)$ is the enthalpy of a compound in its standard state at temperature T. To be precise, the enthalpies of Cu2S and FeS in the matte and FeO and SiO2 in the slag should be represented in the heat balance by $H(T)$ which is their enthalpy in the solutions, including their heats of mixing. The error introduced by using $H^0(T)$ rather than $H(T)$ is negligible (page 111). This substitution is also made in the heat demand equation (3.11).

For this example it is:

$$\begin{aligned} \text{heat demand} = {} & \{H^0 1475(Cu_2S) - H^0 298(Cu_2S)\} \cdot \text{kg-moles } Cu_2S \\ & + \{H^0 1475(FeS) - H^0 298(FeS)\} \cdot \text{kg-moles } FeS \\ & + \{H^0 1500(FeO)^{*} - H^0 298(FeO)\} \cdot \text{kg-moles } FeO \\ & + \{H^0 1500(SiO_2)^{*} - H^0 298(SiO_2)\} \cdot \text{kg-moles } SiO_2 \\ & + \{H^0 1525(SO_2) - H^0 298(SO_2)\} \cdot \text{kg-moles } SO_2 \\ & + \left[\frac{\text{Radiative and convective heat loss/hour}}{\text{Concentrate feed rate, tonnes/hour}}\right] \end{aligned}$$

where 1475, 1500 and 1525 are specified matte, slag, and off-gas temperatures respectively.

The preceding mass and heat balance equations have been solved by a linear equation manipulation technique (Gaussian elimination with equilibration and partial pivoting) (23). The solution (per tonne of dry concentrate feed) is:

---

* Although their melting points are above 1500 K, the enthalpies of FeO and SiO2 are calculated for the liquid state because they combine to form a liquid slag. Cu2S and FeS are liquid at 1475 K. Heats of solution are discussed on page 91 .

O2 feed = 226 kg

SiO2 in feed = 89 kg
(and in slag)

Cu2S in matte = 432 kg

FeS in matte = 226 kg

SO2 in offgas = 359 kg

FeO in slag = 207 kg

heat supply = 1859 MJ

heat demand = 1859 MJ

The answer to the problem indicates that an O2/concentrate ratio of .226 and an SiO2/concentrate ratio of .089 are required to keep the furnace in thermal and stoichiometric balance. Additional information which can be extracted from these results includes:

$$\begin{aligned}\text{matte mass} &= \text{Cu2S} + \text{FeS}\\ &= 658 \text{ kg}\end{aligned}$$

$$\begin{aligned}\%\ \text{Cu in matte} &= \frac{\text{Cu2S} \cdot (\text{wt\% Cu in Cu2S} / 100)}{\text{matte mass}}\\ &= 52.4\ \%\ \text{Cu}\end{aligned}$$

$$\begin{aligned}\text{slag mass} &= \text{FeO} + \text{SiO2}\\ &= 296 \text{ kg}\end{aligned}$$

This simple example is analogous to Inco operating data (8). The calculated O2/concentrate, SiO2/concentrate, matte/concentrate, and slag/concentrate ratios all lie within

10% of the corresponding Inco data. A relatively large difference in matte grade (52.4 vs 41.8 %Cu) is attributable to a difference in concentrate grade (30.1 at Inco vs 34.8 %Cu for pure chalcopyrite examined in this example).

4.2 EXAMPLE II, ADJUSTING THE O2/N2 RATIO

This example demonstrates the effect of oxidant composition on flash furnace operation.

"WHAT ARE THE OXYGEN AND FLUX REQUIREMENTS FOR A FURNACE OPERATING AUTOGENOUSLY AS IN EXAMPLE I, WITH THE EXCEPTION OF THE OXIDANT HAVING AN O2/N2 MASS RATIO OF 1/1 (46.7 VOLUME % OXYGEN), I.E. THE OXIDANT IS HIGHLY OXYGEN-ENRICHED AIR"?

Solution:

For this example a new mass balance equation must be introduced to account for the nitrogen:

$$\text{mass N in} = \text{mass N out} \qquad (3.6)$$

$$\text{mass N in} = \frac{\text{mass O in oxidant}}{\text{O2/N2 mass ratio}}$$

In addition, the heat demand equation must now include the heat required to heat the outgoing nitrogen from 298 to off-gas temperature, 1525 K, i.e.:

$$\text{heat demand (this example)} = \text{heat demand (Example I)} + \left[\begin{array}{l}\text{sensible heat of nitrogen} \\ \text{leaving furnace}\end{array}\right]$$

where:

$$\text{sensible heat of } N_2 = \{H^0_{1525(N_2)} - H^0_{298(N_2)}\} \cdot \text{kg-moles } N_2$$

Note here that the presence of N_2 (at 298 K) in the oxidant does not change heat supply Equation 3.10.

The resultant mass and heat balance equations have been solved to yield:

O_2 in oxidant = 276 kg
N_2 in oxidant = 276 kg
SiO_2 in feed = 122 kg
Cu_2S in matte = 432 kg
FeS in matte = 134 kg
SO_2 in offgas = 426 kg
FeO in slag = 282 kg
heat supply = 2339 MJ
heat demand = 2339 MJ

Thus for this example, an O2/concentrate ratio of .276 and an SiO2/concentrate ratio of .122 are required to maintain steady-state autogenous operation. Additional information which may be obtained from these results includes:

$$\text{matte mass} = Cu_2S + FeS$$
$$= 566 \text{ kg}$$

$$\% \text{ Cu in matte} = \frac{Cu_2S \cdot (\text{wt\% Cu in } Cu_2S / 100)}{\text{matte mass}}$$
$$= 60.9 \% \text{ Cu}$$

$$\text{slag mass} = FeO + SiO_2$$
$$= 404 \text{ kg}$$

Summarizing the results of this example, oxidant nitrogen requires heat to raise it to the off-gas temperature. This necessitates an increase in the O2/concentrate ratio (i.e. more oxidation) to maintain the furnace in thermal balance. This increase in degree of oxidation produces (i)more slag (hence higher flux requirement) and (ii) a matte phase more concentrated in copper.

The closest industrial parallel of this example is the Outokumpu flash furnace in Harjavalta, Finland. However, the Outokumpu furnace operates with a slightly lower O2/N2 mass ratio, i.e., 0.76 (40 volume % oxygen), and hence requires an even higher degree of oxidation, producing a matte with 65% Cu (1).

4.3 EXAMPLE III, ADJUSTING OXIDANT TEMPERATURE

The third example demonstrates that preheated air can also be used as oxidant in an autogenously operating flash furnace.

"WHAT ARE THE OXYGEN AND FLUX REQUIREMENTS FOR A FURNACE OPERATING AUTOGENOUSLY WITH THE SPECIFICATIONS OF EXAMPLE I, WITH THE EXCEPTION THAT THE OXIDANT IS AIR (O2/N2 MASS RATIO = .30), PREHEATED TO 1000 K?"

Solution:

In addition to modifying Equation 3.6 (the nitrogen balance) to account for air as oxidant, the only equation which changes from its equivalent in Example II is the heat supply equation. Recalling that:

$$\text{heat supply} = H298(\text{reactants}) - H298(\text{products}) + HT(\text{reactants}) - H298(\text{reactants}) \qquad (3.10)$$

it is necessary in this 'preheat' example to include oxidant sensible heat as part of the heat supply.

The heat supply equation becomes:

$$\begin{aligned} \text{heat supply} = {} & \text{H298(reactants)} - \text{H298(products)} \\ & + \{H^0 1000(O2) - H^0 298(O2)\} \cdot \text{kg-moles O2} \\ & + \{H^0 1000(N2) - H^0 298(N2)\} \cdot \text{kg-moles N2} \end{aligned}$$

where {H298(reactants) - H298(products)} contains the same terms as in the previous examples. Mass and heat balance equations are again solved simultaneously to yield:

O2 in oxidant = 272 kg
N2 in oxidant = 897 kg
SiO2 in feed = 119 kg
Cu2S in matte = 432 kg
FeS in matte = 141 kg
SO2 in offgas = 421 kg
FeO in slag = 277 kg
heat supply = 3195 MJ
heat demand = 3195 MJ

Thus for this example, an O2/concentrate of .272 and an SiO2/concentrate ratio of .119 are required to maintain the furnace at steady state. Additional information obtained from these results includes:

matte mass = Cu2S + FeS
= 573 kg

$$\% \text{ Cu in matte} = \frac{\text{Cu2S} \cdot (\text{wt\% Cu in Cu2S} / 100)}{\text{matte mass}}$$

$$= 60.2 \% \text{ Cu}$$

$$\text{slag mass} = \text{FeO} + \text{SiO2}$$

$$= 396 \text{ kg}$$

At present, there are no flash furnaces operating autogenously using preheated air, possibly due to the large oxidant and off-gas masses. Oxygen enrichment is a more practical method for obtaining autogenous operation. This example shows, however that it is possible to use preheated air oxidant to produce the same matte and slag products as when using oxygen-enriched air (Example II). Choice of oxidant is discussed further in Chapter 7-8.

4.4 MORE PRECISE APPLICATION OF THE MODEL

The examples in this chapter have been based upon simplified feed and product specifications. Chapter 8 and Appendix 1 show how the model is modified to manipulate more realistic feed and product specifications, for example:

(a) variations in concentrate mineralogy, i.e. pyrite, pyrrhotite, and 'rock' constituents such as CaO and Al2O3;

(b) variations in slag and matte constitution, i.e. Fe3O4 in the matte and slag and rock constituents in the slag;

(c) water in the feed;

(d) recycling of revert materials such as flue dust.

CHAPTER 5

IMPORTANCE OF FURNACE CONTROL

5.0 INTRODUCTION

Any copper smelter benefits significantly by having (i) controlled operation and (ii) smelting furnace products of consistent temperature and composition. This chapter discusses the importance of controlling matte and slag composition and product temperature.

5.1 MATTE COMPOSITION CONTROL

Matte produced by smelting furnaces is the primary feed to the following stage of the copper smelting and refining process, i.e. converting. A brief discussion of the converting process is presented now to demonstrate the importance of matte composition control.

Typically, matte is tapped from the smelting furnace into 15-35 tonne capacity ladles (24). The matte is then transferred to cylindrical converters, where its iron and sulphur are oxidized to yield blister copper (∿99% Cu), slag, and off-gas (4-10% SO2). The oxidation occurs by blowing air into the molten matte via submerged tuyeres. The converting operation is autogenous and in fact heat from the oxidation reactions is utilized to smelt concentrates and/or to melt copper scrap in the converter.

An important operational characteristic of converting is that, unlike smelting, it is a batch operation. Typically, two or three converters service a smelting furnace and thus scheduling is important to ensure that production bottlenecks do not develop in the converting operation. Scheduling is also important to ensure a steady stream of off-gas from the converters to the sulphur fixation plant.

Principal oxidation reactions which occur in converting may be represented by:

$$\mathrm{FeS} + 3/2\ \mathrm{O2} = \mathrm{FeO} + \mathrm{SO2}$$

$$\Delta H^{0}298 = -460\ \mathrm{MJ/kg\text{-}mol\ FeS} \qquad (2.2)$$

$$\mathrm{Cu2S} + \mathrm{O2} = 2\mathrm{Cu} + \mathrm{SO2}$$

$$\Delta H^{0}298 = -220\ \mathrm{MJ/kg\text{-}mol\ Cu2S} \qquad (5.2)$$

The amount of FeS per unit of copper in the matte is the most important parameter effecting the converter operation. As can be seen, Reaction 2.2 affects:

(a) the converter oxygen (i.e. air) requirement per unit of copper, which must be known to (i) ensure the correct degree of oxidation in the converter and (ii) calculate the blowing rate of air into the converter which maintains the required schedule;

(b) the amount of heat generated from the oxidation reactions, which must be known to determine how much copper scrap or concentrate must be added to the converter to prevent overheating;

and determines:

(c) the amount of FeO produced (which determines the quantity of SiO2 required to form the converter slag).

Consequently, matte composition has an important role in converter scheduling, converter mass and heat balances, and

SiO2 and scrap requirements. It follows that efficient control of matte composition leads to much smoother converting operations.

5.2 FLASH FURNACE SLAG COMPOSITION CONTROL

Silica is added to the concentrate feed as a slag fluxing agent. The amount required depends on (i)the amount of slag generated per unit of concentrate and (ii)the desired concentration of silica in the slag; generally 26-36 wt% SiO2.

The amount of slag generated per unit of concentrate smelted depends on the extent of iron oxidation of the concentrate. As the oxygen/concentrate feed mass ratio increases more FeO is formed and hence more silica is required. (Reaction 2.3)

The optimum slag silica content depends largely on whether the slag is to be discarded or sold directly or whether it is to be processed furthur to recover the small amount of copper which it contains. A slag which is to be discarded must be low in copper values. This is best obtained by making a slag which is saturated in silica (33-36 wt%). An example of this type of operation is Inco's Sudbury smelter which directly discards slag from its copper flash furnace. The slag from this furnace contains 33% SiO2 (8).

For a slag which is to be processed for copper recovery, either by milling or electric furnace settling and reduction, the copper content is not as significant because most of the copper is recovered by this secondary processing. A small slag mass is important, however, to minimize the capital and operating expenditures of the treatment facility. For this reason, the silica content of the slag should be kept low (26-30 wt%) to minimize slag mass. An example of this type of operation is the Outokumpu smelter in Harjavalta where the slag is milled to recover copper. The silica content of the slag is only 27% (16).

In summary, silica requirement is determined by the oxygen/concentrate mass ratio and a target SiO2 content of the slag. Control of the slag SiO2 content is important to minimize copper loss or the mass of slag being produced.

5.3 FLASH FURNACE PRODUCT TEMPERATURE CONTROL

Flash furnace product temperatures must be controlled so as to maintain the matte and the slag above their melting points (∿1375 K and ∿1425 K respectively) (1). In addition, the matte and the slag should be maintained within an optimum operational temperature range which avoids disadvantages of excessively hot or cold operation as is discussed immediately below.

The superheat required in the slag depends principally on obtaining optimum fluidity and optimum separation of the slag from the matte. Overheating should be avoided to reduce slag line refractory wear in the furnace. Conversely, a slag which is too cold entrains more copper than a hot fluid slag and has to be avoided as well.

Matte must have sufficient superheat to avoid excessive skulling in the transfer ladles between the smelting furnace and the converters. In addition, if the matte does not contain sufficient superheat, the first stage of the converting process may produce a cold, viscous converter slag which can cause foaming and excessive copper losses to the converter slag.

Temperature control is also important to avoid (i) excessive refractory wear throughout the furnace at high temperatures or (ii) magnetite buildup on the furnace walls or bottom at low temperatures. Operating the furnace hotter than necessary is also a direct waste of energy (hydrocarbon fuel or the energy used to produce oxygen or to preheat the oxidant).

5.4 SUMMARY

Operating a furnace with products of consistent temperature and composition has been demonstrated to minimize:

- (a) flash furnace refractory wear;
- (b) energy and/or oxygen consumption;
- (c) primary metal losses to slag;
- (d) operational problems in converting matte to blister copper.

Industry has proven that improved control leads to smoother operation (25-28). The following chapter discusses how flash furnaces can be controlled.

CHAPTER 6

FLASH FURNACE CONTROL

6.0 INTRODUCTION

The steady-state model of copper flash smelting which was described in Chapter 3 can be applied as the principal component of a computer-assisted furnace control package. Furnace control in this context means obtaining and maintaining a prescribed steady-state operation.

This chapter discusses how flash furnace control is affected by both choice of oxidant and choice of control parameter.

6.1 CONTROL PARAMETERS

The particular mode of steady-state operation in which a furnace operates can be described by the specifications of the variables; (i) O2/concentrate ratio, (ii) O2/N2 mass ratio and (iii) oxidant temperature (Chapter 4). Consequently, these variables can be used as control parameters. Hydrocarbon fuel consumption can be added to this list for flash furnaces which are not operating autogenously. Although the effects of hydrocarbon additions to furnaces and to the steady-state model are discussed (page 54), this thesis primarily studies autogenous flash smelting.

These control parameters can be used singly or in combination with each other to control (i.e. maintain or change) product composition and furnace temperature as operating conditions and requirements vary.

Relationships between these control parameters and furnace operating variables such as temperature and concentrate feed rate are shown in the following sections. Although the graphs presented in this thesis are specifically based on smelting a chalcopyrite concentrate as described in Appendix 1, page 107, the relationships demonstrated by these graphs are typical of the smelting of any chalcopyrite based concentrate.

6.1.1 O2/CONCENTRATE RATIO

O2/concentrate feed ratio is the principal parameter controlling the composition of the matte. The examples in Chapter 4 demonstrated, for specific situations, the manner in which it affects (i) the concentration of copper in matte and (ii) the amount of silica required to flux the slag. Figures 6.1 and 6.2 demonstrate these relationships more succinctly. The graphs clearly indicate that silica requirement and concentration of copper in the matte increase with increasing O2/concentrate ratio. These relationships are a consequence of the amount of iron sulphide oxidized to iron oxide (Reaction 2.2). Figure 6.1 also explains why the limits of 0.2-0.34 are applied for subsequent graphs in which O2/concentrate ratio is an axis, since this range includes most industrial matte compositions.

The O2/concentrate feed ratio is employed as a control variable to some extent by all flash smelting operations. It controls furnace temperature by determining how much oxidation takes place and thus how much heat is generated per unit of concentrate smelted. Three curves plotted in Figure 6.3 demonstrate this relationship for the smelting strategies presented in Examples I-III, Chapter 4. Since O2/concentrate feed ratio does affect product composition, however, it should be used as a temperature control parameter only in situations where a change of matte grade is desired or can be tolerated.

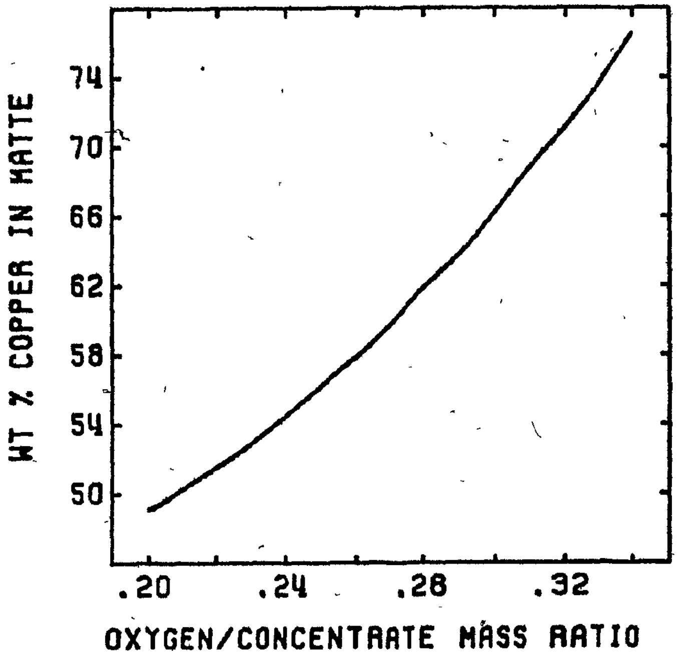

Figure 6.1 Relationship between O2/concentrate feed ratio and concentration of copper in the matte.

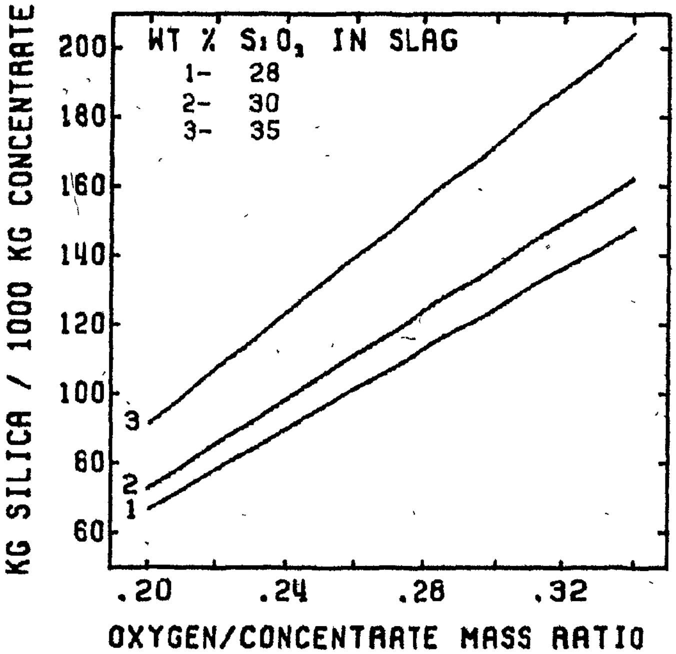

Figure 6.2 Silica required to produce slags as a function of O2/concentrate feed ratio.

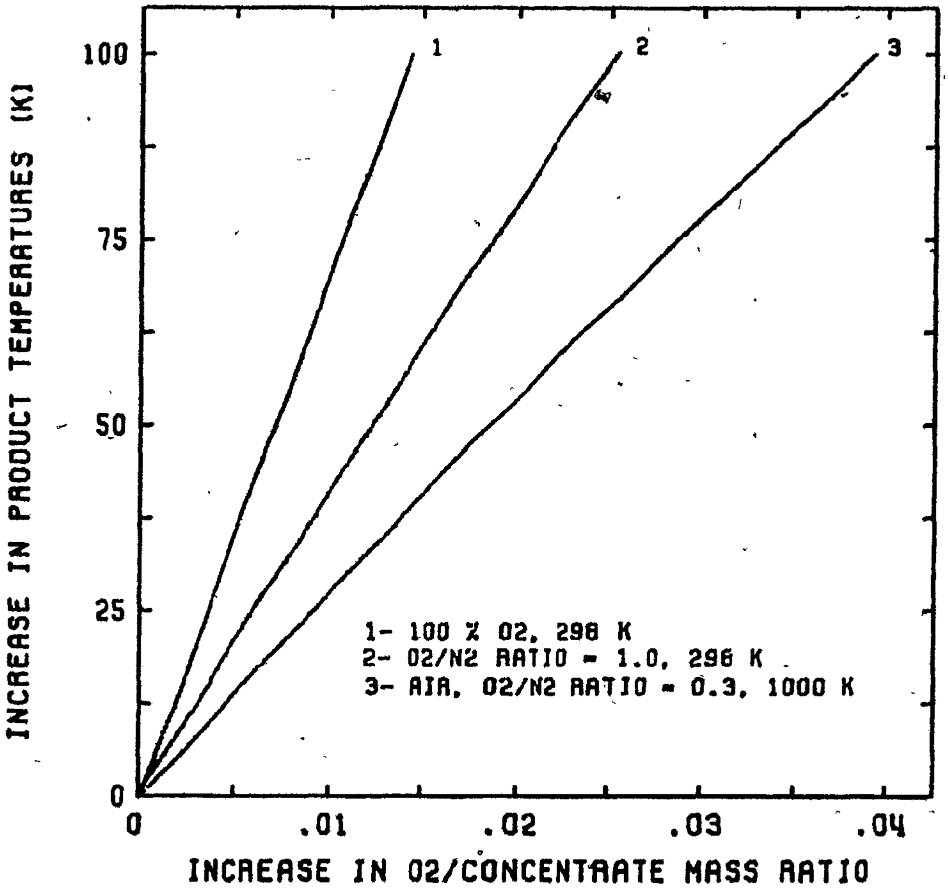

Figure 6.3 Product temperatures as a function of oxygen/concentrate feed ratio. The initial O2/concentrate ratio does not significantly affect the relationships.

6.1.2 O2/N2 MASS RATIO

Oxidant O2/N2 mass ratio (commonly represented in terms of volume % O2 in the oxidant) is used as a temperature control parameter in flash furnaces where oxygen enriched air is employed as the oxidant. It affects furnace temperature since nitrogen entering the furnace behaves as a coolant, i.e. it requires heat to bring it up to the off-gas temperature.

Figure 6.4 shows how increasing the O2/N2 ratio (represented in the figure in terms of volume % O2) affects furnace temperature for furnaces operating originally with (i) an O2/N2 ratio of 1, (i.e., 46.7 volume % O2) and (ii) air. This figure must be interpreted carefully since a unit percentage increase in volume % O2 of air is more significant in terms of reducing the nitrogen content than the same percentage increase of oxygen-enriched air (Figure 6.5).

An important consequence of varying the O2/N2 mass ratio of the oxidant is that the off-gas composition changes (i.e. SO2 concentration, Figure 6.6). This factor can be of concern because sulphur fixation plants operate most efficiently with a feed gas of constant composition.

The O2/N2 mass ratio is not used as a control parameter in the Inco oxygen flash furnace because dilution of the commercial oxygen with air negates the low volume, high SO2 concentration off-gas advantages which the Inco flash furnace offers.

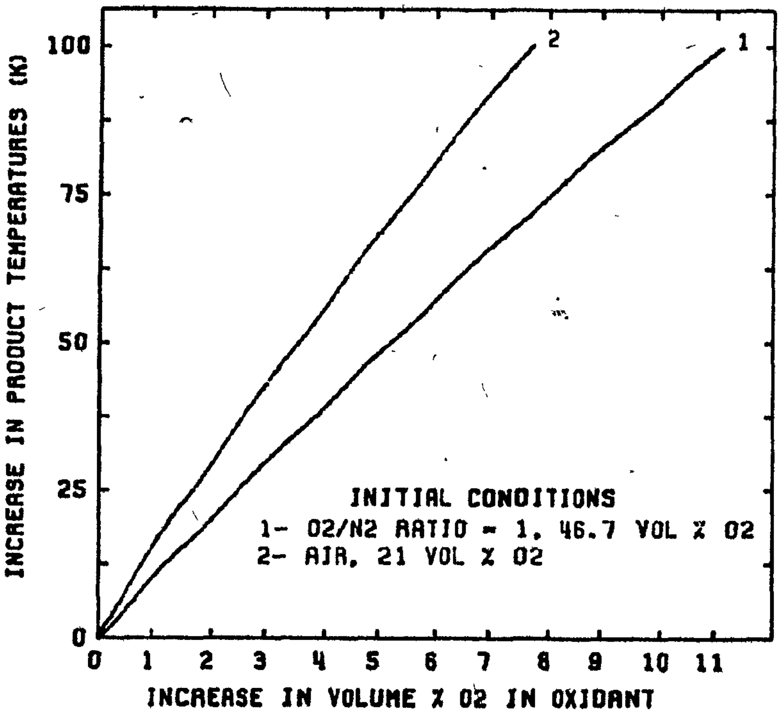

Figure 6.4 Effect of oxygen enrichment of the oxidant on product temperatures. The non-linearity of volume % O2 with the oxidant composition (Figure 6.5) should be noted when comparing curves of this nature.

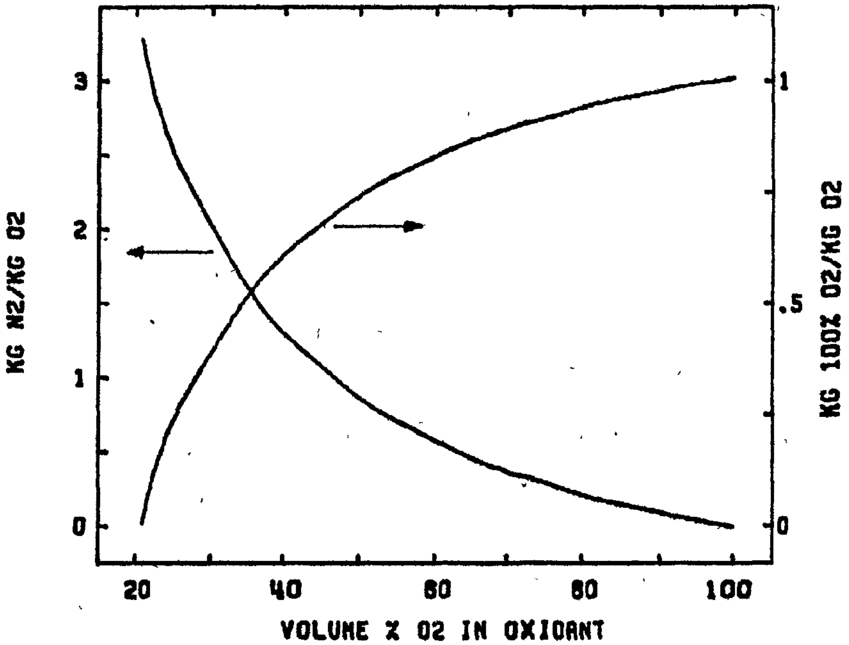

Figure 6.5 Effect of volume % O2 in oxidant on N2/O2 ratio and on the amount pure O2 required to produce the oxidant when combined with air.

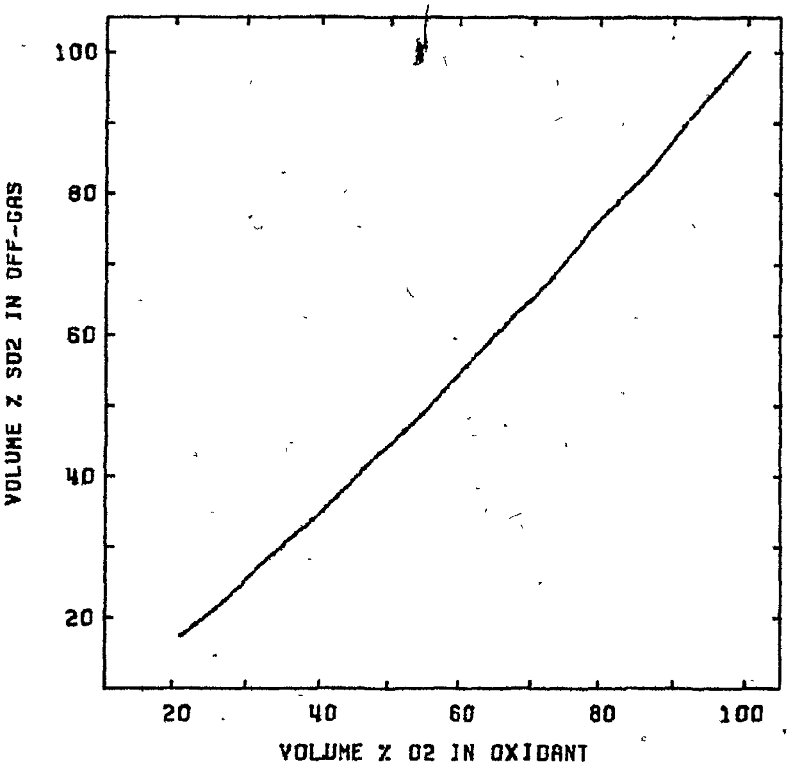

Figure 6.6 Effect of volume %O2 in oxidant on off-gas SO2 concentration. Note that % SO2 in off-gas is not directly proportional to % O2 in oxidant since a portion of the oxygen reacts to form FeO. For this reason, %SO2 is also slightly influenced by the O2/concentrate ratio (which determines how much FeO is generated).

6.1.3 OXIDANT TEMPERATURE

Oxidant temperature can be used as a control variable in flash furnaces operating with preheated air or slightly oxygen enriched air as oxidant. Conceptually it is a very elegant method of control since furnace temperature can be controlled without altering matte, slag, or off-gas composition.

Figure 6.7 shows how oxidant temperature affects product temperatures for the cases of oxygen, oxygen enriched air, and preheated air flash smelting.

A drawback of using oxidant temperature control is that it is difficult to change oxidant temperature as quickly or as reliably as either the O2/concentrate ratio, the O2/N2 mass ratio or the level of hydrocarbon combustion (discussed in the following section).

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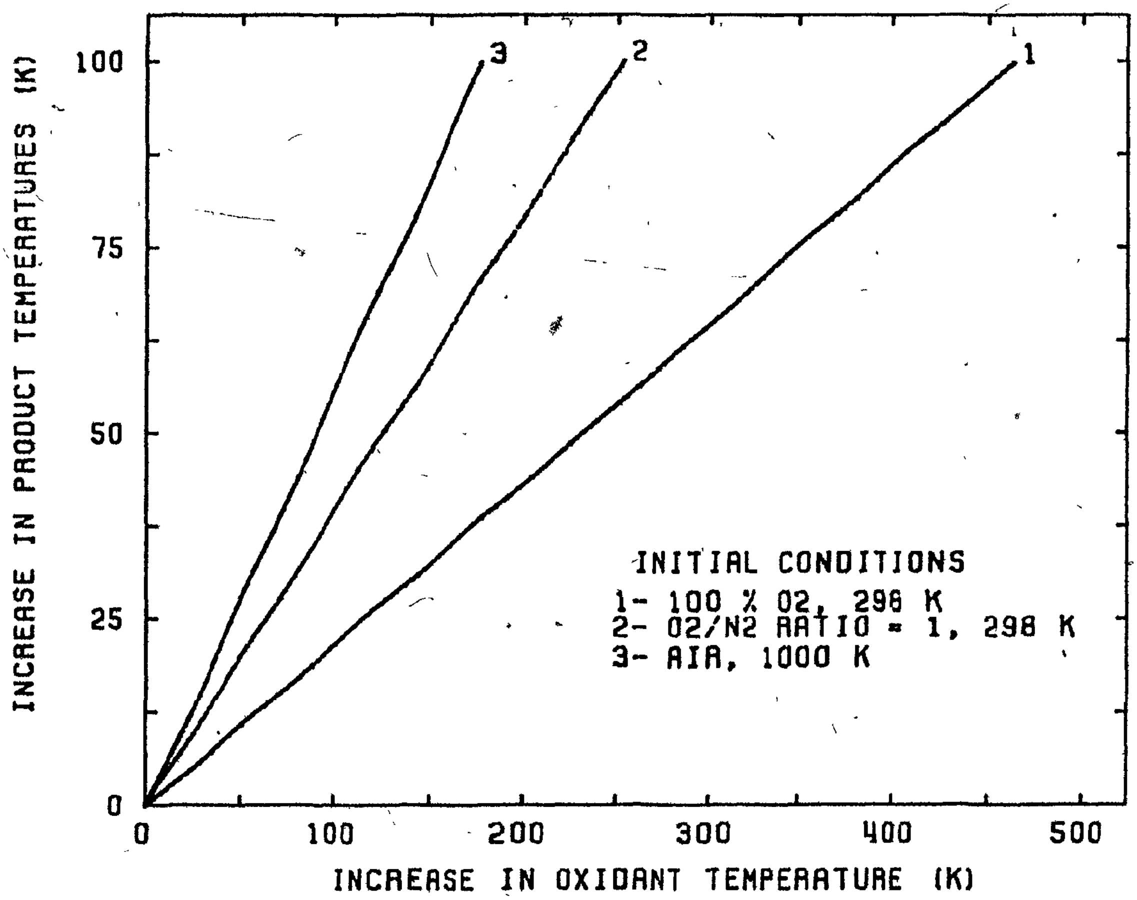

Figure 6.7 Effect of oxidant temperature on product temperatures.

6.1.4 HYDROCARBON FUEL LEVEL

Flash furnaces presently operating with preheated air or slightly oxygen enriched preheated air all employ hydrocarbon combustion in the furnace. In these situations, the amount of hydrocarbon combustion can be used to control furnace temperature (Figure 6.8). (The effect of hydrocarbon fuel additions on the steady-state model is described in Appendix 1).

With hydrocarbon combustion, flash furnace off-gas contains (i) hydrocarbon combustion products and (ii) the nitrogen which was associated with the oxygen required for hydrocarbon combustion. As a consequence, off-gas volume increases and off-gas SO2 concentration decreases. Both of these factors increase the cost and/or decrease the efficiency of off-gas handling and cleaning and sulphur fixation.

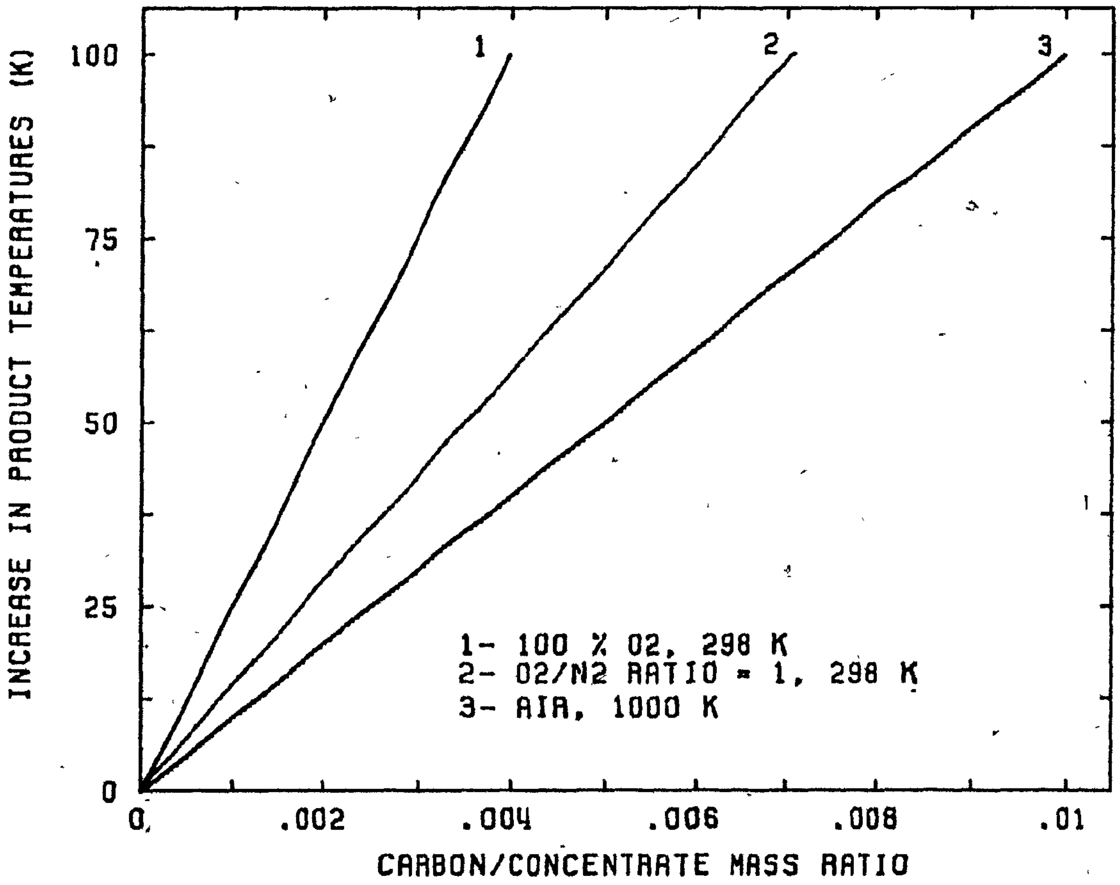

Figure 6.8 Effect of carbon combustion on product temperatures. The carbon is combusted to CO2 with oxidant of the same specifications as that used for smelting the concentrate.

6.1.5 EFFECT OF OXIDANT TYPE ON FURNACE CONTROL

The figures in this chapter have shown that the oxidant O2/N2 ratio determines the extent to which product temperatures are affected by control parameters. This is because the O2/N2 ratio affects the mass of the product nitrogen which in turn affects the magnitude of the change in enthalpy of the products per unit change in temperature. It follows that a furnace producing a low product mass, i.e., operating with a high O2/N2 ratio is more susceptible to changes of a control parameter and hence it is important to pay particular attention to the control of these furnaces.

6.2 CONTROL OF SPECIFIC OPERATING VARIABLES

Concentrate throughput rate, addition of revert materials (e.g. dust) and other changes to furnace operation affect the steady-state operation of a furnace. Hence their effects must be offset to maintain a constant temperature operation.

6.2.1 CONTROL OF FURNACES WITH VARYING CONCENTRATE THROUGHPUT RATES

Concentrate throughput rate is an operating variable which is likely to undergo significant changes during copper smelting. Gradual, long-term fluctuations can be expected as metal market conditions and prices vary while more sudden, short-term fluctuations can also be anticipated as in-smelter demands and bottlenecks affect furnace feed and production rates.

The effect of concentrate throughput rate on the heat balance of the furnace can be understood by examining the heat demand equation:

$$\text{Heat demand} = H_T(\text{products}) - H_{298}(\text{products}) + \begin{bmatrix}\text{Radiative and convective}\\ \text{furnace heat losses}\end{bmatrix} \quad (3.11)$$

The units for the heat loss term are MJ/1000 kg concentrate since the mass and heat balance equations are based on one tonne of concentrate. However, the radiative and convective heat losses are roughly independent of throughput rate, and as a result, heat loss per unit mass of concentrate must change as feed rate changes.

A typical relationship between heat loss/tonne of concentrate and concentrate throughput rate is shown in Figure 6.9. It is clear from this relationship that a decrease in throughput rate (i.e. an increase in radiative and convective heat loss per unit of concentrate) will result in a decrease in steady-state product temperatures unless a compensating change to a control parameter is made.

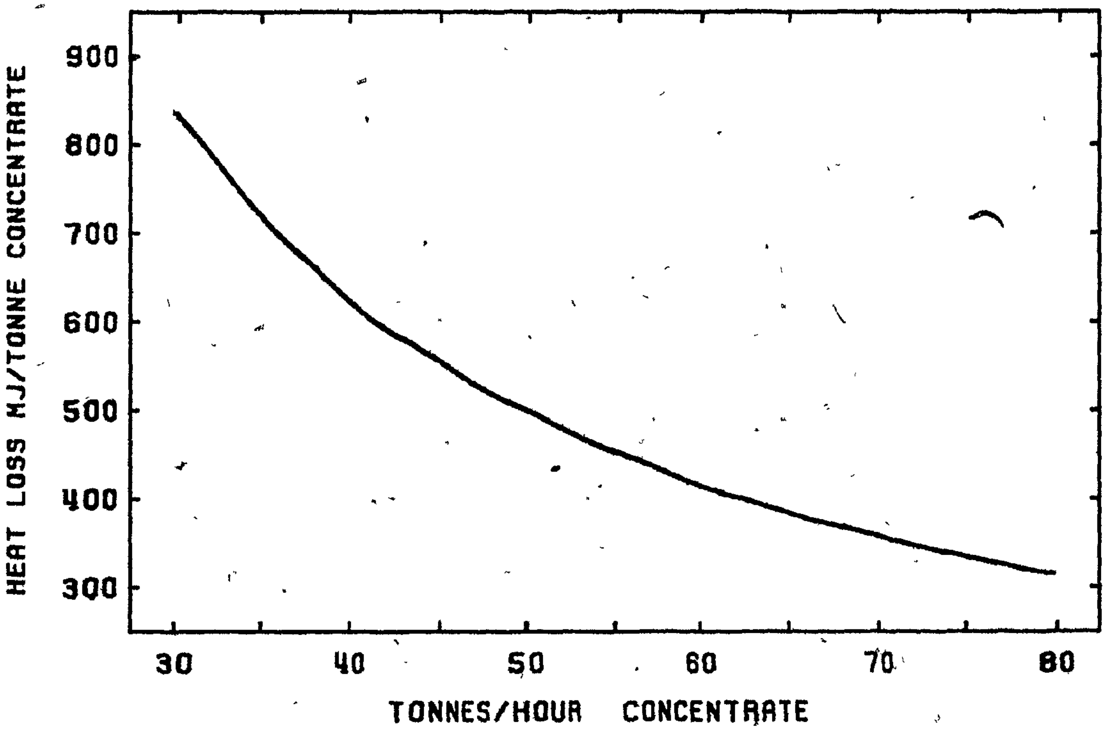

Figure 6.9 Effect of concentrate throughput rate on heat loss/tonne concentrate. In this particular case the furnace heat loss rate is constant at 25000 MJ/hour. Note that the magnitude of increase of heat loss/tonne concentrate increases with decreasing concentrate feed rate.

Changes to the heat balance caused by varying the concentrate throughput rate can be offset by:

(a) O2/concentrate ratio control

Altering the O2/concentrate feed ratio is one option available to compensate for the above-mentioned changes in heat demand. The relationships between the O2/concentrate feed ratio and concentrate throughput rate (while maintaining constant product temperatures) are presented in Figure 6.10 for the three operating strategies presented in Examples I-III, Chapter 4. As would be expected, the O2/concentrate ratio must be increased as throughput rate decreases. However, this also has the potentially adverse effect of changing the composition of the matte (Figure 6.2).

(b) O2/N2 ratio control

O2/N2 mass ratio is another control variable which can be adjusted to compensate for changes in concentrate throughput rate. Figure 6.11 depicts this relationship for the particular situation presented in Example II, Section 4.2. The figure shows that control via O2/N2 ratio adjustment is not practical below ~ 45 tonnes/hour concentrate feed since the required change in the O2/N2 ratio becomes too great. At higher throughput rates, however, it is a viable control option.

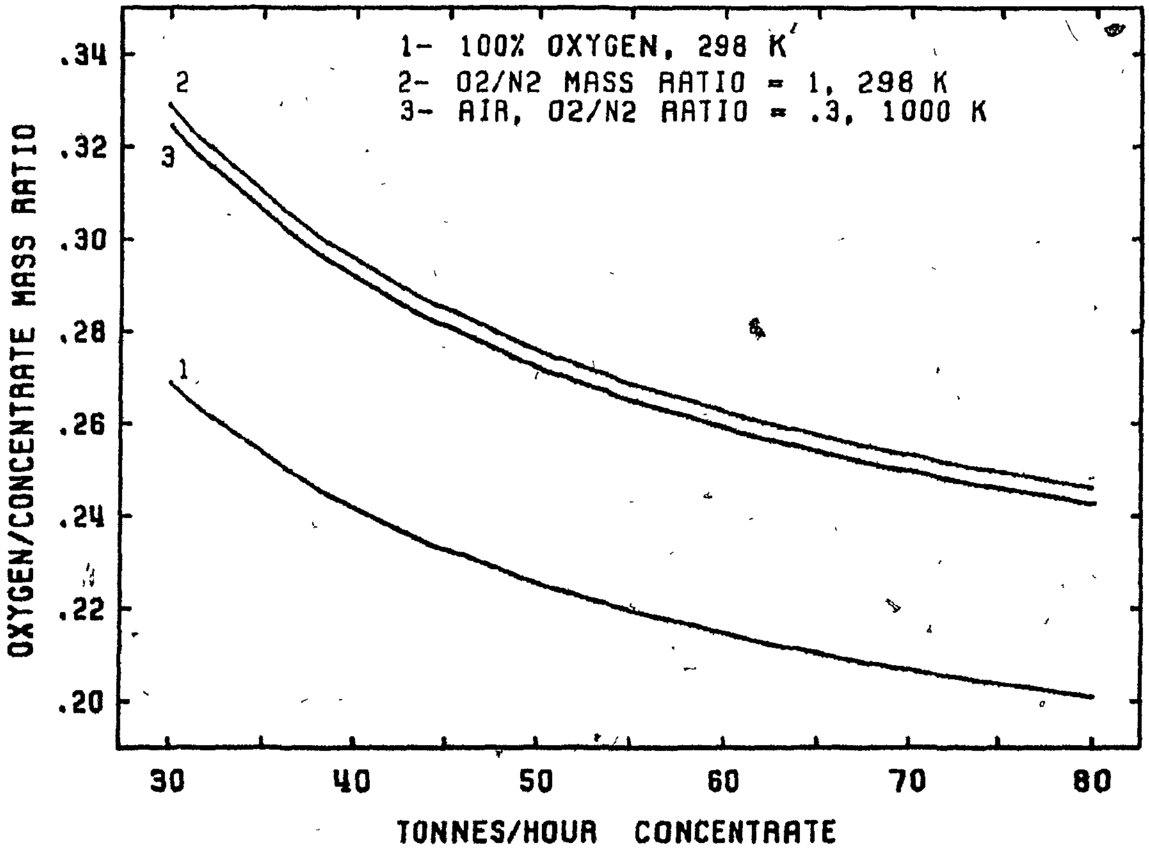

Figure 6.10 Effect of throughput rate on the O2/concentrate ratio required to maintain products at a constant temperature.

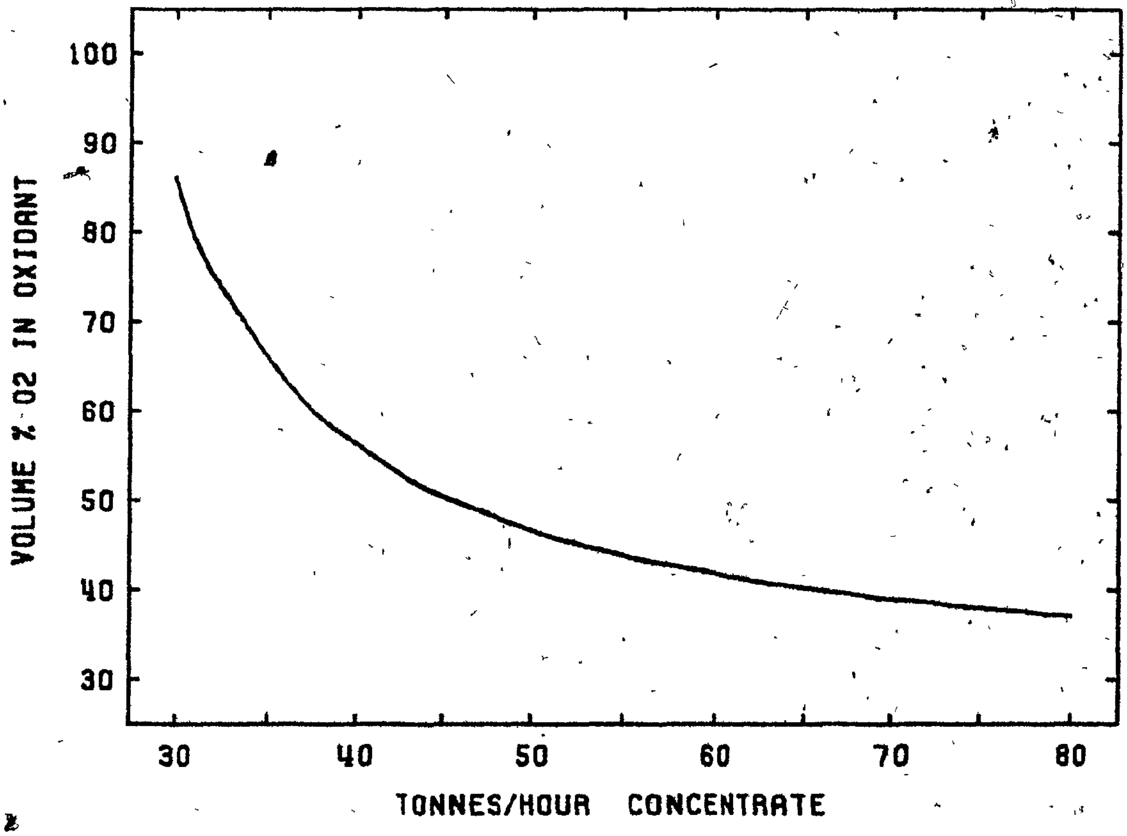

Figure 6.11 Effect of concentrate throughput rate on volume % O2 in oxidant (at 298 K) required to maintain products at a constant temperature.

(c) Oxidant temperature control

Oxidant temperature ~~can~~ also be used to compensate for changes in the concentrate throughput rate as is shown in Figure 6.12. It depicts the required change for the situation presented in Example III, Section 4.3.

Plot curvatures in Figures 6.10-6.12 are all similar. This is attributable to the curvature of Figure 6.9 which shows that heat loss/tonne concentrate smelted increases with decreasing concentrate feed rate. This signifies that, regardless of the method of control chosen, control becomes 'difficult' at low concentrate feed rates because a small change in throughput rate requires a large compensation of a control parameter.

An important compensation of this difficult control at low concentrate throughput rates is the reduced effect of the smelting reactions on the measured output variables (i.e. temperature and composition). This is because there is a large inventory of matte and slag in flash furnaces compared to the matte and slag produced during periods of low concentrate throughput rate. This inventory of matte and slag absorbs disturbances of either composition or temperature for a substantial period before the change is significantly reflected in the output measurement.

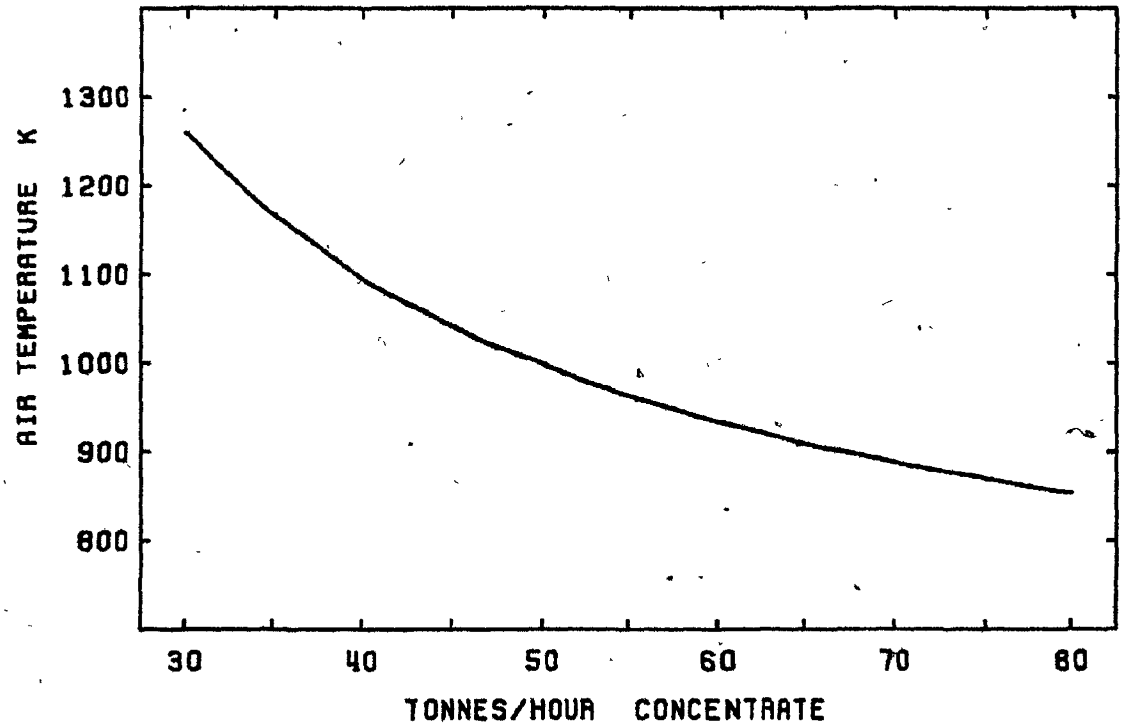

Figure 6.12 Effect of throughput rate on oxidant (i.e. air for this example) temperature required to maintain products at a constant temperature.

6.2.2 CONTROL OF FURNACES WITH REVERT MATERIAL ADDITIONS

Revert materials such as flue dust are regularly recycled to flash furnaces. In the simplified situation in which the flue dust generated from the flash furnace is recycled continuously, its effect on the furnace operation is straightforward. A heat demand term must be included to account for the heat required to heat the dust from inlet to outlet temperature, i.e.:

$$\underset{\text{(with dust recycle)}}{\text{Heat demand}} = \underset{\text{(no dust)}}{\text{Heat demand}} + \{HT_{dust(out)} - HT_{dust(in)}\}\ \text{kg-mol dust} \tag{6.1}$$

where Tdust(out) = temperature of dust leaving furnace (i.e. off-gas temperature)
Tdust(in) = temperature of recycled dust (∿298 K)
kg-mol dust = kg-moles of dust generated (and recycled), kg-moles/1000 kg concentrate.

For the more realistic situation in which perhaps a day's production of dust is recycled in several hours, the modifications to the mass and heat balance are slightly more involved (Appendix 1). In general, however, the addition of a revert material results in an overall increase in heat demand and compensations similar to those required to increase temperature must be made.

6.3 SUMMARY

This chapter has demonstrated how the three control parameters, i.e. (i) O2/concentrate ratio, (ii) O2/N2 ratio and (iii) oxidant temperature affect product temperatures.

Of these parameters, O2/concentrate ratio and O2/N2 ratio are easily changed by adjusting the flow-rates of concentrate, air and/or oxygen. The changes can be carried out quickly with no significant lag time before their effects are reflected in the furnace. The disadvantage of these two control parameters is that they affect product composition. Oxidant temperature, however, does not affect product composition and is thus potentially the most elegant temperature control parameter.

Since control becomes difficult when operating with a high O2/N2 ratio or a low concentrate throughput rate, it is important to devote particular attention to furnaces operating in these modes.

CHAPTER 7

FLASH FURNACE OPTIMIZATION

7.0 INTRODUCTION

The operating mode chosen for a particular smelter is based on criteria and constraints specific to the smelter site or to the company operating the smelter. This chapter disregards these restrictions and examines the fundamental advantages and disadvantages of the various operating modes. In particular, the two reasons cited for the emergence of flash smelting (Section 2.3), i.e. low energy consumption and the production of a low volume, high SO2 concentration off-gas are analyzed as a function of operating mode.

7.1 ENERGY REQUIREMENTS: AUTOGENOUS FLASH SMELTING

Flash furnaces can operate without hydrocarbon fuel additions by employing an oxygen-enriched and/or preheated oxidant. Although these modes are classified 'autogenous' in the sense that no fuel is required in the furnace, energy is consumed in producing pure oxygen and in preheating the oxidant.

Energy consumed in oxygen production varies from 1300-1400 MJ of electrical energy/tonne oxygen, depending on the size of the oxygen plant (29).

Energy consumed in the preheating of oxidant can be represented by the equation:

$$\text{Preheat energy} = \{H^0T(N2) - H^0298(N2)\} \cdot \text{kg-moles } N2 + \{H^0T(O2) - H^0298(O2)\} \cdot \text{kg-moles } O2 \qquad (7.1)$$

where T is the preheat temperature

It should be noted that the preheat energy required is always greater than that determined from Equation 7.1 because the efficiencies of heat exchangers or stoves used for preheating are less than 100%. Typical metallurgical preheat efficiencies are 70-80 percent depending on the size and type of the equipment (21).

7.1.1 ENERGY COMPARISON: PURE O2 VS PREHEATED AIR *

This section compares:

(a) autogenous flash smelting using pure O2, 298 K (Example I, page 24)

with

(b) autogenous flash smelting using air preheated to 1280 K. This preheat temperature has been chosen because at this temperature, all other specifications being identical, the O2/concentrate ratio is the same as for pure O2 flash smelting and hence the matte and slag products in both cases are the same. The only variable in the comparison is oxidant type.

For oxygen flash smelting, 226 kg of 100% O2 are required per tonne concentrate (page 29) and the energy required to produce this oxygen is:

O2 production energy = 1400 MJ/tonne O2 · .226 tonnes O2
= 315 MJ (per tonne concentrate smelted)

In this example, 226 kg oxygen are also required for air flash smelting. The energy required to preheat the oxygen and its associated nitrogen (743 kg N2) to 1280 K is:

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*- All comparisons in this chapter are based on autogenous smelting of chalcopyrite as outlined on page 107.

$$\text{Preheat energy} = \{H^{0}1280(N2) - H^{0}298(N2)\} \cdot \frac{743\ \text{kg N2}}{28\ \text{kg/kg-mol}}$$

$$+\{H^{0}1280(O2) - H^{0}298(O2)\} \cdot \frac{226\ \text{kg O2}}{32\ \text{kg/kg-mol}}$$

$$= 1035\ \text{MJ/tonne concentrate}$$

Thus in this example 100% oxygen smelting requires only about 30% of the energy required by preheated air smelting to the same matte and slag compositions. Results of a more general nature are presented in Figures 7.4-7.5 (page 77).

7.2 ENERGY RECOVERY FROM OFF-GAS

The smelting process transforms some of the chemical energy of the concentrate to thermal energy in the products. Of the three products (matte, slag, off-gas), only the off-gas is processed for energy recovery. Potentially recoverable sensible heat of the off-gas is represented by:

$$\text{Off-gas energy} = \{H^{0}T(SO2) - H^{0}298(SO2)\} \cdot \text{kg-moles SO2} \quad (7.2)$$

$$+\{H^{0}T(N2) - H^{0}298(N2)\} \cdot \text{kg-moles N2}$$

where T is the off-gas temperature.

This energy can be recovered as high pressure steam in waste heat boilers. The actual amount of energy which can be recovered from the off-gas depends on the efficiency of the waste heat boiler and the purposes for which the resulting steam is used. The maximum heat available as described by Equation 7.2 is used for the following initial comparison.

7.2.1 EXAMPLE COMPARISON, ENERGY RECOVERY FROM OFF-GAS

This example compares the recoverable energies of the two smelting modes presented on page 69. Oxygen flash smelting produces an off-gas of 359 kg SO2/tonne concentrate (page 29) with a sensible heat of:

$$\text{Off-gas energy} = \{H^0 1525(SO_2) - H^0 298(SO_2)\} \cdot \text{kg-moles } SO_2 \quad (7.2)$$
$$= 355 \text{ MJ/tonne concentrate}$$

The equivalent air flash smelting produces an off-gas of SO2 and N2 with the sensible heat:

$$\begin{aligned}\text{Off-gas energy} &= \{H^0 1525(SO_2) - H^0 298(SO_2)\} \cdot \text{kg-moles } SO_2 \quad (7.2)\\ &\quad + \{H^0 1525(N_2) - H^0 298(N_2)\} \cdot \text{kg-moles } N_2\\ &= 1390 \text{ MJ/tonne concentrate}\end{aligned}$$

In this comparison both smelting modes release the same amount of chemical energy. The greater amount of heat in the air flash smelting off-gas is due to the thermal energy of the preheated air.

7.3 NET ENERGY CONSUMPTION

The previous two sections have calculated the input energy requirements and potentially recoverable off-gas energies for pure O2 and preheated air flash smelting. Net energy consumption is then:

$$\text{Net energy consumption} = \text{energy required} - \begin{bmatrix}\text{energy recovered} \\ \text{from off-gas}\end{bmatrix} \quad (7.3)$$

Table 7.1 summarizes net energy consumption for the pure O2 and preheated air flash smelting discussed in the previous two sections. A negative net energy consumption value means more energy is recovered from the off-gas than is required to preheat or oxygen-enrich the oxidant.

Table 7.1 Net energy consumption, oxygen and preheated air flash smelting (MJ/1000 kg concentrate).

	Oxygen flash smelting, no heat recovery	Air flash smelting, no heat recovery	Oxygen flash smelting, 100% heat recovery	Air flash smelting, 100% heat recovery
Energy required	315	1035	315	1035
Recoverable energy	0	0	355	1390
Net energy consumption	315	1035	-40	-355

The table demonstrates that 100% oxygen smelting requires less energy than preheated air smelting if no heat is recovered. However, if all of the off-gas heat is recovered, both oxygen and air preheat smelting recover more heat from the off-gas than is required to produce the oxidant.

This relationship between net energy consumption and off-gas heat recovery is demonstrated more vividly by Figure 7.1. The figure indicates that oxygen and air flash smelting consume equivalent quantities of energy when 70% of the off-gas energy is recovered and that air preheat is energetically favoured above 70% heat recovery while oxygen smelting is favoured below 70%.

The critical value of 70% heat recovery is particular to this example. The same approach, however, can be used to determine the critical heat recovery percentage for different concentrates and in situations where both oxygen production and preheat energy differ from those defined in this example.

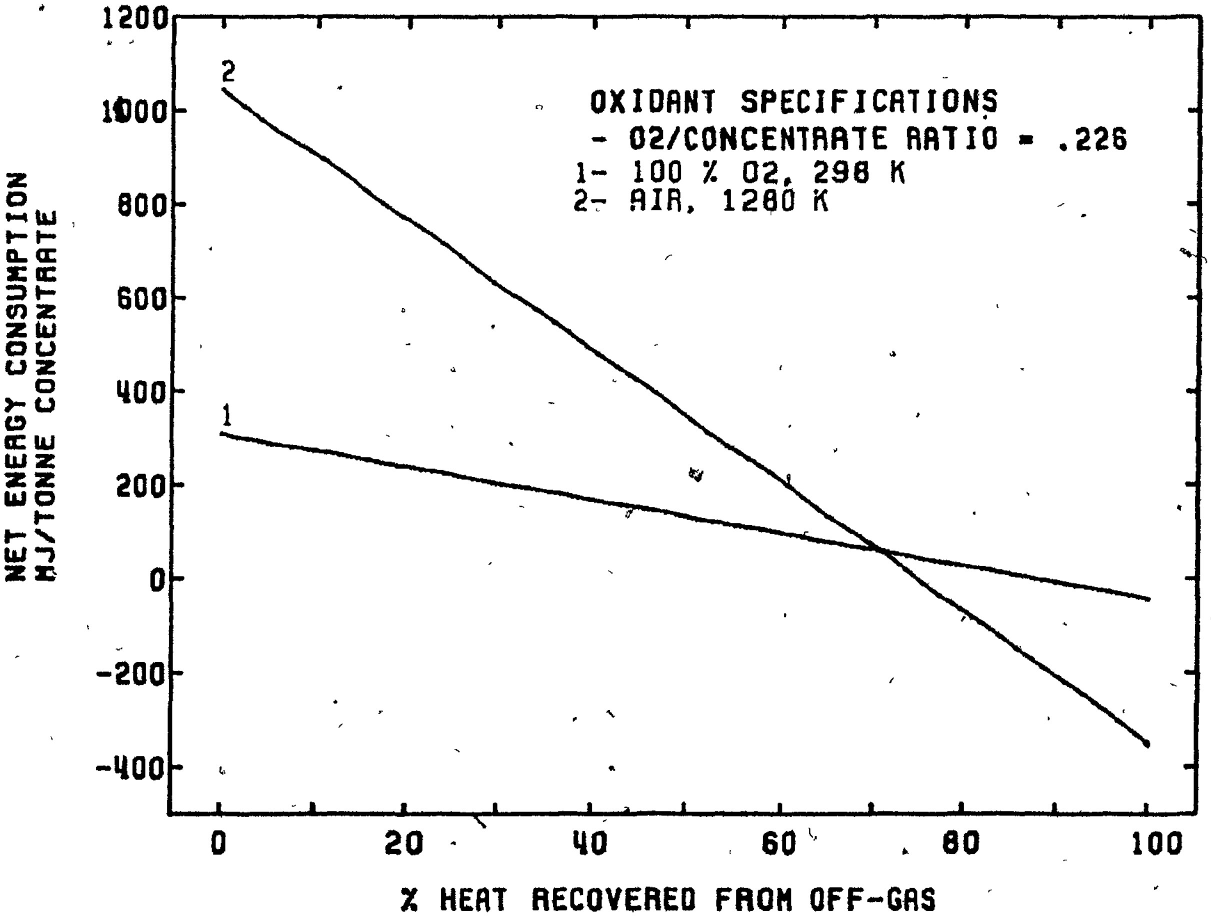

Figure 7.1 Effect of energy recovery from off-gas on the net energy consumption of oxygen and preheated-air flash smelting. The energies required for oxygen production and air preheat are defined on page 68. Negative values indicate more energy is recovered from the off-gas than is required to preheat or oxygen-enrich the oxidant.

7.4 EFFECT OF O2/CONCENTRATE RATIO ON NET ENERGY CONSUMPTION

The O2/concentrate ratio, as discussed on page 46, controls the degree of oxidation of concentrate, and thus the quantity of heat generated from the oxidation reactions. Increasing the O2/concentrate ratio results in a proportionate increase in heat supply. This increase is attributable to an increased amount of FeS oxidation (Reaction 2.2).

Specified product temperatures can be maintained while increasing the O2/concentrate ratio (i) by decreasing the O2/N2 ratio of the oxidant (i.e. increasing the amount of N2 passing through the furnace) or (ii) by decreasing the oxidant temperature. These in turn decrease the net energy consumption by reducing either (i) the amount of pure oxygen which must be produced, or (ii) the energy required to preheat the oxidant. The amount of pure oxygen required decreases even though the O2/concentrate ratio increases because the increase in heat generated allows for a larger component of air in the oxidant.

Figures 7.2 and 7.3 show the effects of increasing the O2/concentrate ratio on (i) the amount of pure oxygen required to oxygen-enrich air to the autogenous level and (ii) the temperature of the oxidant for autogenous smelting with preheated air. Figures 7.4 and 7.5 show the net energy consumption for smelting in these modes for operation with (i) no heat recovery and with (ii) 100% heat recovery.

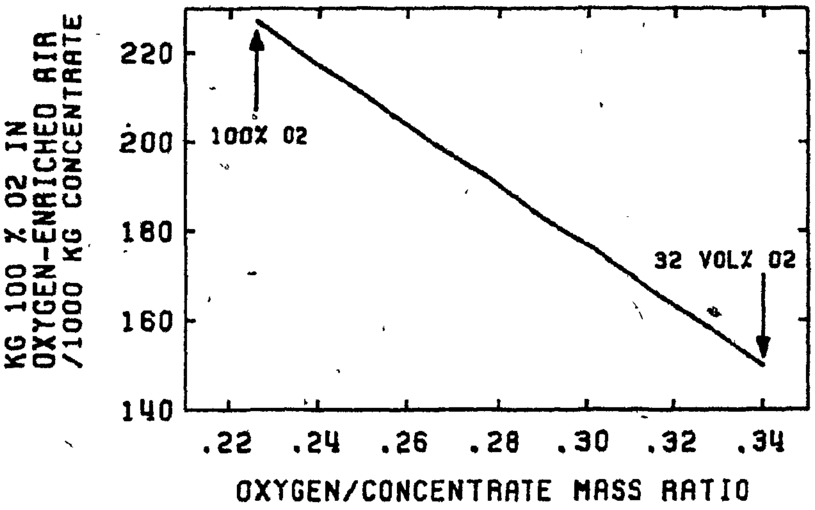

Figure 7.2 Effect of O2/concentrate ratio on the mass of pure O2 required for autogenous smelting with oxygen-enriched air (298 K), page 107. Volume % O2 in oxidant ranges from 100% with O2/concentrate ratio of 0.226 to 32% with O2/concentrate ratio of 0.34 (Figure 7.7). Oxidant temperature is constant at 298 K.

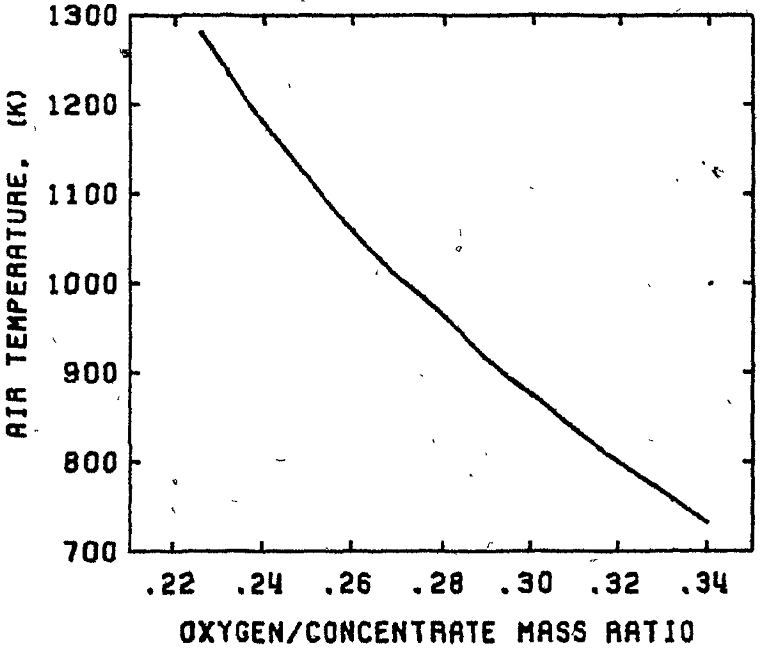

Figure 7.3 Effect of O2/concentrate ratio on air preheat temperature required for autogenous smelting with air, page 107.

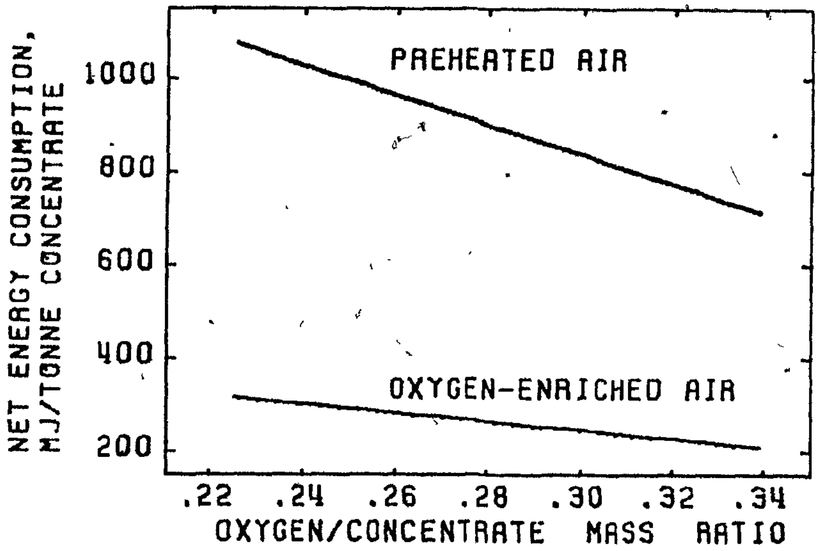

Figure 7.4 Effect of O2/concentrate ratio on net energy consumption with no off-gas energy recovery.

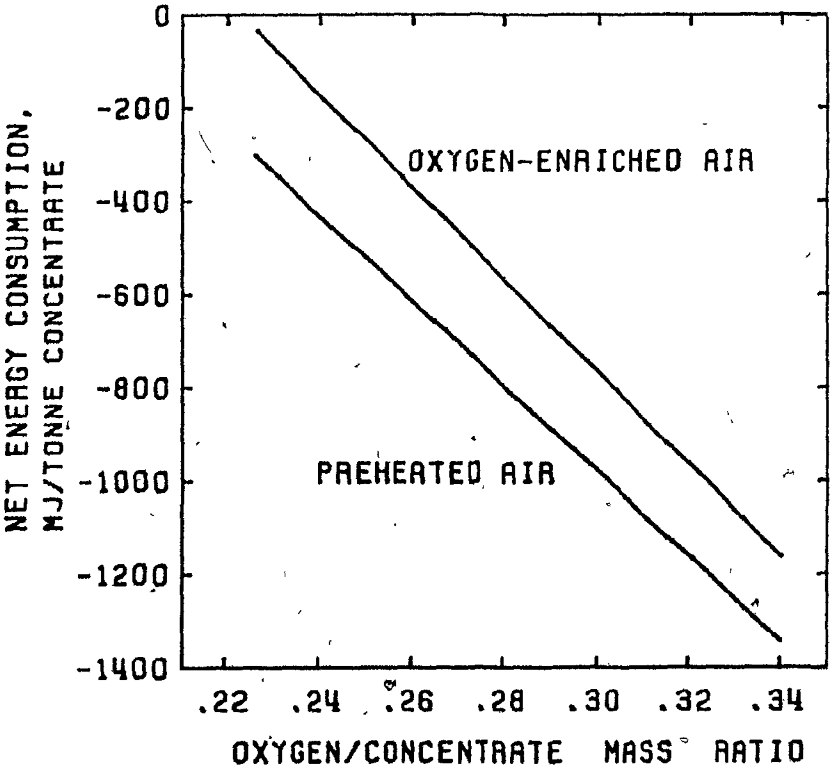

Figure 7.5 Effect of O2/concentrate ratio on net energy consumption with 100% off-gas heat recovery. The negative values indicate more energy is recovered from the off-gas than is required to produce the oxidant.

Both figures represent autogenous smelting of chalcopyrite as in Figures 7.2-7.3.

Note that the preheat temperature and oxygen requirement corresponding to a particular O2/concentrate ratio in Figures 7.4-7.5 can be obtained from Figures 7.2-7.3. The choice of O2/concentrate ratio as the abscissa for these and subsequent figures is convenient because it (i) gives a direct indication of the oxygen requirement and (ii) is directly related to matte composition and flux requirement (Figures 6.1-6.2, page 47).

The above figures show that from an energy standpoint, it is advantageous in all cases to operate with as high an O2/concentrate ratio as possible. The upper limit of O2/concentrate ratio is, however, limited industrially by a combination of the following factors:

(a) slag copper losses; copper content of slag is proportional to % Cu in matte which in turn is proportional to the O2/concentrate ratio (Figure 6.1) (30). This is especially important if the slag is to be discarded or sold without further processing to recover its copper values.

(b) removal of impurities; minor elements such as Pb, Sb, Bi, and As are removed in the converting of matte to blister copper. If the concentration of copper in matte is very high (i.e. if there is very little oxidation to be carried out in the converter), there may not be sufficient converting time to remove these impurities from the matte before copper is formed (31).

(c) magnetite buildup; solid magnetite may build up on furnace walls and bottom as conditions in the furnace become increasingly oxidizing.

Presently, for these reasons, flash furnaces are generally producing mattes with concentrations of less than 70 wt% copper.

The choice of oxidant, i.e. preheated air or oxygen-enriched air, is not clear on the basis of flash furnace energy considerations alone because the amount of heat recovery affects the decision. Oxygen-enriched air is a more practical oxidant for autogenous flash smelting than preheated air because it produces a lower volume, higher SO2 concentration off-gas (following section). The energy requirements for gas handling and cleaning and sulphur fixation are thus reduced, and the gas handling equipment can be of more compact and economical design (page 87).

7.5 CONCENTRATION OF SO2 IN OFF-GAS

7.5.1 AUTOGENOUS SMELTING WITH OXYGEN OR OXYGEN ENRICHED AIR

The concentration of SO2 in flash furnace off-gases should be maintained as high as possible for efficient sulphur fixation. Figure 6.6 showed the effect of volume % O2 in oxidant on off-gas SO2 concentration and indicated that a smelter operating its flash furnace with the highest possible volume % O2 in oxidant will produce off-gases with the highest concentration of SO2. This is clearly true for the flash furnace itself but it may not be the case when flash furnace and converter off-gases are blended to form a combined feed-gas for a sulphur fixation plant.

This apparent anomaly is explained by the low SO2 concentrations of converter off-gases, about 4-5% SO2, due to ambient air infiltration into the converter flues. In contrast flash furnace off-gases are not significantly diluted by ambient air and hence they are much more concentrated in SO2. Thus, from the point of view of producing a combined off-gas high in SO2 concentration, it can be seen that the maximum possible amount of sulphur in the concentrate should be oxidized in the flash furnace.

Figure 7.6 demonstrates the effect of O2/concentrate ratio on the distribution of sulphur oxidation between flash furnace and converter. Maximum sulphur oxidation fraction in the flash furnace is clearly obtained at the highest possible O2/concentrate ratio. Operation of this nature requires a relatively low level of oxygen enrichment (Figure 7.7).

The relationship between the O2/concentrate ratio and combined furnace-converter off-gas SO2 concentration is presented in Figures 7.8-7.9 for two modes of converter operation. Figure 7.8 depicts the situation for converters with about 4-5% SO2 in their off-gas, i.e. about 300% dilution in their off-gas. The figure points out that overall smelter off-gas SO2 concentration increases significantly with O2/concentrate ratio in the flash furnace.

Figure 7.9 represents the ideal situation in which there is no dilution of converter off-gas by ambient air. The figure indicates that if there is no air infiltration the highest overall SO2 concentration off-gas is obtained by operating at a low O2/concentrate ratio in the flash furnace. A low O2/concentrate ratio is required because this minimizes the amount of nitrogen required in the oxidant for autogenous operation (Figure 7.7).

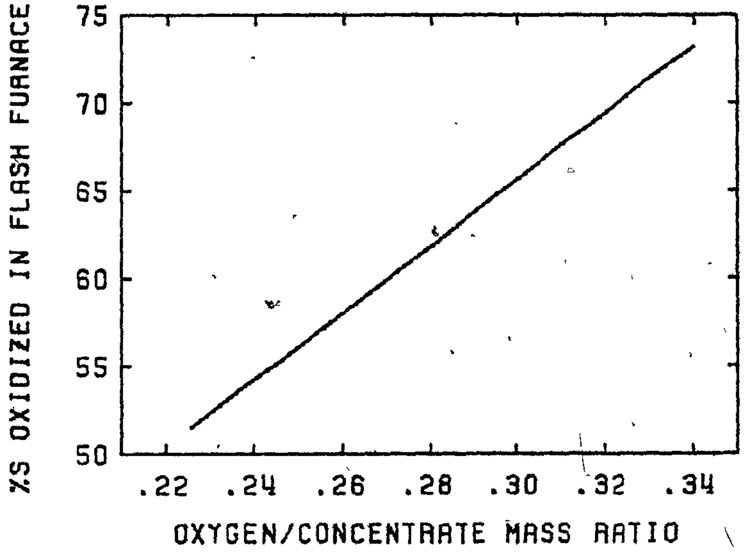

Figure 7.6 Effect of O2/concentrate ratio on the proportion of the sulphur in concentrate oxidized in the flash furnace, the remainder being oxidized in the converter.

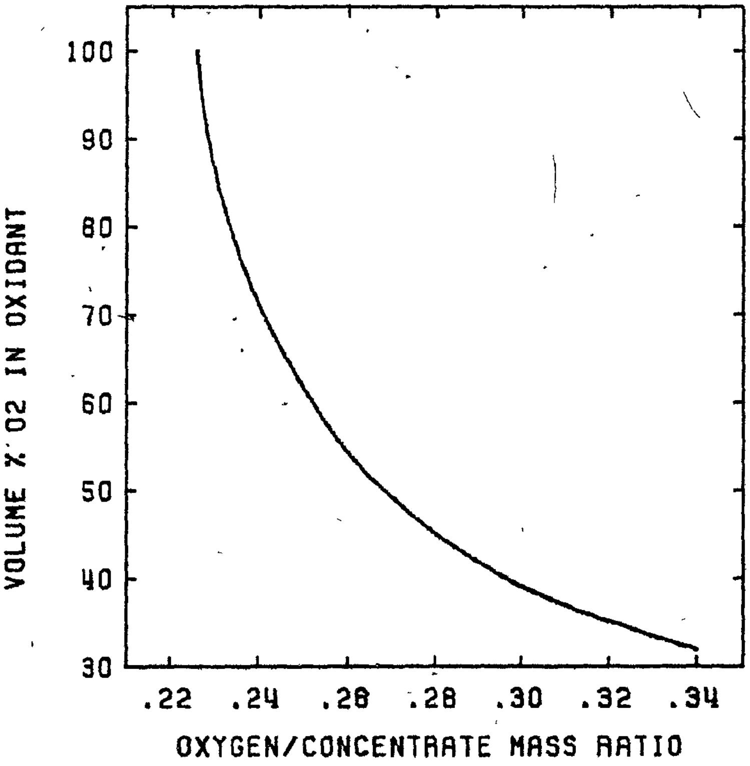

Figure 7.7 Effect of O2/concentrate ratio on volume % O2 in oxidant (at 298 K) which creates autogenous smelting.

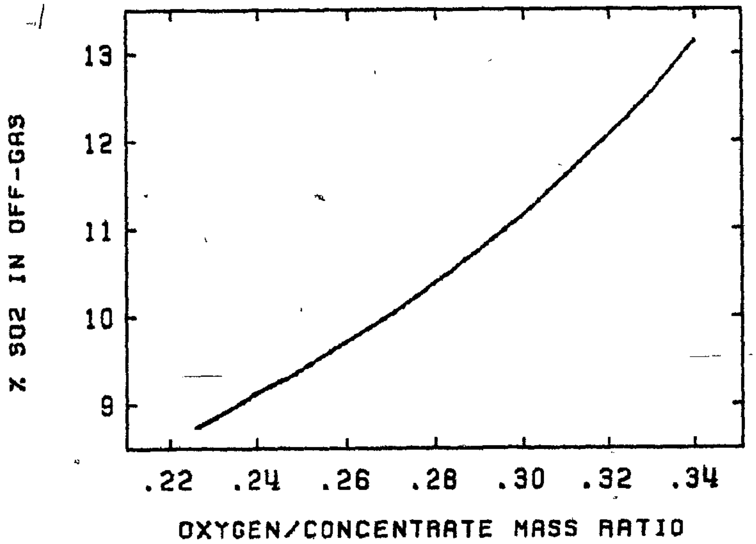

Figure 7.8 % SO2 in combined furnace-converter off-gas as a function of furnace O2/concentrate ratio. The furnace operates autogenously with oxygen-enriched air (Figure 7.7). The converter off-gas is diluted 300% by ambient air infiltration into the converter flues.

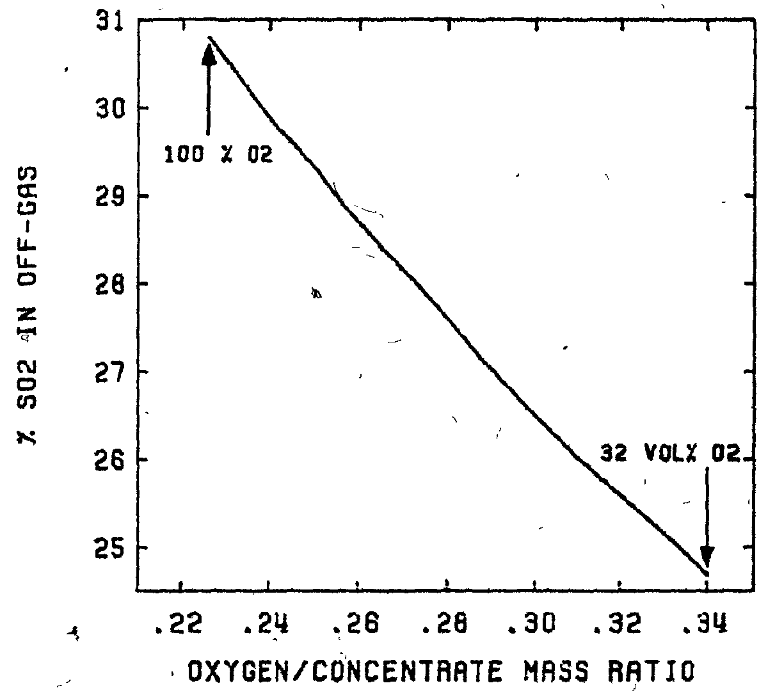

Figure 7.9 % SO2 in combined furnace-converter off-gas as a function of furnace O2/concentrate ratio. The furnace operates autogenously with oxygen-enriched air (Figure 7.7). There is no dilution of converter off-gas by ambient air.

7.5.2 AUTOGENOUS SMELTING WITH PREHEATED AIR

The off-gases generated by flash furnaces operated autogenously with preheated air would be about 18% SO_2. The exact concentration is influenced by the O_2/concentrate ratio which determines the proportions of SO_2 and FeO produced in the furnace. The amount of FeO increases in proportion to O_2/concentrate ratio and hence the N_2/SO_2 ratio in the off-gas increases and SO_2 concentration decreases.

Figure 7.10 presents the relationship between the O_2/concentrate ratio in an air flash furnace and the SO_2 concentration of combined furnace-converter off-gas for the case of a low (4-5% SO_2) concentration converter off-gas (the corresponding air preheat temperatures were presented in Figure 7.3). The figure demonstrates that the overall SO_2 concentration increases in proportion to O_2/concentrate ratio. This is similar to flash furnaces operating with oxygen-enriched air (Figure 7.8), although the SO_2 concentrations are somewhat lower.

Overall smelter SO_2 concentration is not a function of O_2/concentrate ratio when there is no air dilution of converter off-gas. This follows because, if both furnace and converter employ air as oxidant, and neither off-gas is diluted, the combined off-gas has a relatively constant SO_2 concentration of about 18%.

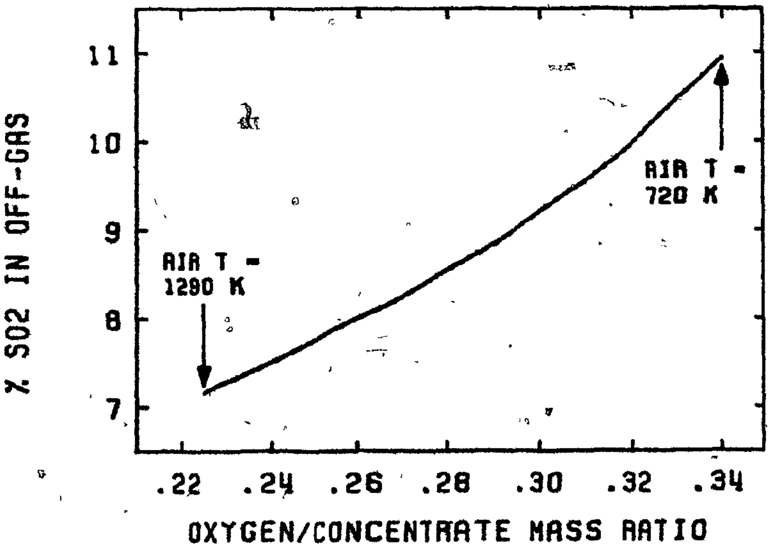

Figure 7.10 % SO2 in combined furnace-converter off-gas as a function of furnace O2/concentrate ratio for a furnace operating autogenously with preheated air (Figure 7.3). The converter off-gas is diluted 300% by ambient air infiltration into the converter flues.

Figures 7.8-7.10 represent average SO2 concentrations generated in processing a unit of chalcopyrite to blister copper under conditions specified above. The converter off-gas SO2 concentration actually varies somewhat (+/- 2%) depending on the stage of the converting cycle. The SO2 concentration is lower when iron is being oxidized (and thus the N2/SO2 ratio in the off-gas is higher) than when the only reaction is that of Cu2S oxidation to Cu and SO2.

7.5.3 SUMMARY, SO2 EVALUATION

The optimum flash smelting mode for a particular concentrate and smelter location is more involved than a simple addition of energy requirements and calculation of the overall smelter SO2 concentration. Factors such as capital costs, impurity levels in the concentrate, required scrap melting capacity, and availability of energy affect the decision.

However, the information presented earlier in this chapter points towards two alternative optimum operating modes for flash smelting on the basis of off-gas SO2 concentration.

(a) If there is significant infiltration of ambient air into converter off-gas, flash furnaces should operate with oxygen-enriched air at the highest possible O2/concentrate ratio. The precise level of oxygen-enrichment is of course related to the

O2/concentrate ratio (Figure 7.7).

or

(b) If there is little or no infiltration of ambient air into converter off-gas, flash furnaces should operate with 100% O2.

7.6 SMELTER ENERGY REQUIREMENTS

In addition to the net energy consumed in the smelting furnace itself, energy is also required for drying concentrate, compressing air for converting, slag cleaning, anode refining, scrubbing off-gas, and recovering sulphur.

Although it is beyond the scope of this work to study smelter energy requirements in detail (see (21,32)), the effects of flash furnace operating mode on overall energy requirements can be summarized as:

(a) an increase O2/concentrate ratio increases the concentration of copper in matte (Figure 6.2) and thus decreases the energy required for converting;

(b) the O2/concentrate ratio affects the copper content of flash furnace slag--slag cleaning energy requirements may be reduced if the slag copper concentration is low enough (low O2/concentrate ratio) to permit selling the slag without further processing for Cu recovery;

(c) the extent of oxygen enrichment of the oxidant and the

O_2/concentrate ratio both affect the overall SO_2 concentration of the off-gas. SO_2 concentration is indicative of the total off-gas volume which in turn has a direct effect on the energy requirements and costs of gas cleaning and sulphur fixation (33).

CHAPTER 8

DISCUSSION

8.0 INTRODUCTION

This chapter justifies the assumptions made in the examples presented in the previous chapters and points out which assumptions, though valid for comparative studies, might not be valid for particular furnace control or optimization applications. The chapter also discusses (i) how flash furnace operating mode influences the amount of magnetite formed in the furnace, (ii) the versatility of flash furnaces to operate autogenously in different modes, and (iii) future work.

8.1 VALIDITY OF EXAMPLE CALCULATIONS

8.1.1 CONCENTRATE MINERALOGY

The concentrate in all examples discussed in this thesis has been pure chalcopyrite (i.e. $CuFeS_2$, 34.6% Cu). Industrial concentrates, however, range typically from 20-30 wt% Cu, i.e., about 60-90 wt% of the concentrate is chalcopyrite. The remainder is a combination of sulphides and oxides. The sulphides are mainly pyrite (FeS_2) and pyrrhotite (~FeS). Minor amounts of other sulphides such as Cu_2S, Cu_5FeS_4, Ni_3S_2, PbS, and ZnS may also be present. The oxides consist of silica and gangue-type constituents such as CaO and Al_2O_3.

Each of these components has an effect on the mass and heat balances and product composition. For example, pyrite dilutes the matte and hence lowers the copper concentration in matte for a specified O_2/concentrate ratio. Silica in the concentrate reduces the flux requirements while CaO and Al_2O_3 affect slag melting point and viscosity (30).

All of these factors should be considered for a specific application. However, their cumulative effect on the required oxidant specifications is not very large and the trends exhibited in Chapter 6 for furnace control still apply. Appendix 1 compares the simplified examples presented in this thesis with an industrial-type concentrate.

8.1.2 PRODUCT CONSTITUTION

Product constitution has also been somewhat simplified in the previous examples. Heats of solution have been ignored as has been the presence of Fe(+3) ions (conveniently represented as Fe3O4) in slag and matte. These factors should be considered for specific applications.

The heat of solution of FeS and Cu2S is negligible (34), while the heat of solution of FeO and SiO2 can be represented by the reaction:

$$\underset{\substack{\text{liquid} \\ 1500\text{ K}}}{2\text{FeO}} + \underset{\substack{\text{liquid} \\ 1500\text{ K}}}{\text{SiO2}} = \underset{\substack{\text{liquid} \\ 1500\text{ K}}}{2\text{FeO.SiO2}} \qquad (2.3)$$

$$\Delta H^{0}1500 = +27 \text{ MJ/kg-mol SiO2}$$

For precision, this term should be included in heat demand Equation 3.11 as is shown in Appendix 1.

The presence of magnetite in flash furnace matte and slag is well documented (30,35). Magnetite can be represented in mass and heat balance equations by introducing Fe3O4 as a component of matte and slag. Of course, since new unknowns (i.e. mass of Fe3O4 in matte and slag) are introduced, specifications regarding their concentrations must be provided. These specifications can be estimated from published data or obtained by analyzing specific matte and slag samples.

In general, the net effect of the heat of solution of slag and the presence of magnetite are nearly offsetting in terms of the heat balance and the effects on the mass balances are not significant (Appendix 1, page 118).

8.1.3 NET ENERGY CONSUMPTION CALCULATIONS

The energy requirement of 1400 MJ per tonne oxygen (Chapter 7, net energy consumption calculations) can be disputed as being too low. The argument for this point of view is that the 1400 MJ represents electrical energy which is often generated from hydrocarbon-fired generating plants. These plants convert thermal energy to electrical energy with an efficiency of 30-35%. With this contention, the actual energy requirement for oxygen production is(1400/.33 ≈ 4200 MJ) per tonne.

The justification for 1400 MJ is that it is a realistic value for many locations which are serviced by hydro-electric or nuclear power. The most efficient method of utilizing these energy sources is in fact by conversion to electrical energy. The availability of electricity from these sources should increase in the future as a consequence of rising hydrocarbon fuel prices amd falling resources. As a result, 1400 MJ/tonne O2 is a useful value for energy calculations which are to be applied to processes for the future.

Another questionable aspect of the net energy consumption approach used in Chapter 7 is the energy credit given for off-gas heat recovery. Equivalent credit is given regardless of the oxidant type. The significance of oxidant type on off-gas heat recovery is that heat (recovered as high pressure steam) is used more efficiently as a source of heat for preheating air than as a source of power to drive compressors to produce oxygen. Thus, if there is no direct use of the heat recovered from the off-gases, the difference in energy utilization efficiencies should be considered when comparing specific smelting modes (21).

8.1.4 RADIATIVE AND CONVECTIVE HEAT LOSSES

A value of 25000 MJ/hour was chosen as the heat loss rate for the examples in this thesis since it approximates the average heat loss rate for most flash furnaces (21). Heat loss rates vary somewhat, depending on furnace design and operating practice. The heat loss rates for the compact Inco oxygen or Outokumpu oxygen-enriched flash furnaces are slightly lower than this average, while larger air-operated flash furnaces have larger heat losses (10,21).

Furnace heat losses consist of (i) a radiative component from the furnace chamber into the gas uptake and (ii) a convective component from the exterior surface of the furnace to the ambient air. The relationship between operating temperature and heat loss rate depends on the the relative proportions of these components, since radiative heat loss is more sensitive to temperature than convective heat loss.

The temperature of the flash furnace 'flame' created by concentrate reacting with the oxidant also affects heat loss rate since radiation from the flame to the furnace walls and roof is a component of total heat losses. Flame temperature as used here is analogous to the adiabatic flame temperature often cited for hydrocarbon fuels, and is defined as the temperature at which the enthalpy of the products equals the enthalpy of the reactants. It is determined by solving the equation:

Enthalpy of reactants = Enthalpy of products (8.1)

where:

Enthalpy of reactants = HT(reactants) (8.2)

and:

Enthalpy of products = HTflame(products) (8.3)

where Tflame is the flame temperature.

Product compositions in the flame temperature calculations are assumed to be the same as those for matte, slag, and off-gas (Chapter 3). Although part of the concentrate may be over-oxidized while part remains unreacted until equilibrium is attained in the matte and slag, this should not have a significant effect on flame temperature.

Flame temperature is calculated in the computer program subsequent to solving the mass and heat balance equations. The results are shown in Figure 8.1 which demonstrates the effect of O2/concentrate ratio on flame temperature. As expected, flame temperature increases with increasing O2/concentrate ratio and decreases with decreasing O2/N2 oxidant ratio.

Although it is beyond the scope of this work to estimate the extent to which heat loss rate depends on flame temperature, this effect should be considered in flash smelting control. It is likely to be most significant with Inco-type oxygen flash furnaces since the flame temperature is higher and is more sensitive to changes of O2/concentrate ratio than are oxygen-enriched or air flash smelting operations.

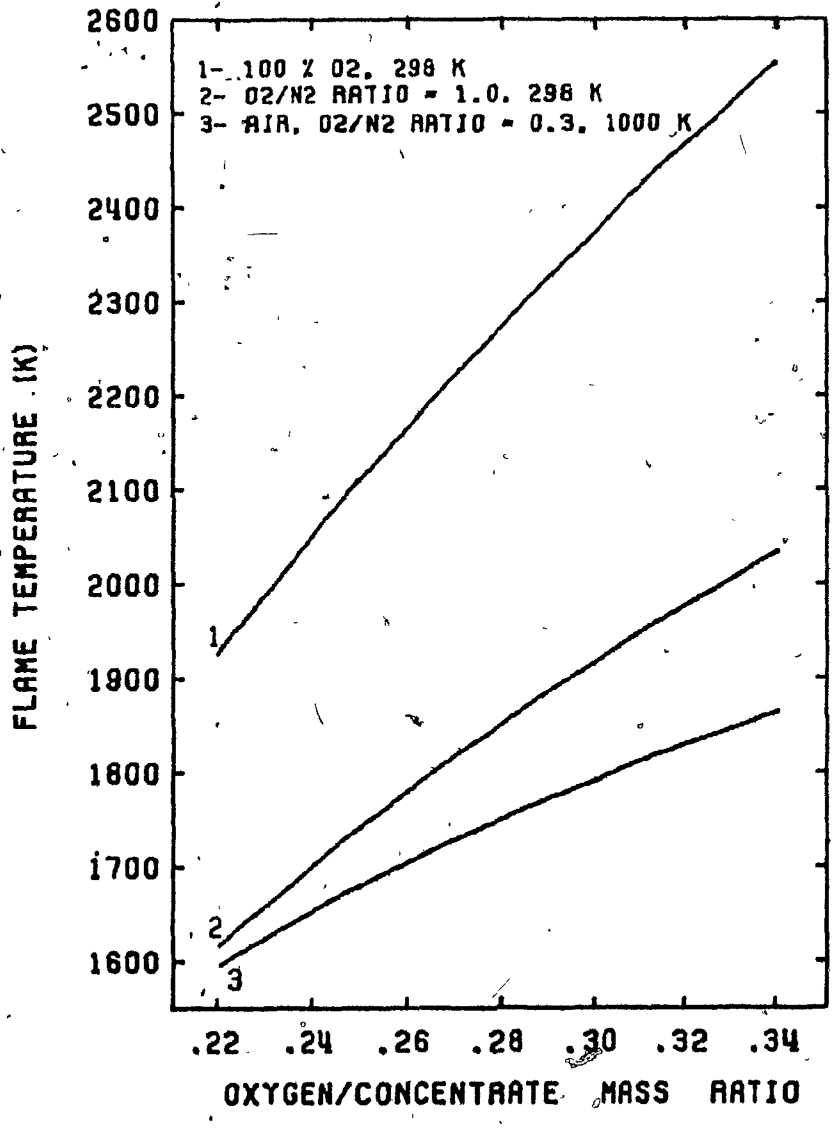

Figure 8.1 Effect of O2/concentrate ratio on flame temperature as defined on page 94.

8.2 EFFECT OF FLAME TEMPERATURE ON MAGNETITE FORMATION

The formation of solid magnetite in flash furnaces is a matter of concern especially under highly oxidizing conditions (i.e. with a high O2/concentrate ratio and consequently a high %Cu in matte). Problems associated with magnetite include build-up of solid magnetite on the furnace hearth and increased losses of copper in slag. The significance of magnetite build-up is that it reduces the effective volume of the furnace, which can be a factor contributing to the shortening of furnace campaign life.

The tendency towards magnetite formation in the flash furnace flame is indicated by the reaction:

$$\underset{\text{liquid}}{3FeO} + .5O_2 = \underset{\text{solid}}{Fe_3O_4} \qquad (8.4)$$

Figure. 8.2 shows the effects of partial pressure of O2 and temperature on this reaction. The figure shows that for a specified partial pressure of oxygen, solid magnetite is less likely to form if the flame temperature is high. Magnetite melts at 1865 K so the formation of solid magnetite is clearly not a problem in flames which are above 1865 K.

The tendency towards formation of solid magnetite in copper smelting furnaces is determined by the equilibrium between matte, slag, and furnace atmosphere, i.e.:

$$\underset{\text{solid}}{3Fe_3O_4} + \underset{\text{liquid}}{FeS} = \underset{\text{liquid}}{10FeO} + \underset{\text{gas}}{SO_2} \qquad (8.5)$$

Although flame temperature does not directly affect this equilibrium, it is clearly advantageous to form as little Fe_3O_4 in the flame as possible, i.e. reaction 8.5 may not be fast enough to eliminate magnetite formed in the flame. This is obtained by operating with a high flame temperature.

It is interesting to note that flame temperature similarly affects Cu_2O formation in the flame (for the reaction $Cu_2S + 1.5O_2 = Cu_2O + SO_2$). Although copper content of slag is determined by a combination of entrained Cu_2S and equilibrium between matte and slag, it is advantageous to produce as little Cu_2O in the flame as possible.

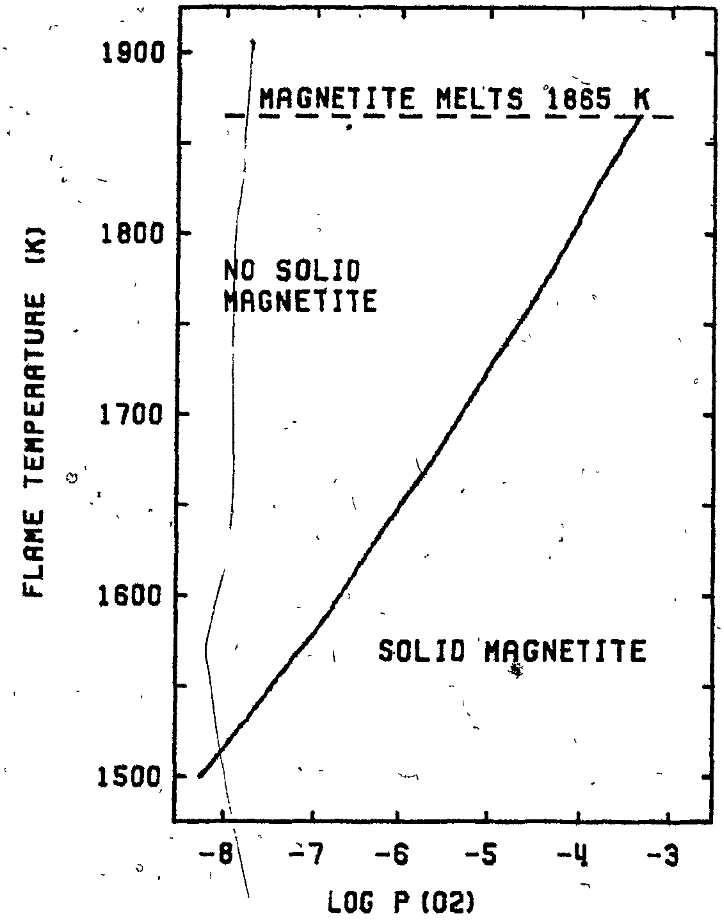

Figure 8.2 Effects of O2 partial pressure and reaction temperature (analogous with flame temperature for flash furnaces) on the reaction:

$3FeO_{\text{liquid}} + .5O_2 = Fe_3O_{4\,\text{solid}}$

8.3 AUTOGENOUS FLASH SMELTING FLEXIBILITY

Figures 7.3 and 7.7 (repeated for convenience on page 101) demonstrate that there are many autogenous flash smelting modes available. The options range from:

(a) low O2/concentrate ratio with either (i) oxygen or highly oxygen-enriched air or (ii) high temperature preheated air;

to

(b) high O2/concentrate ratio with either (i) low degree of oxygen enrichment or (ii) low temperature preheated air.

In addition to these choices, it is possible to operate autogenously in the areas beneath the curves of Figures 7.3 and 7.7 by operating with preheated oxygen-enriched air. For example, employing an oxidant of 40% O2 at 800 K requires an O2/concentrate ratio of .24 to maintain product temperatures under the prescribed conditions of Figure 7.3 and 7.7. This mode of smelting also has the advantage of having all three oxidant variables (i.e. O2/N2 ratio, O2/concentrate ratio, and oxidant temperature) available as possible control parameters.

Autogenous smelting is also possible above the operating lines presented in Figures 7.3 and 7.7 by adding coolants to the furnace. The following section discusses the ramifications of adding water as a coolant into an oxygen flash furnace.

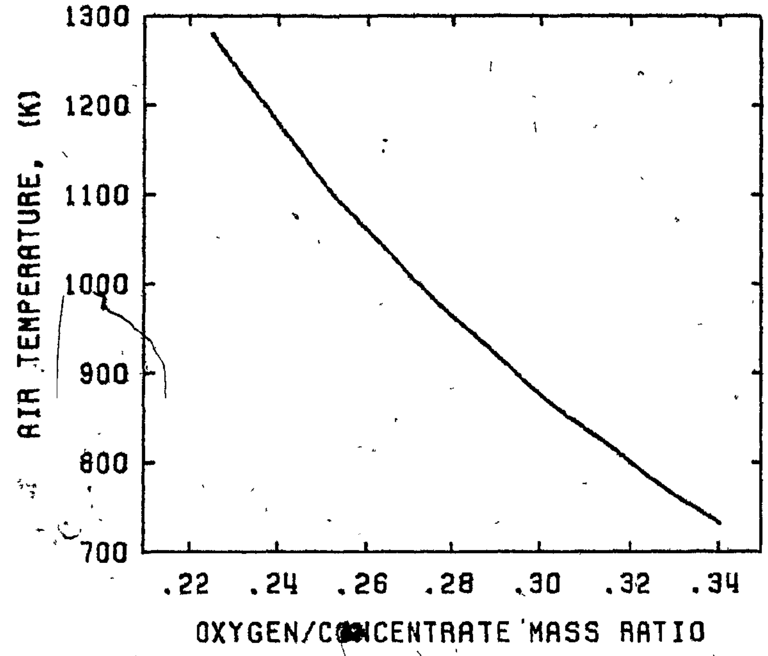

Figure 7.3 Effect of O2/concentrate ratio on air preheat temperature required for autogenous smelting, page 107.

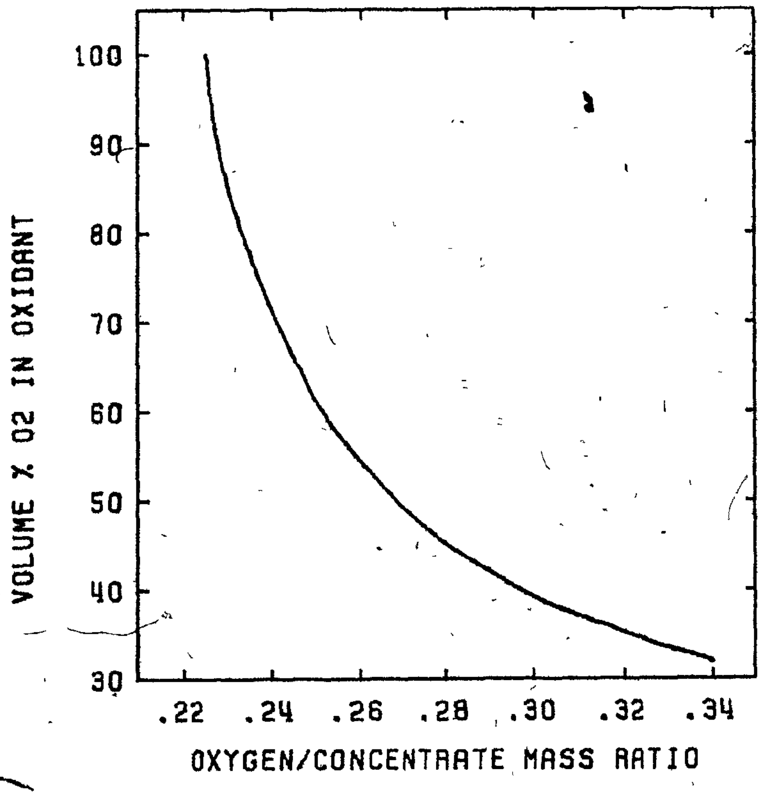

Figure 7.7 Effect of O2/concentrate ratio on volume % O2 in oxidant (at 298 K) required for autogenous smelting of chalcopyrite, page 107.

8.3.1 WATER ADDITIONS TO OXYGEN FLASH SMELTING

The benefits of operating at high O2/concentrate ratio and with high O2/N2 ratio oxidant have been discussed in Chapter 7. It is possible to operate at a higher O2/concentrate ratio than that specified by Figure 7.7 for a given oxidant by replacing the cooling effect of nitrogen by that of a more effective coolant. Both Inco and Outokumpu have suggested adding oxides (such as flue dusts) as possible coolants while Inco has suggested the injection of water into the furnace. (8,17)

Although the addition of water certainly may entail some practical problems, such as even distribution of water in the furnace and the danger of steam explosions, there are conceptual advantages. These are discussed below by comparing autogenous furnace operations using an O2/concentrate ratio of .34 for the cases of:

(a) oxygen-enriched air, 32% O2 (630 kg N2, 150 kg 100% O2, 340 kg total O2; all per 1000 kg concentrate);
(b) 100% O2 (340 kg O2) with 170 kg water per 1000 kg concentrate. The effect of water additions to the heat and mass balance equations is discussed on page 111.

The most obvious advantage of substituting the cooling effect of nitrogen by water is that off-gas volume decreases and hence concentration of SO2 in off-gas increases.

This advantage is a consequence of water requiring approximately 4 times more heat per unit mass than nitrogen to raise its temperature from 298 to 1500 K. This difference is largely due to the enthalpy of vaporization of water. Cooling the off-gas to condense the water will further increase the SO_2 concentration to 100% (when pure oxygen is the oxidant). This high volume, high SO_2 concentration off-gas is ideal feed for sulphur fixation.

Another conceptual advantage of operating with 100% oxygen plus water injection is that, as the water could be injected as [illegible] sheath surrounding the flame (not in the flame itself), it would not appreciably affect the flame temperature per se. Consequently flame temperature of the oxygen furnace would be about 2500 K (Figure 8.1) while the oxygen-enriched flame of this example would be around 1700 K. The advantages of less magnetite and copper oxide formation previously attributed to high flame temperatures would thus apply for flash furnaces operating with oxygen and water injection.

Of course the penalty which must be paid when operating with oxygen and water instead of oxygen-enriched air is the energy required to produce the additional oxygen. For this example, 190 kg more pure oxygen per tonne concentrate is required for oxygen-water flash smelting than for oxygen-enriched air flash smelting. Furthermore, off-gas scrubbing is certainly more involved since the water in the off-gas demands special consideration with respect to drying and possibly corrosion control.

8.4 FUTURE WORK

The steady-state model developed in this thesis is a powerful tool in its present form. It could be applied with greater effect, however, as the core of a real time flash furnace control package. The changes required to modify the model to control a particular furnace can be summarized as follows:

(a) minor modifications to the mass and heat balance equations of the type as mentioned earlier in this chapter and outlined in Appendix 1.

(b) an iterative loop within the program to enable the mass and heat balance equations to be solved if the specifications for some of the equations are dependent on the solutions of the mass and heat balances. For example the heat loss rate may be expressed in terms of calculated flame temperature.

(c) flags to notify the operator when discrepancies between the model and actual operation suggest errors in feed or output measurements.

The model can also be used for precise optimization studies (Chapter 7) by using precise energy and feed specifications which apply to a particular concentrate and precise costs which apply to a specific smelter location.

Finally, similar models can also be developed for other non-ferrous furnaces such as nickel, lead, and zinc.

CHAPTER 9

CONCLUSIONS

(1) FLASH SMELTING IS THE BEST PROCESS AVAILABLE FOR SMELTING COPPER SULPHIDE CONCENTRATES. IT CONSUMES LESS ENERGY THAN ALTERNATIVE SMELTING PROCESSES AND IT PRODUCES A STEADY STREAM OF HIGH SO2 CONCENTRATION OFF-GAS WHICH IS EXCELLENT FEED FOR SULPHUR FIXATION.

(2) FLASH FURNACES SHOULD BE OPERATED AUTOGENOUSLY. FUEL IS USED MORE EFFICIENTLY FOR PREHEATING AIR OR PRODUCING OXYGEN AND THEREBY REDUCING THE HEAT REQUIREMENT CREATED BY NITROGEN IN FLASH FURNACE OFF-GASES.

(2A) AUTOGENOUS FURNACE OPERATION ALSO AVOIDS GASEOUS HYDROCARBON COMBUSTION PRODUCTS IN FLASH FURNACE OFF-GASES THEREBY MINIMIZING OFF-GAS VOLUMES AND MAXIMIZING SO2 CONCENTRATIONS. THIS MINIMIZES THE SIZES OF THE GAS COLLECTION AND SULPHUR FIXING SYSTEMS REQUIRED FOR THE PROCESS.

(3) FLASH FURNACES SHOULD PRODUCE THE HIGHEST POSSIBLE MATTE GRADE (%CU IN MATTE), I.E. THEY SHOULD OPERATE WITH THE HIGHEST POSSIBLE O2/CONCENTRATE RATIO. THIS MODE OF OPERATION UTILIZES MOST EFFICIENTLY THE CHEMICAL ENERGY OF THE CONCENTRATE AND MINIMIZES THE AMOUNT OF CONVERTING REQUIRED. THE UPPER LIMIT OF MATTE GRADE IS DETERMINED BY FACTORS OTHER THAN ENERGY MINIMIZATION, FOR EXAMPLE EXCESSIVE LOSSES OF COPPER IN SLAG OR INSUFFICIENT IMPURITY REMOVAL DURING CONVERTING.

(3A) EFFLUENT GAS VOLUMES FOR THE COMBINED SMELTING/CONVERTING PROCESS ARE MINIMIZED AND COMBINED SO_2 CONCENTRATIONS ARE MAXIMIZED BY CARRYING OUT AS MUCH OXIDATION AS POSSIBLE IN THE FLASH FURNACE, I.E. BY OPERATING WITH A HIGH O_2/CONCENTRATE RATIO AND ITS CONSEQUENT HIGH MATTE GRADE. THIS IS BECAUSE THE EFFLUENT GASES FROM CONVERTING ARE UNAVOIDABLY DILUTED BY INFILTRATED AIR WHILE THOSE FROM FLASH FURNACES ARE NOT.

(4) OXYGEN-ENRICHED AIR IS A MORE PRACTICAL OXIDANT FOR AUTOGENOUS FLASH SMELTING THAN PREHEATED AIR BECAUSE IT PRODUCES A LOWER VOLUME, HIGHER SO_2 CONCENTRATION OFF-GAS. ALSO IT IS IN MOST CASES MORE EFFICIENT IN TERMS OF ENERGY CONSUMPTION.

(5) OF ALL THE AUTOGENOUS FLASH SMELTING MODES, SMELTING WITH PURE O_2 PRODUCES THE LOWEST GRADE MATTE, I.E. SMELTING WITH PURE O_2 IS AUTOGENOUS WITH A LOW O_2/CONCENTRATE RATIO. THIS MIGHT BE ADVANTAGEOUS FROM THE STANDPOINTS OF (I) IMPURITY REMOVAL DURING CONVERTING AND OF (II) PRODUCING FLASH FURNACE SLAGS LOW IN COPPER. HOWEVER IT IS DISADVANTAGEOUS FROM THE POINTS OF VIEW OF (I) ENERGY CONSUMPTION (CONCLUSION 3) AND (II) OFF-GAS VOLUMES AND SO_2 CONCENTRATIONS (CONCLUSION 3A).

(6) FLASH FURNACE OPERATING TEMPERATURE CAN BE CONTROLLED BY VARYING (I) O_2/CONCENTRATE RATIO, (II) O_2/N_2 RATIO AND/OR (III) OXIDANT TEMPERATURE. O_2/CONCENTRATE RATIO AND O_2/N_2 RATIO HAVE INADVERTANT SIDE AFFECTS IN THAT THEY AFFECT MATTE, SLAG, AND OFF-GAS COMPOSITIONS. OXIDANT TEMPERATURE IS, HOWEVER, A TRULY INDEPENDENT CONTROL PARAMETER.

(7) THE MODEL DEVELOPED IN THIS THESIS IS USEFUL IN DETERMINING OPTIMUM CONDITIONS FOR SMELTING UNDER ANY GIVEN PRESCRIBED SET OF CONDITIONS. IT IS ALSO USEFUL AS THE CORE OF A REAL-TIME FURNACE CONTROL SYSTEM.

APPENDIX 1

MODIFICATIONS TO STEADY-STATE MODEL

The examples and figures presented in the thesis are based on the following simplified data:

concentrate: chalcopyrite ($CuFeS_2$), 298 K

flux: silica (SiO_2), 298 K

matte: Cu_2S-FeS, 1475 K

slag: 70% FeO, 30 wt% SiO_2, 1500 K

off-gas: SO_2, 1525 K

throughput: 50 tonnes/hour of concentrate
(unless explicitly studied as a variable)

radiative and convective heat loss rate : 25000 MJ/hour

oxidant: as specified

fuel: none

This appendix demonstrates how the equations in the steady-state model are modified to deal with more realistic feed and product specifications.

A1.1 CONCENTRATE MINERALOGY

Most industrial copper concentrates consist largely of chalcopyrite, pyrite (FeS_2) and pyrrhotite (FeS)*. The relative amounts of these minerals in the concentrate can be determined from its chemical analysis by solving the equations:

$$\text{kg-moles Cu in concentrate} = CuFeS_2 \quad \text{(kg-moles)}$$

$$\text{kg-moles Fe in concentrate} = CuFeS_2 + FeS_2 + FeS_{1.14} \quad \text{(kg-moles)}$$

$$\text{kg-moles S in concentrate} = 2 \cdot CuFeS_2 + 2 \cdot FeS_2 + 1.14 \cdot FeS_{1.14} \quad \text{(kg-moles)}$$

The only effect of pyrite and pyrrhotite on the mass and heat balance equations (Chapter 3) is to modify the heat supply, Equation 3.10 (page 18):

$$\text{Heat supply} = H_{298}(\text{reactants}) - H_{298}(\text{products}) + H_T(\text{reactants}) - H_{298}(\text{reactants}) \quad (3.10)$$

in which the term H_{298}(reactants) becomes:

$$\begin{aligned} H^0_{298}(\text{reactants}) = {} & H^0_{298}(CuFeS_2) \cdot \text{kg-moles } CuFeS_2 \\ & + H^0_{298}(FeS_2) \cdot \text{kg-moles } FeS_2 \\ & + H^0_{298}(FeS_{1.14}) \cdot \text{kg-moles } FeS_{1.14} \end{aligned}$$

---

* Pyrrhotite does not have a precise mineralogical composition; it is best represented by the formula $Fe_{(n-1)}S_{(n)}$ with n varying from 8-16. Fe_7S_8 ($FeS_{1.14}$) is the most common form.

Rock-type constituents such as CaO and Al_2O_3 in the concentrate behave inertly in flash furnaces and enter the slag. They affect the heat demand (Equation 3.11):

$$\text{heat demand (with rock)} = \text{heat demand (no rock)} + \{H^0T(\text{rock}) - H^0 298(\text{rock})\} \cdot \text{kg-moles rock}$$

where T is the slag temperature.

A1.2 MAGNETITE IN SLAG AND MATTE

The effect of magnetite in furnace slag is taken into account by making small adjustments to both mass and heat balance equations.

The output term in the iron balance (Equation 3.3, page 25) becomes;

$$\text{mass Fe out (with magnetite)} = \text{mass Fe out (no magnetite)} + \text{mass } Fe_3O_4 \text{ in slag} \cdot \frac{\%\text{Fe in } Fe_3O_4}{100}$$

the output term in the oxygen balance (Equation 3.5, page 26) becomes;

$$\text{mass O out (with magnetite)} = \text{mass O out (no magnetite)} + \text{mass } Fe_3O_4 \text{ in slag} \cdot \frac{\%\text{O in } Fe_3O_4}{100}$$

the silica balance (Equation 3.7, page 26) becomes;

$$\text{mass SiO2 in} = \text{mass SiO2 out}$$

$$= (\text{mass FeO} + \text{mass SiO2} + \text{mass Fe3O4}) \cdot \frac{\text{\% SiO2 in slag}}{100}$$

the heat supply (Equation 3.10, page 27) becomes;

$$\underset{\text{(with magnetite)}}{\text{heat supply}} = \underset{\text{(no magnetite)}}{\text{heat supply}} - H^0 298(\text{Fe3O4}) \cdot \text{kg-moles Fe3O4}$$

and the heat demand (Equation 3.11, page 28) becomes;

$$\underset{\text{(with magnetite)}}{\text{heat demand}} = \underset{\text{(no magnetite)}}{\text{heat demand}} + \{H^0 T(\text{Fe3O4}) - H^0 298(\text{Fe3O4})\} \cdot \text{kg-moles Fe3O4}$$

where T is the slag temperature.

Finally a new equation is required to depict the relationship of the magnetite in the slag:

$$\text{Fe3O4 mass} = \text{slag mass} \cdot (\text{wt\% Fe3O4 in slag} / 100)$$

$$= (\text{mass FeO} + \text{mass Fe3O4} + \text{mass SiO2}) \cdot \frac{\text{wt \% Fe3O4}}{100}$$

The proportion of Fe3O4 in slag can be determined from industrial data. Exactly parallel relationships can be prepared to account for magnetite in matte.

A1.3 HEAT OF MIXING OF SLAG

Equation 2.3 (page 6) is representative of the heat of mixing of FeO and SiO2 in the slag:

$$\underset{\substack{\text{liquid}\\1500\text{ K}}}{2FeO} + \underset{\substack{\text{liquid}\\1500\text{ K}}}{SiO_2} = \underset{\substack{\text{liquid}\\1500\text{ K}}}{2FeO.SiO_2} \qquad (2.3)$$

$$\Delta H^0 1500 = .27 \text{ MJ/kg-mol } SiO_2$$

$$= .19 \text{ MJ/kg } FeO$$

This heat effect can be included in the heat demand (Equation 3.11, page 28):

$$\begin{array}{ll} \text{heat demand} & = \text{heat demand} \\ \text{(including heat} & \quad\text{(ignoring heat} \\ \text{of mixing)} & \quad\text{of mixing)} \\ & \quad + .19 \cdot \text{mass FeO} \end{array}$$

A1.4 WATER ADDITIONS

Water additions (298 K) into the furnace affect the heat demand (Equation 3.11, page 28) which becomes:

$$\begin{array}{ll} \text{heat demand} & = \text{heat demand} \\ \text{(with water)} & \quad\text{(no water)} \\ & \quad + \{H^0T(H_2O) - H^0 298(H_2O)\} \cdot \text{kg-moles } H_2O \end{array}$$

where T is the off-gas temperature.

Since the water forms a constituent of the off-gas, it also affects off-gas volume and the concentration of SO_2 in off-gas.

A1.5 FUEL ADDITIONS

The addition of fuel is also easily incorporated into the steady-state model. For the case of a pure carbon fuel burning to CO_2, the following equations must be modified:

the input term of the oxygen balance, Equation 3.5;

$$\underset{\text{(with carbon)}}{\text{O in}} = \underset{\text{(no carbon)}}{\text{O in}} + \frac{32 \text{ kg } O_2/\text{kg-mol } CO_2}{12 \text{ kg C/kg-mol } CO_2} \cdot \text{kg C in}$$

the heat supply, Equation 3.10;

$$\underset{\text{(with carbon)}}{\text{heat supply}} = \underset{\text{(no carbon)}}{\text{heat supply}} + H^0_{298}(C) \cdot \text{kg-moles C} - H^0_{298}(CO_2) \cdot \text{kg-moles } CO_2$$

and the heat demand, Equation 3.11;

$$\underset{\text{(with carbon)}}{\text{heat demand}} = \underset{\text{(no carbon)}}{\text{heat demand}} + \{H^0_T(CO_2) - H^0_{298}(CO_2)\} \cdot \text{kg-moles } CO_2$$

where T is the off-gas temperature.

Since the combustion products (i.e. CO_2 and the N_2 associated with the combustion oxygen) form a constituent of the off-gas, they also affect off-gas volume and concentration of SO_2 in off-gas.

A1.6 FLUE DUST

Flue dust generated from flash furnaces consists mostly of metal oxides; the exact composition being dependent on the composition of the concentrate. Many of the oxides (eg, Cu_2O, ZnO, PbO) react with SO_2 and SO_3 in the off-gas handling system to become sulphates ($CuSO_4$, $ZnSO_4$, $PbSO_4$) (19).

Although the flue dust is generally recycled back to the flash furnace, the instantaneous rate of dust generation and recycle need not be equal. Consequently, their effects on the mass and heat balances should be studied independently. This section demonstrates how the generation of a Cu_2O flue dust and the recycle of a $CuSO_4$ dust affect the mass and heat balances. Other components of flue dust affect the balances in a similar manner.

Cu2O out

The generation of Cu2O affects the following equations:

the output term of the copper balance, Equation 3.2;

$$\underset{\text{(with Cu2O)}}{\text{Cu out}} = \underset{\text{(no Cu2O)}}{\text{Cu out}} + \text{mass Cu2O} \cdot \frac{\text{\%Cu in Cu2O}}{100}$$

the output term of the oxygen balance, Equation 3.5;

$$\underset{\text{(with Cu2O)}}{\text{O out}} = \underset{\text{(no Cu2O)}}{\text{O out}} + \text{mass Cu2O} \cdot \frac{\text{\%O in Cu2O}}{100}$$

the heat supply, Equation 3.10;

$$\underset{\text{(with Cu2O)}}{\text{heat supply}} = \underset{\text{(no Cu2O)}}{\text{heat supply}} - H^0 298(\text{Cu2O}) \cdot \text{kg-moles Cu2O}$$

and the heat demand, Equation 3.11;

$$\underset{\text{(with Cu2O)}}{\text{heat demand}} = \underset{\text{(no Cu2O)}}{\text{heat demand}} + \{H^0 T(\text{Cu2O}) - H^0 298(\text{Cu2O})\} \cdot \text{kg-moles Cu2O}$$

where T is the off-gas temperature.

CuSO4 in

Recycling CuSO4 affects the following equations:

the input term of the copper balance, Equation 3.2;

$$\underset{\text{(with CuSO4)}}{\text{Cu in}} = \underset{\text{(no CuSO4)}}{\text{Cu in}} + \text{mass CuSO4} \cdot \frac{\text{\%Cu in CuSO4}}{100}$$

the input term of the oxygen balance, Equation 3.5;

$$\underset{\text{(with CuSO4)}}{\text{O in}} = \underset{\text{(no CuSO4)}}{\text{O in}} + \text{mass CuSO4} \cdot \frac{\text{\% O in CuSO4}}{100}$$

the input term of the sulphur balance, Equation 3.4;

$$\underset{\text{(with CuSO4)}}{\text{S in}} = \underset{\text{(no CuSO4)}}{\text{S in}} + \text{mass CuSO4} \cdot \frac{\text{\% S in CuSO4}}{100}$$

and the heat supply, Equation 3.10;

$$\underset{\text{(with CuSO4)}}{\text{heat supply}} = \underset{\text{(no CuSO4)}}{\text{heat supply}} + H^{0}298(\text{CuSO4}) \cdot \text{kg-moles CuSO4.}$$

Other components of flue dust can be treated in an exactly analogous manner.

A1.7 EXAMPLES: MODIFIED FEED AND PRODUCT SPECIFICATIONS

"A CONCENTRATE IS SMELTED IN AN INCQ TYPE (OXYGEN) FLASH FURNACE. WHAT ARE THE OXYGEN AND FLUX REQUIREMENTS WHICH WILL PERMIT THE FURNACE TO OPERATE AUTOGENOUSLY WITH THE FOLLOWING FEED AND PRODUCT SPECIFICATIONS?"

concentrate:	26% Cu, 30% Fe, 33% S, 5% SiO_2, 6% $CaO-Al_2O_3$
flux:	80% SiO_2, 20% $CaO-Al_2O_3$
matte:	Cu_2S-FeS, 1475 K
slag:	30% SiO_2, remainder FeO, CaO, Al_2O_3, 1500 K
off-gas:	SO_2, 1525 K
throughput:	50 tonnes/hour of concentrate
radiative and convective heat loss:	25000 MJ/hour
oxidant:	100% O_2

This problem, except for the feed and product specifications, is identical to Example 1, page 24 . Solving the modified mass and heat balance equations yields:

O_2 feed = 236 kg

SiO_2 in flux = 68 kg

Cu_2S in matte = 326 kg

FeS in matte = 209 kg

SO_2 in offgas = 376 kg

FeO in slag = 215 kg

heat supply = 1971 MJ

heat demand = 1971 MJ

Thus this concentrate requires an O2/concentrate ratio of .236 for autogenous smelting, only 4% greater that required under the conditions specified in Example I, page 24. Additional operating data for this example are:

$$\text{matte mass} = Cu_2S + FeS = 535 \text{ kg}$$

$$\%\ Cu \text{ in matte} = \frac{Cu_2S \cdot (\text{wt\% } Cu \text{ in } Cu_2S / 100)}{\text{matte mass}} = 48.6\ \%\ Cu$$

$$\text{slag mass} = FeO + SiO_2 + \text{rock} = 393 \text{ kg}$$

The differences between these numbers and the equivalent values of Example I, page 24 (i.e. matte mass = 658 kg, %Cu in matte = 52.4, slag mass = 296 kg) are explained by the lower concentration of copper in the concentrate and the presence of rock constituents in both concentrate and flux.

MAGNETITE EFFECT

Solving this example again with a modification to the slag composition to include magnetite (i.e. 10% Fe_3O_4) yields a slight decrease in the O2/concentrate ratio to .234. The concentration of copper in matte is 47.9%.

COMBINING MAGNETITE AND HEAT OF MIXING EFFECTS

Including the heat of mixing of slag to this example (with 10% Fe3O4 in slag) results in an O2/concentrate ratio of .239 and 48.6% copper in matte. This is nearly identical to the operating conditions of Example I, and thus the combined effect of magnetite in slag and the heat of mixing of slag is negligible.

A1.8 SUMMARY

In general, the mass and heat balances can be easily adjusted to account for varying feed and product specifications. The simplified specifications chosen for the examples in the text are, however, justified for general comparisons.

8

APPENDIX 2

THERMODYNAMIC DATA

The following values for $H^0 298$ were used (MJ/kg-mol):

CO2	-394
CuFeS2	-190
Cu2S	-79
FeO	-264
Fe3O4	-1117
FeS	-100
FeS1.14	-100
FeS2	-171
SO2	-297

The following data were used for $(H^0 T - H^0 298)$, MJ/kg-mol:

CO2	-25.24 + .057 T	
Cu2S	-12.76 + .089 T	(solid to liquid)
FeO	- 9.35 + .068 T	(solid to liquid)
Fe3O4	+58.78 + .213 T	(solid to liquid)
H2O	+23.65 + .045 T	(liquid to gas)
N2	- 9.72 + .031 T	(under 1200 K)
N2	-13.80 + .034 T	(above 1200 K)
O2	-10.38 + .033 T	
SiO2	-42.24 + .086 T	(solid to liquid)
SO2	-25.68 + .058 T	

The data for CuFeS2 was obtained from:

"Thermodynamic properties of copper and its inorganic compounds", E. G. King, A. D. Mah and L. B. Pankratz, INCRA Monograph II.

All other data were obtained from:

"Thermochemical properties of inorganic substances", I. Barin, O. Knacke, and O. Kubachewski, Springer-Verlag, Berlin, 1977.

APPENDIX 3

FLASH FURNACE SIMULATION COMPUTER PROGRAM

```
/LOAD WATFIV
C
C
C       FLASH FURNACE SIMULATION: A BASIS FOR CONTROL AND
C       OPTIMIZATION.
C
C       ERIC H PARTELPOEG,     COPYRIGHT AUGUST 1980
C
C
C
      IMPLICIT REAL*4(A-Z)
      REAL*8 A(12,12),B(12,12),WKAREA(144),A1(4,4),B1(4,4),WKAR1(16)
      COMMON H298(20),HH(20,2)
      INTEGER I,II,N,M,IA,IDGT,IER,INT,N6,N9,NN
      CALL HH298
      CALL HHH
      N6=6
      N9=9
      XX=99.
C
C     OPTION FOR INTRODUCTION
C
      WRITE(N6,101)
      CALL RNC(N9,1,OPT,1,1.,2.,XX)
      IF(OPT.EQ.1.)CALL INTRO(1.)
C
C
C
C     OPTION TO USE PRE-PROGRAMMED DATA
C
      WRITE(N6,131)
      CALL RNC(N9,1,OPT,1,1.,2.,XX)
      IF(OPT.EQ.1.)CALL FDATA(CUC,FEC,SC,SIC,RC,H2OG,SIF,RF,H2OF,CUMOL,
     +     PIE,PIRR,THRU,HL,O2IN,O2OX,TOX,TM,TS,TG,FUEL,H2O,REVERT,RVRTH,
     +      SIS,MAGS,MAGM)
      IF(OPT.EQ.1.)GO TO 40
C
C
C     --  ENTER DATA --
 9    WRITE(N6,100)
C     -- ENTER CONCENTRATE AND FLUX CHEMICAL ANALYSIS
```

```
C         -- CUC  =  % COPPER IN CONCENTRATE
C         -- FEC  =  % IRON IN CONCENTRATE
C         --  SC  =  % SULPHUR IN CONCENTRATE
C         -- SIC  =  % SILICA IN CONCENTRATE
C         --  RC  =  % ROCK IN CONCENTRATE
C         -- H2OC =  % WATER IN CONCENTRATE
C         -- SIF  =  % SILICA IN FLUX
C         --  RF  =  % ROCK IN FLUX
C         -- H2OF =  % WATER IN FLUX
      CALL RNC(N9,1,CUC,0,15.,34.48,XX)
      CALL RNC(N9,1,FEC,0,15.,50.,XX)
      CALL RNC(N9,1,SC,0,20.,40.,XX)
      CALL RNC(N9,1,SIC,0,0.,25.,XX)
      CALL RNC(N9,1,H2OC,0,0.,20.,XX)
      CALL RNC(N9,1,SIF,0,70.,100.,XX)
      CALL RNC(N9,1,H2OF,0,0.,20.,XX)
C
      RF=100.-SIF
C     -- CALCULATE AND CHECK IF MINERALOGY IS FEASIBLE
C         --   CUMOL   =  MOLES CU IN   =  MOLES CHALCOPYRITE
C         --    PIE    =  MOLES PYRITE
C         -- PIRR    =  MOLES PYRRHOTITE
      CALL MINER(CUC,FEC,SC,SIC,RC,CUMOL,PIE,PIRR)
C
C     -- ENTER OPERATING DATA
      WRITE(N6,102)
C     --   OPERATING DATA
C         --   THRU   =  CONCENTRATE THROUGHPUT, TONNE/HOUR
C         --     HL   =  RADIATIVE & CONVECTIVE HEAT LOSS, MJ/HOUR
C         --   O2IN   =  O2/CONCENTRATE FEED RATIO
C         --   O2OX   =  %O2 IN OXIDANT
C         --    TOX   =  OXIDANT TEMPERATURE
C         --     TM   =  MATTE TEMPERATURE
C         --     TS   =  SLAG TEMPERATURE  (K)
C         --     TG   =  GAS TEMPERATURE  (K)
C         --   FUEL   =  CARBON, TONNE/HOUR
C         --    H2O   =  WATER, TONNE/HOUR
C         -- REVERT   =  REVERTS, TONNE/HOUR
C         --  RVRTH   =  REVERT HEAT REQUIREMENT, MJ/TONNE
C         --UNK SETS THE UNKNOWN
      UNK=0.
      CALL RNC(N9,1,THRU,0,10.,125.,UNK)
      CALL RNC(N9,1,HL,0,0.,90000.,UNK)
      CALL RNC(N9,1,O2IN,0,.15,.45,UNK)
      CALL RNC(N9,1,O2OX,0,21.,100.,UNK)
      CALL RNC(N9,1,TOX,0,298.,1300.,UNK)
      CALL RNC(N9,1,TM,0,1300.,1600.,XX)
      CALL RNC(N9,1,TS,0,1300.,1700.,XX)
      CALL RNC(N9,1,TG,0,1300.,1700.,XX)
      CALL RNC(N9,1,FUEL,0,0.,100.,UNK)
      CALL RNC(N9,1,H2O,0,0.,100.,UNK)
      CALL RNC(N9,1,REVERT,0,0.,30.,XX)
      CALL RNC(N9,1,RVRTH,0,-1000.,2000.,XX)
C     --  ENTER SLAG & MATTE DATA
      WRITE(N6,103)
C     -- READ %SIO2, %FE3O4
C         --  SIS   =  %SIO2 IN SLAG
```

```
C          --  MAGS =  %FE3O4 IN SLAG
C          --  MAGM =  %FE3O4 IN MATTE
C
      CALL RNC(N9,1,SIS,0,25.,38.,XX)
      CALL RNC(N9,1,MAGS,0,0.,15.,XX)
      CALL RNC(N9,1,MAGM,0,0.,10.,XX)
C
C     --  OPTION TO INSPECT
C
40    WRITE(N6,104)
      CALL RNC(N9,1,OPT,1,1.,2.,XX)
C     --  IF OPT = 1, PRINT DATA
C     --  IF OPT = 2, GIVE OPTION TO EDIT DATA
      IF(OPT.EQ.2.)GO TO 50
C     -- PRINT DATA
      WRITE(N6,105)CUC,FEC,SC,SIC,H2OC,SIF,H2OF
      WRITE(N6,106)O2IN,O2OX,TOX,THRU,HL,TM,TS,TG,FUEL,H2O,REVERT,RVRTH
      WRITE(N6,107)SIS,MAGS,MAGM
C
50    WRITE(N6,111)
C     -- OPTION TO EDIT
C
      CALL RNC(N9,1,OPT,1,1.,3.,XX)
      IF(OPT.EQ.3.)CALL INTRO(2.)
      IF(OPT.EQ.3.)GO TO 40
      IF(OPT.EQ.2.)GO TO 85
C     -- IF OPT  = 1, EDIT
C     -- IF OPT  = 2, PROCEED TO CALCULATIONS, I.E. STATEMENT # 85
C     -- ENTER CODE NUMBER OR ZERO TO END EDIT
C
C
      UNK=0.
51    WRITE(N6,108)
      CALL RNC(N9,1,OPT,1,0.,22.,XX)
C     -- ENTER NEW VALUE
      IF(OPT.EQ.0.)GOTO 40
      IF(OPT.EQ.1.)GO TO 60
      IF(OPT.EQ.2.)GO TO 61
      IF(OPT.EQ.3.)GOTO 62
      IF(OPT.EQ.4.)GOTO 63
      IF(OPT.EQ.5.)GOTO 64
      IF(OPT.EQ.6.)GOTO 65
      IF(OPT.EQ.7.)GOTO 66
      IF(OPT.EQ.8.)GOTO 67
      IF(OPT.EQ.9.)GOTO 68
      IF(OPT.EQ.10.)GOTO 69
      IF(OPT.EQ.11.)GOTO 70
      IF(OPT.EQ.12.)GOTO 71
      IF(OPT.EQ.13.)GOTO 72
      IF(OPT.EQ.14.)GOTO 73
      IF(OPT.EQ.15.)GOTO 74
      IF(OPT.EQ.16.)GOTO 75
      IF(OPT.EQ.17.)GOTO 76
      IF(OPT.EQ.18.)GOTO 77
      IF(OPT.EQ.19.)GOTO 78
      IF(OPT.EQ.20.)GOTO 79
      IF(OPT.EQ.21.)GOTO 80
```

```
      IF(OPT.EQ.22.)GO TO 81
60    WRITE(N6,140)
      CALL RNC(N9,1,CUC,0,15.,34.48,XX)
      GOTO 51
61     WRITE(N6,141)
      CALL RNC(N9,1,FEC,0,15.,50.,XX)
      GOTO 51
62    WRITE(N6,142)
      CALL RNC(N9,1,SC,0,20.,40.,XX)
      GOTO 51
63     WRITE(N6,143)
      CALL RNC(N9,1,SIC,0,0.,25.,XX)
      GOTO 51
64     WRITE(N6,144)
      CALL RNC(N9,1,H2OC,0,0.,20.,XX)
      GOTO 51
65     WRITE(N6,145)
      CALL RNC(N9,1,SIF,0,60.,100.,XX)
      GOTO 51
66     WRITE(N6,146)
      CALL RNC(N9,1,H2OF,0,0.,20.,XX)
      GOTO 51
67     WRITE(N6,147)
      CALL RNC(N9,1,O2IN,0,.15,.45,UNK)
      GOTO 51
68     WRITE(N6,148)
      CALL RNC(N9,1,O2OX,0,21.,100.,UNK)
      GOTO 51
69     WRITE(N6,149)
      CALL RNC(N9,1,TOX,0,298.,1300.,UNK)
      GO TO 51
70     WRITE(N6,150)
      CALL RNC(N9,1,THRU,0,10.,100.,XX)
      GOTO 51
71     WRITE(N6,151)
      CALL RNC(N9,2,HL,0,0.,90000.,UNK)
      GOTO 51
72     WRITE(N6,152)
      CALL RNC(N9,1,TM,0,1300.,1600.,XX)
      GOTO 51
73     WRITE(N6,153)
      CALL RNC(N9,1,TS,0,1300.,1700.,XX)
      GOTO 51
74     WRITE(N6,154)
      CALL RNC(N9,1,TG,0,1300.,1700.,XX)
      GO TO 51
75     WRITE(N6,155)
      CALL RNC(N9,1,FUEL,0,0.,100.,UNK)
      GO TO 51
76     WRITE(N6,156)
      CALL RNC(N9,1,H2O,0,0.,100.,UNK)
      GOTO 51
77     WRITE(N6,157)
      CALL RNC(N9,1,REVERT,0,0.,30.,XX)
      GOTO 51
78     WRITE(N6,158)
      CALL RNC(N9,1,RVRTH,0,-1000.,2000.,XX)
```

```
      GOTO 51
79     WRITE(N6,159)
      CALL RNC(N9,1,SIS,0,25.,38.,XX)
      GO TO 51
80     WRITE(N6,160)
      CALL RNC(N9,1,MAGS,0,0.,15.,XX)
      GO TO 51
81     WRITE(N6,161)
      CALL RNC(N9,1,MAGM,0,0.,10.,XX)
      GO TO 51
C
C    OPTION TO SPECIFY MATTE GRADE
C
85     CONTINUE
      WRITE(N6,132)
      CALL RNC(N9,1,MG,1,1.,2.,XX)
C
C     -- START CHECK TO ENSURE THERE IS ONLY ONE UNKNOWN
C        (BESIDES O2IN IF MATTE GRADE IS SPECIFIED)
C
      TEST=0.
      IF(MG.EQ.2.)GO TO 83
        WRITE(N6,135)
      CALL RNC(N9,1,CUMAT,0,35.,79.,XX)
      O2IN=-1.
      GO TO 84
83    IF(O2IN.EQ.-1.)TEST=TEST+1
84    IF(O2OX.EQ.-1.)TEST=TEST+1
      IF(TOX.EQ.-1.)TEST=TEST+1
      IF(HL.EQ.-1.)TEST=TEST+1
      IF(FUEL.EQ.-1.)TEST=TEST+1
      IF(H2O.EQ.-1.)TEST=TEST+1
      IF(TEST.NE.1.)GOTO 86
      GOTO 90
86    WRITE(N6,109)
C     -- WRITE, THERE MUST BE ONE, BUT ONLY ONE UNKNOWN; EDIT
      GO TO 40
C
C        CHECK IF MINERALOGY IS STILL OK
C
90    CALL MINER(CUC,FEC,SC,SIC,RC,CUMOL,PIE,PIRR)
C
C
      IF(MG.EQ.1.)GO TO 91
C
C    IF MATTE GRADE IS NOT SPECIFIED, GO TO STATEMENT # 92
C
      GO TO 92
  91    CONTINUE
C
C     CALCULATION OF MATTE, SLAG, O2 MASSES AND ENTHALPIES
C     MATTE GRADE IS SPECIFIED
C
C  VARIABLES BEGINNING WITH 'M' REPRESENT KG-MOLES/1000 KG CONC
C  VARIABLES BEGINNING WITH 'H' REPRESENT HEAT CONTENT, MJ/1000 KG CONC
C  ALL OTHER VARIABLES ARE MASSES, KG/1000 KG CONC, (INCLUDING 'MATTE')
C
```

```
C
      MATTE=CUC/CUMAT*1000.
      FE3O4M=MAGM/100.*MATTE
      MMAGM=FE3O4M/231.541
      MCU=CUC*10./63.54
      MFE=FEC*10./55.847
      FES=MATTE-MCU/2.*159.14-FE3O4M
      MFES=FES/87.91
      MCU2S=MCU/2.
      CU2S=MCU2S*159.14
      MFEM=MAGM*3.+MFES
      MSM=MFES+MCU2S
      MFESG=MFE-MFEM
      SLAG=MFESG*71.847/(1-MAGS/100.-SIS/100.*(100./SIF)
     + +3*71.847*MAGS/100./231.541)
      FE3O4S=SLAG*MAGS/100.
      MMAGS=MAGS/100.*SLAG/231.541
      MFEOS=MFESG-3.*MMAGS
      FEO=MFEOS*71.847
      SIO2=SIS/100.*SLAG
      FLUX=(SIO2-SIC*10.)/(SIF/100.)
      ROCK=RC*10.+FLUX*RF/100.
      MSO2=SC*10./32.06-MSM
      MO2=MSO2+2.*(MMAGM+MMAGS)+.5*MFEOS
      SO2=MSO2*64.06
      O2IN=MO2*32./1000.
      H2O1=H2OC*10.+H2OF*FLUX/100.
      HCU2S=CU2S*(HH(1,1)*TM+HH(1,2))
      HFES=FES*(HH(4,1)*TM+HH(4,2))
      HSO2=SO2*(HH(10,1)*TG+HH(10,2))
      HFEO=FEO*(HH(14,1)*TS+HH(14,2))
      HSIO2=SIO2*(HH(9,1)*TS+HH(9,2))
      HMAGM=FE3O4M*(HH(3,1)*TM+HH(3,2))
      HMAGS=FE3O4S*(HH(3,1)*TS+HH(3,2))
      HROCK=ROCK*(HH(15,1)*TS+HH(15,2))
      HH2O=H2O1*(HH(5,1)*TG+HH(5,2))
      HMATTE=HCU2S+HFES+HMAGM
      HSLAG=HFEO+HSIO2+HMAGS+HROCK
C
C
C       GENERATION AND SOLUTION OF EQUATIONS TO CALCULATE THE UNKNOWN
C       MATTE GRADE IS SPECIFIED AND THUS MASS BALANCE IS SPECIFIED
C       THE HEAT BALANCE MUST BE SOLVED
C
C       INITIALIZE MATRICES AT ZERO
C
        DO 1201 I= 1,4
        DO 1201 II=1,4
        A1(I,II)=0.
 1201   B1(I,II)=0.
C
C
C       INITIALIZE COEFFICIENT MATRIX
C
        A1(1,1)=-1.
        A1(2,2)=-1.
      A1(3,1)=1.
```

```
      A1(3,2)=-1.
C
C       INITIALIZE RIGHT HAND SIDES OF EQUATIONS
C
      HST=CUMOL*183.51*H298(1)+PIE*119.97*H298(5)+PIRR*92.4*H298(4)
      HHST=CU2S*H298(2)+FES*H298(3)+SO2*H298(8)+FEO*H298(10)
     ++FE3O4S*H298(7)+FE3O4M*H298(7)
      HST=HST-HHST
      HDT=HMATTE+HSLAG+HSO2
C
C         FINALIZE EQUATIONS BY BRANCHING TO APPROPRIATE STATEMENT
C         NUMBER (DEPENDING ON THE UNKNOWN)
C
       IF(TOX.EQ.-1.)GO TO 1225
       IF(O2OX.EQ.-1.)GO TO 1250
       IF(FUEL.EQ.-1.)GOTO 1275
       IF(H2O.EQ.-1.)GO TO 1300
       IF(HL.EQ.-1.)GO TO 1325
C
C
 1225     CONTINUE
C         SETTING UP MATRIX TO SOLVE FOR OXIDANT TEMPERATURE
C
       O2XX=800.*O2OX/(700.+O2OX)
       O2=O2IN*1000.
       FUELO2=FUEL/THRU*32./12.*1000.
       O2T=O2+FUELO2
       N2=O2T*(100.-O2XX)/O2XX
       HN2=N2*(HH(7,1)*TG+HH(7,2))
      A1(1,3)=O2T*HH(8,1)+N2*HH(6,1)
      B1(1,4)=HST-(O2T*HH(8,2)+N2*HH(6,2))
      HDT=HDT+H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +    +HN2
      B1(2,4)=-HDT
      GOTO 1350
C
 1250     CONTINUE
C            SETTING UP MATRIX TO SOLVE FOR NITROGEN MASS
C
       O2=O2IN*1000.
       FUELO2=FUEL/THRU*32./12.*1000.
       O2T=O2+FUELO2
      A1(1,3)=TOX*HH(6,1)+HH(6,2)
      A1(2,3)=TG*HH(7,1)+HH(7,2)
      B1(1,4)=HST-O2T*(TOX*HH(8,1)+HH(8,2))
      HDT=HDT+H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
      B1(2,4)=-HDT
      GO TO 1350
C
```

```
 1275   CONTINUE
C         SETTING UP MATRIX TO SOLVE FOR FUEL
C
        O2XX=800.*O2OX/(700.+O2OX)
        O2=O2IN*1000.
        N2=O2*(100.-O2XX)/O2XX
        HN2=N2*(HH(7,1)*TG+HH(7,2))
      A1(1,3)=H298(9)/THRU*1000.+32./12./THRU*1000.*((100.-O2XX)/O2XX*
     +    (HH(6,1)*TOX+HH(6,2))+HH(8,1)*TOX+HH(8,2))
      A1(2,3)=44./12./THRU*1000.*(HH(11,1)*TG+HH(11,2))
     +     +32./12./THRU*1000.*(100.-O2XX)/O2XX*
     +     (HH(7,1)*TG+HH(7,2))
      B1(1,4)=HST-(O2*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=HDT+H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +   +HL/THRU + REVERT*RVRTH/THRU
     +   +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +    +HN2
      B1(2,4)=-HDT
      GO TO 1350
C
 1300    CONTINUE
C            SETTING UP MATRIX TO SOLVE FOR H2O REQUIREMENT
C
        O2XX=800.*O2OX/(700.+O2OX)
        O2=O2IN*1000.
        FUELO2=FUEL/THRU*32./12.*1000.
        O2T=O2+FUELO2
        N2=O2T*(100.-O2XX)/O2XX
        HN2=N2*(HH(7,1)*TG+HH(7,2))
      A1(2,3)=TG*HH(5,1)+HH(5,2)
      B1(1,4)=HST-(O2T*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=HDT+H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +    +HN2
      B1(2,4)=-HDT
      GO TO 1350
C
 1325   CONTINUE
C         SETTING UP MATRIX TO SOLVE FOR HEAT LOSS
C
        O2XX=800.*O2OX/(700.+O2OX)
        O2=O2IN*1000.
        FUELO2=FUEL/THRU*32./12.*1000.
        O2T=O2+FUELO2
        N2=O2T*(100.-O2XX)/O2XX
        HN2=N2*(HH(7,1)*TG+HH(7,2))
      A1(2,3)=1.
      B1(1,4)=HST-(O2*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=HDT+H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +    +REVERT*RVRTH/THRU
     +   +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +   -FUEL/THRU*1000.*H298(9)
     +   +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +     +HN2
      B1(2,4)=-HDT
```

```
C
C
1350    CONTINUE
C
C        SET ARGUMENTS OF IMSL LINEAR EQUATION SOLUTION
C        (FOR SUBROUTINE LEQT1F)
C
        N=3
        M=4
        IA=4
        IDGT=4
C
C       SOLVE THE LINEAR EQUATIONS.
C
        CALL LEQT1F(A1,M,N,IA,B1,IDGT,WKAR1,IER)
C
       HS=B1(1,4)
       HD=B1(2,4)
C
C          THE FINAL RESULT (B1(3,4)) REPRESENTS THE UNKNOWN PARAMETER
C
        IF(TOX.EQ.-1.)GOTO 1400
        IF(O2OX.EQ.-1.)GO TO 1425
        IF(FUEL.EQ.-1.)GOTO 1450
        IF(H2O.EQ.-1.)GO TO 1475
        IF(HL.EQ.-1.)GO TO 1500
C
C
 1400    TOX=B1(3,4)
        WRITE(N6,121)TOX
        GO TO 1525
C
C
 1425    N2=B1(3,4)
        O2OX=O2T/32./(O2T/32.+N2/28.)*100.
        WRITE(N6,122)O2OX
        GO TO 1525
C
 1450    FUEL=B1(3,4)
        FUELO2=FUEL/THRU*32./12.*1000.
        O2T=O2+FUELO2
        WRITE(N6,123)FUEL
        GO TO 1525
C
 1475    H2O=B1(3,4)*THRU/1000.
        WRITE(N6,124)H2O
        GO TO 1525
C
 1500    HL=B1(3,4)*THRU
        WRITE(N6,125)HL
C
C
      GO TO 1525
C
C
  92  CONTINUE
C
```

```
C
C     GENERATION AND SOLUTION OF EQUATIONS TO CALCULATE THE UNKNOWN
C     MATTE GRADE IS NOT SPECIFIED
C
C     INITIALIZE MATRICES AT ZERO
C
      DO 201 I= 1,12
      DO 201 II=1,12
      A(I,II)=0.
201   B(I,II)=0.
C
C     INITIALIZE POSSIBLE ZERO ASSAYS TO SMALL NON-ZERO VALUES
C     TO AVOID ERRORS IN SOLUTION OF EQUATIONS, EFFECT ON
C     RESULT IS NEGLIGIBLE
C
      IF(MAGS.EQ.0.)MAGS =.005
      IF(MAGM.EQ.0.)MAGM=.005
      IF(RF.EQ.0.)RF=.005
      IF(RC.EQ.0.)RC=.005
      IF(O2OX.GT.99.99)O2OX=99.99
      ON=(O2OX/100.*32.)/((1.-O2OX/100.)*28.)
C
C     INITIALIZE COEFFICIENT MATRIX
C
      A(1,1)=.79854
      A(2,2)=.6353
      A(2,4)=.7773
      A(2,6)=.7236
      A(2,7)=.7236
      A(3,1)=.20146
      A(3,2)=.3647
      A(3,3)=.50
      A(4,4)=SIS/(100.-SIS)
      A(4,5)=-1.
      A(4,7)=SIS/(100.-SIS)
      A(4,8)=SIS/(100.-SIS)
      A(5,1)=MAGM/(100.-MAGM)
      A(5,2)=MAGM/(100.-MAGM)
      A(5,6)=-1.
      A(6,4)=MAGS/(100.-MAGS)
      A(6,5)=MAGS/(100.-MAGS)
      A(6,7)=-1.
      A(6,8)=MAGS/(100.-MAGS)
      A(7,5)=-RF/SIF
      A(7,8)=1.
      A(8,3)=.50
      A(8,4)=.2227
      A(8,6)=.2764
      A(8,7)=.2764
      A(9,1)=H298(2)
      A(9,2)=H298(3)
      A(9,3)=H298(8)
      A(9,4)=H298(10)
      A(9,6)=H298(7)
      A(9,7)=H298(7)
      A(9,9)=-1.
      A(10,1)=HH(1,1)*TM+HH(1,2)
```

```
      A(10,2)=HH(4,1)*TM+HH(4,2)
      A(10,3)=HH(10,1)*TG+HH(10,2)
C
C     .19 IS THE HEAT REQUIRED TO FORM FAYALITE (MJ/KG FEO)
C     THIS COULD BE ADDED TO THE FOLLOWING TERM IF DESIRED
C     THE EFFECT ON THE HEAT BALANCE IS NOT VERY SIGNIFICANT
C
      A(10,4)=HH(14,1)*TS+HH(14,2)
      A(10,5)=HH(9,1)*TS+HH(9,2)+(H2OF/SIF)*(HH(5,1)*TG+HH(5,2))
      A(10,6)=HH(3,1)*TM+HH(3,2)
      A(10,7)=HH(3,1)*TS+HH(3,2)
      A(10,8)=HH(15,1)*TS+HH(15,2)
      A(10,10)=-1.
      A(11,9)=1.
      A(11,10)=-1.
C
C     INITIALIZE RIGHT HAND SIDES OF EQUATIONS
C
      HST=CUMOL*183.51*H298(1)+PIE*119.97*H298(5)+PIRR*92.4*H298(4)
      B(1,12)=CUC*10.
      B(2,12)=FEC*10.
      B(3,12)=SC*10.
      B(4,12)=0.
      B(5,12)=0.
      B(6,12)=0.
      B(7,12)=RC*10.
      B(11,12)=0.
C
C       FINALIZE EQUATIONS BY BRANCHING TO APPROPRIATE STATEMENT
C       NUMBER (DEPENDING ON THE UNKNOWN)
C
      IF(O2IN.EQ.-1.)GO TO 200
      IF(TOX.EQ.-1.)GO TO 225
      IF(O2OX.EQ.-1.)GO TO 250
      IF(FUEL.EQ.-1.)GOTO 275
      IF(H2O.EQ.-1.)GO TO 300
      IF(HL.EQ.-1.)GO TO 325
C
C
200   CONTINUE
C      SETTING UP MATRIX TO SOLVE FOR O2/CONC RATIO
C
      O2XX=800.*O2OX/(700.+O2OX)
      FUELO2=FUEL/THRU*32./12.*1000.
      A(8,11)=-1.
      A(9,11)=HH(8,1)*TOX+HH(8,2)+(100.-O2XX)/O2XX
     +    *(HH(6,1)*TOX+HH(6,2))
      A(10,11)=(100.-O2XX)/O2XX*(HH(7,1)*TG+HH(7,2))
      B(8,12)=-FUELO2
      B(9,12)=HST-FUELO2*((100.-O2XX)/O2XX*(HH(6,1)*TOX+HH(6,2))
     +       +(HH(8,1)*TOX+HH(8,2)))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +   +FUELO2*((100.-O2XX)/O2XX*(HH(7,1)*TG+HH(7,2)))
```

```
      B(10,12)=-HDT
      GO TO 350
C
225   CONTINUE
C        SETTING UP MATRIX TO SOLVE FOR OXIDANT TEMPERATURE
C
      O2XX=800.*O2OX/(700.+O2OX)
      O2=O2IN*1000.
      FUELO2=FUEL/THRU*32./12.*1000.
      O2T=O2+FUELO2
      N2=O2T*(100.-O2XX)/O2XX
      HN2=N2*(HH(7,1)*TG+HH(7,2))
      A(9,11)=O2T*HH(8,1)+N2*HH(6,1)
      B(8,12)=O2
      B(9,12)=HST-(O2T*HH(8,2)+N2*HH(6,2))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +   +HN2
      B(10,12)=-HDT
      GOTO 350
C
250   CONTINUE
C         SETTING UP MATRIX TO SOLVE FOR NITROGEN MASS
C
      O2=O2IN*1000.
      FUELO2=FUEL/THRU*32./12.*1000.
      O2T=O2+FUELO2
      A(9,11)=TOX*HH(6,1)+HH(6,2)
      A(10,11)=TG*HH(7,1)+HH(7,2)
      B(8,12)=O2
      B(9,12)=HST-O2T*(TOX*HH(8,1)+HH(8,2))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
      B(10,12)=-HDT
      GO TO 350
C
275   CONTINUE
C       SETTING UP MATRIX TO SOLVE FOR FUEL
C
      O2XX=800.*O2OX/(700.+O2OX)
      O2=O2IN*1000.
      N2=O2*(100.-O2XX)/O2XX
      HN2=N2*(HH(7,1)*TG+HH(7,2))
      A(9,11)=H298(9)/THRU*1000.+32./12./THRU*1000.*((100.-O2XX)/O2XX*
     +    (HH(6,1)*TOX+HH(6,2))+HH(8,1)*TOX+HH(8,2))
      A(10,11)=44./12./THRU*1000.*(HH(11,1)*TG+HH(11,2))
     +      +32./12./THRU*1000.*(100.-O2XX)/O2XX*
     +      (HH(7,1)*TG+HH(7,2))
      B(8,12)=O2
      B(9,12)=HST-(O2*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
```

```
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,1)*TG+HH(5,2))*1000.
     +   +HN2
      B(10,12)=-HDT
      GO TO 350
C
C
300   CONTINUE
C          SETTING UP MATRIX TO SOLVE FOR H2O REQUIREMENT
C
      O2XX=800.*O2OX/(700.+O2OX)
      O2=O2IN*1000.
      FUELO2=FUEL/THRU*32./12.*1000.
      O2T=O2+FUELO2
      N2=O2T*(100.-O2XX)/O2XX
      HN2=N2*(HH(7,1)*TG+HH(7,2))
      A(10,11)=TG*HH(5,1)+HH(5,2)
      B(8,12)=O2
      B(9,12)=HST-(O2T*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +  +HL/THRU + REVERT*RVRTH/THRU
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +    +HN2
      B(10,12)=-HDT
      GO TO 350
C
C
325   CONTINUE
C       SETTING UP MATRIX TO SOLVE FOR HEAT LOSS
C
      O2XX=800.*O2OX/(700.+O2OX)
      O2=O2IN*1000.
      FUELO2=FUEL/THRU*32./12.*1000.
      O2T=O2+FUELO2
      N2=O2T*(100.-O2XX)/O2XX
      HN2=N2*(HH(7,1)*TG+HH(7,2))
      A(10,11)=1.
      B(8,12)=O2
      B(9,12)=HST-(O2*(TOX*HH(8,1)+HH(8,2))+N2*(TOX*HH(6,1)+HH(6,2)))
      HDT=H2OC*10.*(HH(5,1)*TG+HH(5,2))
     +    +REVERT*RVRTH/THRU
     +  +H2O/THRU*(HH(5,2)*TG+HH(5,2))*1000.
     +  -FUEL/THRU*1000.*H298(9)
     +  +FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
     +     +HN2
      B(10,12)=-HDT
C
350   CONTINUE
C
C       SET ARGUMENTS OF IMSL LINEAR EQUATION SOLUTION
C       (FOR SUBROUTINE LEQT1F)
C
      N=11
      M=12
      IA=12
      IDGT=4
```

```
C
C       SOLVE THE LINEAR EQUATIONS
C
        CALL LEQT1F(A,M,N,IA,B,IDGT,WKAREA,IER)
C
        CU2S=B(1,12)
        FES=B(2,12)
        SO2=B(3,12)
        FEO=B(4,12)
        SIO2=B(5,12)
        FE3O4M=B(6,12)
        FE3O4S=B(7,12)
        ROCK=B(8,12)
        HS=B(9,12)
        HD=B(10,12)
C
C           THE FINAL RESULT (B(11,12)) REPRESENTS THE UNKNOWN PARAMETER
C
        IF(O2IN.EQ.-1.)GOTO 375
        IF(TOX.EQ.-1.)GOTO 400
        IF(O2OX.EQ.-1.)GO TO 425
        IF(FUEL.EQ.-1.)GOTO 450
        IF(H2O.EQ.-1.)GO TO 475
        IF(HL.EQ.-1.)GO TO 500
C
375     O2=B(11,12)
        O2T=O2+FUELO2
        O2IN=O2/1000.
        WRITE(N6,120)O2IN
        GO TO 525
C
400     TOX=B(11,12)
        WRITE(N6,121)TOX
        GO TO 525
C
425     N2=B(11,12)
        O2OX=O2T/32./(O2T/32.+N2/28.)*100.
        WRITE(N6,122)O2OX
        GO TO 525
C
450     FUEL=B(11,12)
        FUELO2=FUEL/THRU*32./12.*1000.
        O2T=O2+FUELO2
        WRITE(N6,123)FUEL
        GO TO 525
C
475     H2O=B(11,12)*THRU/1000.
        WRITE(N6,124)H2O
        GO TO 525
C
500     HL=B(11,12)*THRU
        WRITE(N6,125)HL
C
525     CONTINUE
1525        CONTINUE
        O2XX=800.*O2OX/(700.+O2OX)
        N2=O2T*(100.-O2XX)/O2XX
```

```
      MATTE=CU2S+FES+FE3O4M
      SLAG=FEO+SIO2+FE3O4S+ROCK
      FLUX=(SIO2-SIC*10.)/(SIF/100.)
      H2OTOT=H2OF/SIF*SIO2 +H2OC*10.+H2O/THRU*1000.
      GASNM3=(SO2/64.+N2/28.+H2OTOT/18.+FUEL/THRU/12.*1000)*22.4
      CUMAT=CU2S*.79854/MATTE*100.
      PERSO2=SO2/64.*22.4/GASNM3*100.
C
C     CALCULATION OF SENSIBLE HEAT OF PRODUCTS AND
C     FLAME TEMPERATURE
C
      HCU2S=CU2S*(HH(1,1)*TM+HH(1,2))
      HFES=FES*(HH(4,1)*TM+HH(4,2))
      HSO2=SO2*(HH(10,1)*TG+HH(10,2))
      HFEO=FEO*(HH(14,1)*TS+HH(14,2))
      HSIO2=SIO2*(HH(9,1)*TS+HH(9,2))
      HMAGM=FE3O4M*(HH(3,1)*TM+HH(3,2))
      HMAGS=FE3O4S*(HH(3,1)*TS+HH(3,2))
      HROCK=ROCK*(HH(15,1)*TS+HH(15,2))
      HN2=N2*(HH(7,1)*TG+HH(7,2))
      HH2O=H2OTOT*(HH(5,1)*TG+HH(5,2))
      CO2=FUEL/THRU*44./12.*1000.
      HCO2=FUEL/THRU*44./12.*1000.*(HH(11,1)*TG+HH(11,2))
      HMATTE=HCU2S+HFES+HMAGM
      HSLAG=HFEO+HSIO2+HMAGS+HROCK
      HGAS=HSO2+HN2+HH2O+HCO2
      HPRD=HMATTE+HSLAG+HGAS
      HLOSS=HL/THRU
      PERSO2=(SO2/64.)/(SO2/64.+N2/28.+H2OTOT/18.+CO2/44.)*100.
      FTHPRD=HPRD+HLOSS
      FTTRM1=CU2S*HH(1,1)+FES*HH(4,1)+SO2*HH(10,1)+FEO*HH(14,1)
     +   +SIO2*HH(9,1)+FE3O4M*HH(3,1)+FE3O4S*HH(3,1)
     +   +ROCK*HH(15,1)+N2*HH(7,1)+H2OTOT*HH(5,1)
     +   +FUEL/THRU*44./12.*1000.*HH(11,1)
      FTTRM2=CU2S*HH(1,2)+FES*HH(4,2)+SO2*HH(10,2)+FEO*HH(14,2)
     +   +SIO2*HH(9,2)+FE3O4M*HH(3,2)+FE3O4S*HH(3,2)
     +   +ROCK*HH(15,2)+N2*HH(7,2)+H2OTOT*HH(5,2)
     +   +FUEL/THRU*44./12.*1000.*HH(11,2)
      FT=(FTHPRD-FTTRM2)/FTTRM1
      WRITE(N6,126)CUMAT,O2IN,FT
      WRITE(N6,162)
C
C     OPTION TO SUPPRESS ADDITIONAL RESULTS
C
      CALL RNC(N9,1,OPT,1,1.,2.,XX)
      IF(OPT.EQ.1.)GO TO 600
      WRITE(N6,127)PERSO2,FLUX,SIO2,CU2S,FES,FE3O4M,FEO,FE3O4S,ROCK
      WRITE(N6,128)O2T,HLOSS,HD,HCU2S,HFES,HMAGM,HSO2,HN2,HCO2,HH2O,
     +HSIO2,HFEO,HMAGS,HROCK
C
C     GIVE OPTION TO CONTINUE
C
600   WRITE(N6,130)
      CALL RNC(N9,1,OPT,1,1.,2.,XX)
      IF(OPT.EQ.1.)GO TO 40
C
C
```

```
 101   FORMAT(1H ,'DO YOU WANT (ENTER 1), NOT WANT (ENTER 2), AN ',
      +    'INTRODUCTION?')
 100   FORMAT(1H ,'ENTER THE FOLLOWING INFORMATION; ONE VALUE PER LINE:'
      +   /1H ,'%CU IN CONCENTRATE'
      +   /1H ,'%FE IN CONCENTRATE'
      +   /1H ,'%S IN CONCENTRATE'
      +   /1H ,'%SIO2 IN CONCENTRATE'
      +   /1H ,'%H2O IN CONCENTRATE'
      +   /1H ,'%SIO2 IN FLUX'
      +   /1H ,'%H2O IN FLUX'/)
 102   FORMAT(1H ,'ENTER THE FOLLOWING INFORMATION; ONE VALUE PER LINE:'
      +    /1H ,'ENTER "-1" IF THE PARAMETER IS THE UNKNOWN'
      +    /1H ,'CONCENTRATE THROUGHPUT, TPH '
      +    /1H ,'RADIATIVE AND CONVECTIVE HEAT LOSS  MJ/H'
      +    /1H ,'O2/CONC MASS RATIO'
      +    /1H ,'VOLUME % O2 IN OXIDANT'
      +    /1H ,'OXIDANT TEMPERATURE  K'
      +    /1H ,'MATTE TEMPERATURE  K'
      +    /1H ,'SLAG TEMPERATURE  K'
      +   /1H ,'OFF-GAS TEMPERATURE K'
      +    /1H ,'FUEL, CARBON TPH'
      +    /1H ,'WATER, TPH'
      +    /1H ,'REVERTS, TPH'
      +    /1H ,'REVERT HEAT REQUIREMENT, MJ/T'/)
 103   FORMAT(1H ,'ENTER THE FOLLOWING SLAG AND MATTE DATA'/1H ,
      +     '%SIO2 IN SLAG'/1H ,'%FE3O4 IN SLAG'/1H ,'%FE3O4 IN MATTE'/)
 104   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) TO INSPECT DATA?'/)
 105   FORMAT(1H ,'THE FOLLOWING DATA HAS BEEN ENTERED'/1H ,
      +     '(1) %CU IN CONC = ',F6.2/1H ,
      +     '(2) %FE IN CONC = ',F6.2/1H ,
      +     '(3) %S IN CONC = ',F6.2/1H ,
      +     '(4) %SIO2 IN CONC = ',F6.2/1H ,
      +     '(5) %H2O IN CONC = ',F6.2/1H ,
      +     '(6) %SIO2 IN FLUX = ',F6.2/1H ,
      +     '(7) %H2O IN FLUX = ',F6.2/)
 106   FORMAT(1H ,'(8) O2/CONC MASS RATIO = ',F10.4/1H ,
      +           '(9) VOL % O2 IN OXIDANT = ',F10.4/1H ,
      +           '(10) OXIDANT TEMPERATURE  K = ',F10.4/1H ,
      +           '(11) THROUGHPUT  TPH = ',F10.4/1H ,
      +           '(12) RAD AND CONV HEAT LOSS  MJ/H = ',F10.4/1H ,
      +           '(13) MATTE TEMPERATURE  K = ',F10.4/1H ,
      +           '(14) SLAG TEMPERATURE  K = ',F10.4/1H ,
      +           '(15) OFF-GAS TEMPERATURE  K = ',F10.4/1H ,
      +           '(16) FUEL, C, TPH = ',F10.4/1H ,
      +           '(17) H2O, TPH = ',F10.4/1H ,
      +           '(18) REVERT TPH = ',F10.4/1H ,
      +           '(19) REVERT HEAT REQ"MT, MJ/T = ',F10.4/)
 107   FORMAT(1H ,'(20) %SIO2 IN SLAG = ',F6.2/1H ,
      +           '(21) %FE3O4 IN SLAG = ',F6.2/1H ,
      +           '(22) %FE3O4 IN MATTE = ',F6.2/)
 108   FORMAT(1H ,'ENTER VARIABLE NUMBER (OR "0" TO END EDIT)'/)
 109   FORMAT(1H ,'USER ERROR, YOU MUST ENTER 1 UNKNOWN--EDIT!!'/)
 111   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) TO EDIT? NEED HELP (3)?')
 120   FORMAT(1H ,'O2/CONC MASS RATIO = ',F8.4)
 121   FORMAT(1H ,'OXIDANT TEMPERATURE  K = ',F8.0)
 122   FORMAT(1H ,'VOL %O2 IN OXIDANT = ',F6.2)
 123   FORMAT(1H ,'FUEL NEEDED, C, TPH = ',F6.2)
```

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124   FORMAT(1H ,'WATER NEEDED  TPH = ',F6.2)
125   FORMAT(1H ,'HEAT LOSSES  MJ/H = ',F9.0)
126   FORMAT(1H+,'%CU IN MATTE = ',F6.2/1H ,'O2/CONC RATIO = ',F7.5/1H ,
     + 'FLAME TEMP (K) = ',F7.2/)
127   FORMAT(1H ,'%SO2 IN OFF-GAS = ',F6.3/1H ,'FLUX, KG = ',F7.2/1H ,
     +'SIO2, KG = ',F7.2/1H ,'CU2S, KG = ',F7.2/1H ,'FES, KG = ',
     +F7.2/1H ,'FE3O4M, KG = ',F7.2/1H ,'FEO, KG = ',F7.2/1H ,
     +'FE3O4S, KG = ',F7.2/,'ROCK, KG = ',F7.2)
130   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) TO CONTINUE?'/)
128   FORMAT(1H ,'TOTAL O2, KG = ',F7.2/1H ,'HEAT LOSS, MJ/T = ',
     +F7.2/1H ,'HEAT DEMAND=HEAT SUPPLY = ',F7.2/1H ,'HCU2S, MJ = ',
     +F7.2/1H ,'HFES, MJ = ',F7.2/1H ,'HMAGM, MJ = ',F7.2/1H ,
     +'HSO2, MJ = ',F7.2/1H ,
     +'HN2, MJ = ',F7.2/1H ,'HCO2, MJ = ',F7.2/1H ,
     +'HH2O, MJ = ',F7.2/1H ,'HSIO2, MJ = ',F7.2/1H ,'HFEO, MJ = ',
     +F7.2/1H ,'HMAGS, MJ = ',F7.2/1H ,'HROCK, MJ = ',F7.2/)
131   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) PRE-PROGRAMMED DATA?')
132   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) TO SPECIFY %CU IN MATTE?')
135   FORMAT(1H ,'ENTER DESIRED %CU IN MATTE')
140   FORMAT(1H ,'ENTER %CU IN CONC')
141   FORMAT(1H ,'ENTER %FE IN CONC')
142   FORMAT(1H ,'ENTER %S IN CONC')
143   FORMAT(1H ,'ENTER %SIO2 IN CONC')
144   FORMAT(1H ,'ENTER %H2O IN CONC')
145   FORMAT(1H ,'ENTER %SIO2 IN FLUX')
146   FORMAT(1H ,'ENTER %H2O IN FLUX')
147   FORMAT(1H ,'ENTER O2/CONC (OR -1 IF UNKNOWN)')
148   FORMAT(1H ,'ENTER %O2 IN OXIDANT (OR -1 IF UNKNOWN)')
149   FORMAT(1H ,'ENTER OXIDANT TEMP(K)  (OR -1 IF UNKNOWN)')
150   FORMAT(1H ,'ENTER THRUPUT, TPH')
151   FORMAT(1H ,'ENTER HEAT LOSS, MJ/H (OR -1 IF UNKNOWN)')
152   FORMAT(1H ,'ENTER MATTE TEMP(K)')
153   FORMAT(1H ,'ENTER SLAG TEMP(K)')
154   FORMAT(1H ,'ENTER OFF-GAS TEMP(K)')
155   FORMAT(1H ,'ENTER CARBON,TPH  (OR -1 IF UNKNOWN)')
156   FORMAT(1H ,'ENTER H2O TPH  (OR -1 IF UNKNOWN)')
157   FORMAT(1H ,'ENTER REVERTS, TPH')
158   FORMAT(1H ,'ENTER REVERT HEAT DEMAND, MJ/T')
159   FORMAT(1H ,'ENTER %SIO2 IN SLAG')
160   FORMAT(1H ,'ENTER FE3O4 IN SLAG')
161   FORMAT(1H ,'ENTER % FE3O4 IN MATTE')
162   FORMAT(1H ,'DO YOU WANT(1), NOT WANT(2) TO SUPPRESS ',
     + 'ADDITIONAL RESULTS?')
      STOP
      END
C
C
      SUBROUTINE HHH
C
C
C      HEAT CONTENTS ARE LISTED BELOW
C      -- UNITS ARE MJ/KG
C      HEAT =  FIRST TERM * (T  K)  +  SECOND TERM
C
C     1  CU2S (LIQUID)
C     2  FE2SIO4 (LIQUID)
C     3  FE3O4  (LIQUID)
```

```
C      4  FES   (LIQUID)
C      5  H2O   (LIQUID TO GAS)
C      6  N2 (GAS, < 1200 K )
C      7  N2 (GAS, > 1200 K )
C      8  O2    GAS
C      9  SIO2  LIQUID
C     10  SO2  GAS
C     11  CO2  GAS
C     12  CU  LIQUID
C     13  FE3O4 (50% SOLID, 50% LIQUID)
C     14  FEO  LIQUID
C     15  ROCK (50% CAO, 50% AL2O3, LIQUID)
C
C
C      4  FES1.14
      COMMON H298(20),HH(20,2)
      HH(1,1)=.00056
      HH(1,2)=-.0802
      HH(2,1)=.001033
      HH(2,2)=-.24642
      HH(3,1)=.0009216
      HH(3,2)=.25387
      HH(4,1)=.000811
      HH(4,2)=.051717
      HH(5,1)=.00253
      HH(5,2)=1.31389
      HH(6,1)=.001118
      HH(6,2)=-.34714
      HH(7,1)=.001216
      HH(7,2)=-.4628
      HH(8,1)=.001031
      HH(8,2)=-.3243
      HH(9,1)=.001428
      HH(9,2)=-.70297
      HH(10,1)=.0009106
      HH(10,2)=-.4012
      HH(11,1)=.001303
      HH(11,2)=-.5736
      HH(12,1)=.0005194
      HH(12,2)=-.00354
      HH(13,1)=.0008944
      HH(13,2)=.006402
      HH(14,1)=.000949
      HH(14,2)=-.1302
      HH(15,1)=.001263
      HH(15,2)=.5754
      RETURN
      END
      SUBROUTINE HH298
C
C     H298 OF FORMATION FROM THE ELEMENTS ARE LISTED BELOW
C     -- IMPORTANT NOTE, VALUES ARE MJ/KG
C     -- EXCEPTION; FE2SIO4 VALUE IS FROM FE, O, AND SIO2
C
C     1  CUFES2
C     2  CU2S
C     3  FES
```

```
C      4  FES1.14
C      5  FES2
C      6  FE2SIO4
C      7  FE3O4
C      8  SO2
C      9  CO2   (/kg C)
C     10  FEO
C
C
       COMMON H298(20),HH(20,2)
       H298(1)=1.03756
       H298(2)=.49956
       H298(3)=1.14212
       H298(4)=1.08663
       H298(5)=1.42956
       H298(6)=2.64999
       H298(7)=4.8229
       H298(8)=4.63316
       H298(9)=32.792
       H298(10)=3.68044
       RETURN
       END
C
C
C
       SUBROUTINE MINER (CUC,FEC,SC,SIC,RC,CUMOL,PIE,PIRR)
       COMMON H298(20),HH(20,2)
       N6=6
C
C         THIS SUBROUTINE CALCULATES A CHALCOPYRITE, PYRITE, PYRRHOTITE
C         MINERALOGY FROM CU, FE, AND S ASSAYS
C
       RC=100.-CUC-FEC-SC-SIC
       IF(RC.LT.0.)WRITE(N6,101)
101    FORMAT(1H ,'SUM OF ASSAYS IS GREATER THAN 100; RE-ENTER'/1H ,
     +  'THE CONCENTRATE ASSAYS: %CU, %FE, %S, %SIO2'/)
       IF(RC.LT.0.)GO TO 30
10      CONTINUE
       CUMOL=CUC*10./63.54
       FEMOL=FEC*10./55.847
       SMOL=SC*10./32.06
       X1=FEMOL-CUMOL
       Y1=SMOL-2.*CUMOL
       PIRR=(2.*X1-Y1)/.8571
       PIE=X1-PIRR
       IF(X1.LT.-.05.OR.Y1.LT.-.05)GOTO 25
       IF(PIRR.LT.-.05.OR.PIE.LT.-.05)GO TO 25
       GO TO 50
25     CONTINUE
       WRITE(N6,99)
99     FORMAT(1H ,'CUFES2/FES2/FES1.14 MINERALOGY IMPOSSIBLE; RE-ENTER'
     +  /1H ,'THE CONCENTRATE ASSAYS: %CU, %FE, %S, %SIO2'/)
30     CALL RNC(N9,1,CUC,0,15.,34.48,0.)
       CALL RNC(N9,1,FEC,0,15.,50.,0.)
       CALL RNC(N9,1,SC,0,20.,40.,0.)
       CALL RNC(N9,1,SIC,0,0.,25.,0.)
       RC=100.-CUC-FEC-SC-SIC
```

```
      IF(RC.LT.0.)WRITE(N6,101)
      IF(RC.LT.0.)GO TO 30
      GO TO 10
50    CONTINUE
      RETURN
      END
```

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