A Simulation of the Kalgoorlie Nickel Smelter Flowsheet using METSIM

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ABSTRACT

A steady state heat and mass balance simulation of the Western Mining Kalgoorlie Nickel Smelter (KNS) flowsheet was developed within the framework of the commercial software METSIM. The KNS simulation can achieve all plant setpoints through the adjustment of controlled process inputs, and provides a useful tool for the evaluation of the current flowsheet and potential flowsheet developments. The simulation model and a number of applications are discussed in this paper.

INTRODUCTION

Nickel smelting at the Western Mining Kalgoorlie Nickel Smelter (KNS) involves the removal of iron and sulphur, by selective oxidation, from nickel sulphide concentrates. The process is carried out in two stages, namely, smelting in an integrated flash furnace to produce a low grade matte containing 45 percent nickel, followed by converting to high grade matte, containing 72 percent nickel in Peirce-Smith converters. A detailed outline of the current operations at KNS is available in a recent paper (Slater 1990). The flowsheet is shown in figure 1.

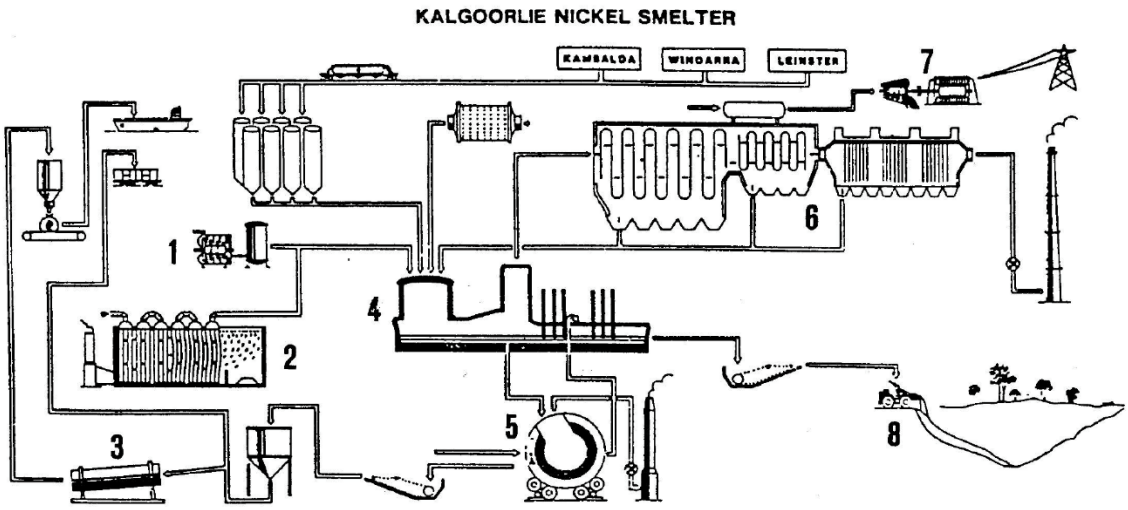

Fig. 1: The current Western Mining Kalgoorlie Nickel Smelter Flowsheet: **1** Oxygen Plant, **2** Air preheater, **3** Product Handling, **4** Flash Furnace, **5** Converter, **6** Offgas Handling, **7** Power Station and **8** Slag Disposal.

Various plant models are currently used at KNS but the objective of this work was to develop a comprehensive flowsheet simulation to obtain a global appreciation of the material and energy flows within the process, and to assess the sensitivity to changes in process inputs and process parameters. The commercial software package METSIM (Bartlet, 1990) was chosen to provide the framework. It is powerful, yet relatively simple to use, and is especially suitable for the simulation of flowsheets incorporating pyrometallurgical operations such as a nickel smelter, since it can handle multiphase, high temperature systems that are undergoing chemical reaction. METSIM is designed for IBM PC/XT/AT/386 compatible computers running under DOS.

The model development was carried out in conjunction with the 1990/91 KNS Vacation Student Program and involved input from 10 third year Metallurgy and Chemical Engineering students from Sydney, Murdoch, Curtin and Melbourne Universities. The KNS Vacation Student Program is run annually and aims to introduce third year students to pyrometallurgical operations and to develop their professional skills through participation in challenging projects.

PROCESS FLOWSHEETING WITH METSIM

The development of a plant simulation or model requires the systematic analysis of the process, namely, the breakdown of the process into modules, the definition of inputs and outputs for each module, the specification of the connection between modules, the definition of the processes within each module and finally the superimposition of the process design criteria on the flowsheet. A model developed in this systematic way not only provides an important tool for the analysis of plant problems, but also provides important insights into the various plant processes and process flows.

The approach used by METSIM for the solution of the flowsheet specification is the sequential modular approach, where each module or so-called unit operation, is balanced in its numbered sequence during the calculation process. Each unit may be capable of up to five fundamental operations, namely, mass balances, phase changes, chemical reactions, heat distributions and splitting the mass amongst specified phases.

All unit operations are linked by streams which transfer matter and energy and which are numbered sequentially to identify their source and destination. All streams must be represented as mixtures of discrete chemical species or components. Each component carries with it an absolute reference number for identification, a descriptive name, a chemical formula, a heat of formation at 25^{o}C, a heat content above 25^{o}C and finally a phase type which may be SI (solid inorganic), SO (solid organic), LI (liquid inorganic), M1 (liquid metal), M2 (liquid matte), M3 (liquid slag) or GC (gas). If the same chemical compound is present in more than one phase, it needs to be identified as two discrete components.

Phase changes and chemical reactions are treated in a strictly sequential manner. If a chemical reaction involves a liquid slag species such as FeO (M3) which is not present as an input, then the species has to be created prior to the reaction by a phase change such as FeO (SI) -> FeO (M3). Further, if a species disappears as a result of a phase change or a chemical reaction, it cannot take part in any subsequent reaction. However, phase changes and chemical reactions can be incomplete. For example, the extent of a reaction must be specified, usually as a decimal fraction between 0.0 and 1.0, where the

specification refers to the first component. If the generic reaction A + B -> C is given an extent of 1.0, the reaction will proceed until all of A is consumed, provided all of B is not consumed first.

Careful consideration must be given to the sequence and extent of all phase changes and chemical reactions when attempting to simulate a relatively complex chemical reactor such as a nickel smelter. In practice, many reactions occur simultaneously and it is not possible, or necessary, to create a reaction sequence which is internally realistic. The sequence only needs to simulate the output chemistry of the process as closely as possible. Later versions of METSIM will incorporate an equilibrium solver capable of handling simultaneous reactions, but the successful application of this approach will require additional expert knowledge such as "activity models" to describe component interactions for complex melts such as mattes and slags.

Once the input species are converted to output species by phase changes and chemical reactions, the mass of each phase can be split amongst the various output streams. For example, a particular output stream may be assigned the respective mass fractions of 1.0 of M3 and 0.05 of M2, which means that it will carry 100 percent of all slag components and 5 percent of all matte components. The latter would simulate an entrainment of matte in the slag phase.

The heat balance within each unit operation is calculated by adding the heat available above 25°C in all input streams, the enthalpy change of all phase transformations and chemical reactions at 25°C and any extra energy addition such as electrical energy. Unit heat loss is subtracted from this total and the remaining available energy used to heat the output streams, either to the same temperature, or to different temperatures, if one or more output streams are assigned preset temperatures. Alternatively, the temperature of all output streams can be nominated, and the heat balance allowed to calculate the resultant heat loss (or gain) for the unit operation. No account is taken of heats of solution, and it is therefore important to select appropriate melt species which minimise any potential error. For example, Fe_2SiO_4 is a more appropriate species for a slag than FeO and SiO_2 separately, since in the latter case, the heat of formation of iron silicate would contribute to a heat of solution.

Once the flowsheet is described in terms of the unit operations, connecting streams, stream components and temperatures, chemistry and heat flows, a control strategy must be developed so that the material and energy flows will obey critical process constraints or setpoints. The control strategy in effect makes the simulation behave as a realistic model. METSIM provides three types of controllers, namely, flow rate controllers, feedforward controllers and feedback controllers. Flow rate controllers fix a stream flow at a nominated setpoint, feedforward controllers fix the flow rates of nominated input streams to a set ratio, while feedback controllers monitor downstream conditions such as matte grade, and provide for the adjustment of preceding stream flows to attain a desired setpoint. These controllers normally simulate actual plant controllers. It has been necessary also to introduce artificial or so-called "thermodynamic" controllers within the KNS flowsheet. These controllers vary the extent of specific chemical reactions to reproduce known process chemistry setpoints, for example, to control the percent nickel reporting to slag for a given matte grade, regardless of the relative masses of matte and slag. Such artificial controllers will not be necessary when an equilibrium solver is made available in the METSIM program.

The flow rates, compositions and temperatures of key input streams have to be defined to complete the description of a flowsheet. METSIM prompts for all essential input stream data, and automatically selects the tear stream for any recycle calculations. The Wegstein method is used for the convergence of recycle streams.

THE KNS FLOWSHEET SIMULATION

The METSIM representation of the KNS plant is shown in figure 2, which illustrates the flowsheet topography and the interconnection between sequentially numbered streams and unit operations. All flows are assumed continuous for the purpose of the simulation. The Preheat Burner (Unit 1), Heat Exchanger (Unit 2) and Process Air Mixer (Unit 3) precede the primary smelter or Flash Furnace which is represented by a combination of a Reaction Shaft/Settler (Unit 4), a Dust Recycle (Unit 5), an Appendage (Unit 7) and an Uptake Shaft (Unit 12). This separation of the primary smelting furnace into discrete units is necessary to allow for the correct representation and control of the process chemistry and for a convenient handling of the recycle dust load. The separation has no adverse effect on the mass and heat balances of the simulation.

The Matte Tap (Unit 6) allows a portion of the Reaction Shaft/Settler matte to be sent directly to the Converter (Unit 9) rather than the Appendage. Unit 8 provides for oxygen enrichment of the converter air, Unit 10 for air ingress under the converter hood and Unit 11 for dust removal from the converter gas. Unit 13 represents the Waste Heat Boiler, Unit 14 the Flash Drum for steam generation, Unit 15 the Electrostatic Precipitator, while Unit 16 provides for a heat loss from dust before it is recycled to the flash furnace.

The chemical components and compositions of input streams which initiate the process are entered by the user. For example, in order to calculate the gas, matte and slag generated by the Reaction Shaft (Unit 4), the constitution of the flash furnace concentrate (stream 1), flux (stream 2), and oil (stream 3), the process air (stream 4), the preheat burner coal (stream 5) and air (stream 6) as well as the oxygen plant oxygen (stream 11) and the tanked oxygen (stream 12), all have to be defined, along with critical initial flow rates, namely, the concentrate (stream 1) flow rate, the oxy plant oxygen (stream 11) and the tanked oxygen (stream 12) flow rates. A typical concentrate may be represented by the components FeS (46.7%), NiS (16.8%), FeS_2 (15.5%), Mg_2SiO_4 (9.4%), SiO_2 (6.7%), $CuFeS_2$ (2.2%), Ca_2SiO_4 (1.4%), Al_2O_3 (0.8%) and CoS (0.5%), which constitute the Solid Inorganic part of the steam, and by H_2O which constitutes the Liquid Inorganic part, or moisture content of the concentrate. Typical concentrate flow rates range from 40 to 70 tonnes/hour.

The definition of all streams in the KNS flowsheet required 45 components, for which enthalpy data was obtained from in-house data bases, rather than verify the data from the extensive METSIM database. The chemistry of the flowsheet was modelled with 27 phase changes, namely, 1 for the Preheat Burner, 7 for the Reaction Shaft/Settler, 10 for the Appendage and 9 for the Converter, as well as 39 chemical reactions, namely, 2 for the Preheat Burner, 17 for the Reaction Shaft/Settler, 7 for the Appendage and 13 for the Converter.

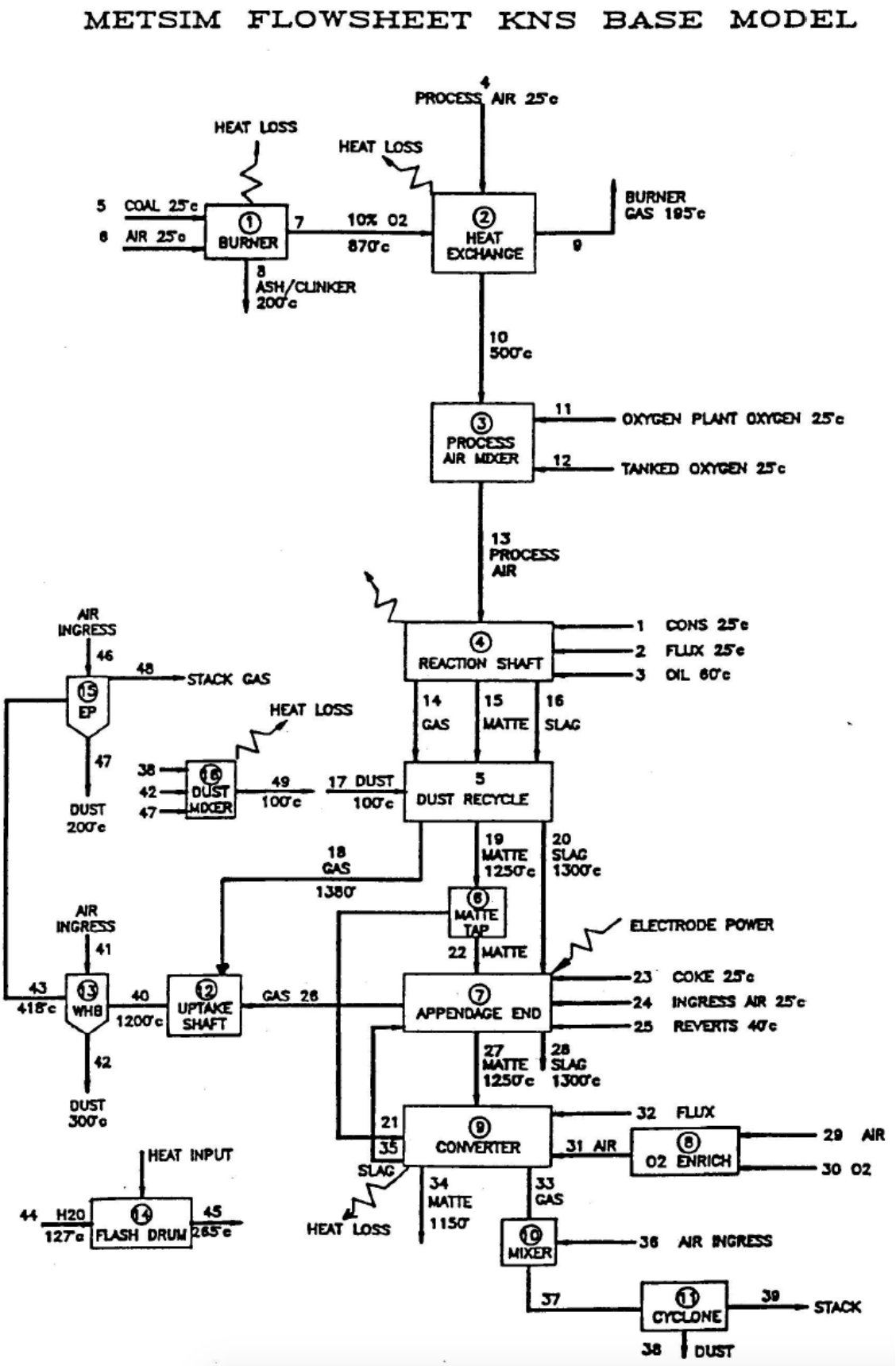

Fig. 2: The METSIM representation of the Kalgoorlie Nickel Smelter Flowsheet.

The importance of the chemical reaction sequence in the simulation of the process chemistry will be illustrated using the 17 reactions for the Reaction Shaft/Settler which are shown below:

1: Coal + 724 O_2 → 679 CO_2 + 208 H_2O + 5 N_2 + SO_2

2: 4 Oil + 1925 O_2 → 1316 CO_2 + 1210 H_2O + 4 SO_2

3: FeS_2 + O_2 → FeS + SO_2

4: 2 $CuFeS_2$ + O_2 → Cu_2S + 2 FeS + SO_2

5: 3 NiS + O_2 → Ni_3S_2 + SO_2

6: Cu_2O + FeS → Cu_2S + FeO

7: CoO + FeS → CoS + FeO

8: 9 NiO + 7 FeS → 3 Ni_3S_2 + 7 FeO + SO_2

9: $2Fe_3O_4$ → 6FeO + O_2

10: $2Ni_3S_2$ + $7O_2$ → 6NiO + $4SO_2$

11: 2 CoS + 3 O_2 → 2 CoO + 2 SO_2

12: 2 Cu_2S + 3 O_2 → 2 Cu_2O + 2 SO_2

13: FeS + O_2 → Fe + SO_2

14: Fe + SO_2 → FeS+O_2

15: O_2 + 2 Fe → 2 FeO

16: 4 FeO + O_2 → 2 Fe_2O_3

17: 2 FeO + SiO_2 → Fe_2SiO_4

Reactions 1 through 5 have and extent of 1.0 and thus consume all of the first component in the presence of excess oxygen. Reaction 1 burns coal added in the flux and reaction 2 burns oil added to the shaft to adjust the heat balance. Reactions 3 and 4 respectively provide for the complete decomposition of solid pyrite and chalcopyrite into the liquid matte components FeS (M2) and Cu_2S (M2), while reaction 5 converts all solid NiS to the liquid matte component Ni_3S_2 (M2).

Reactions 6 through 8 have an extent of 1.0 and respectively convert all solid copper, cobalt and nickel oxides to the liquid matte components Cu_2S (M2), CoS (M2) and Ni_3S_2 (M2). The correct levels of nickel, cobalt and copper in the slag are then set by controlling the extents of reactions 10, 11 and 12, since these reactions convert the liquid sulfides (M2) into liquid slag components (M3).

Reaction 9 has an extent of 1.0 and converts all solid magnetite to the liquid slag component FeO (M3). Reactions 13, 14 and 15 are designed to control the matte composition. Reaction 13 has an extent of 1.0 and converts all FeS to Fe in the matte, leaving only Ni_3S_2 and Fe. The extent of reaction 14 is controlled to partially convert Fe back to FeS and thereby set the desired percent sulfur in the matte which is now based on the components Ni_3S_2, FeS and Fe. Sulfur is normally set at around 23 percent for flash furnace matte.

The removal of iron from matte increases the matte grade (as percent Ni) and oxygen starvation is used to control the extent of this removal through reaction 15, in order to control the matte grade. The total O_2 flow (as process air) is adjusted by a feedback control so that sufficient is available for all reactions up to 14, and also for a partial conversion of Fe to FeO through 15. The extent of reaction 15 is controlled at slightly less than 1.0, so that an amount of oxygen remains to partly oxidise FeO to Fe_2O_3 through 16, and thus to set the appropriate magnetite level in the slag, and also to allow for free oxygen in the reaction shaft off-gas, when the oxygen efficiency is less than one. Finally, reaction 17 has an extent of 1.0 to provide for a maximum formation of iron silicate in the slag.

A total of 32 feedback controllers and 1 feedforward controller were used for the KNS flowsheet simulation. Once initiated, the program adjusts the preheat burner air to give the desired air/coal ratio for an arbitrary initial coal flow rate. The total burner gas flow then is adjusted until the initial process air flow reaches the desired temperature through the heat exchanger. After a fixed amount of oxygen enrichment, the process air flow is adjusted to give the desired matte composition and to burn oil on the shaft at a predetermined oxygen efficiency. Once the correct process air flow is established, an appropriate readjustment is made to the burner gas flow to maintain the desired preheat temperature.

The flux is adjusted to give a target Fe/SiO_2 ratio in the Reaction Shaft slag, the extent of reactions are controlled to give the expected Ni, Cu, Co and magnetite percentages for the slag mass generated, while the "inert" dust load is adjusted as set percent of the total flux and dust flow. An amount of matte is tapped and sent to the Converter while the remainder is passed to the Appendage along with slag, where coke reacts to transfer nickel (and iron) from slag to matte. The cleaned slag is discarded and the matte sent to the Converter where it is blown with a controlled amount of air to give a high grade matte containing either 5 or 1 percent iron.

The heat balance requires that heat losses be accounted for in each of the unit operations. The heat losses were obtained from unpublished plant studies, or calculated using the normal temperatures of input and output streams. For example, the heat loss from the reaction shaft could be assigned a fixed value and the oil adjusted to produce the required slag temperature of 1300^{o}C (along with compatible gas and matte temperatures of 1380^{o}C and 1250^{o}C respectively), or the heat loss could be calculated at a fixed oil flow rate, and with pre-assigned temperatures for the matte slag and gas.

EXAMPLES OF MODEL APPLICATIONS

The METSIM model provides for a complete steady state heat and mass balance profile of the Kalgoorlie Nickel Smelter Flowsheet and is an invaluable tool for flowsheet evaluation, either for the flowsheet in its entirety, or for individual unit processes within the flowsheet. For example, the effect of matte grade on the heat distribution for the flash smelting and the converting processes has been evaluated using a concentrate grade of 10 percent nickel and a feed rate of 72 tonne/hr.

The effect of the matte grade on the heat balance of the flash furnace reaction shaft/settler is shown in figure 3, which was constructed using calculated stream enthalpies. The left

side of the figure shows the available heat, which is made up of contributions from the air preheat, the heat of reaction, and the heat from the burning of oil.

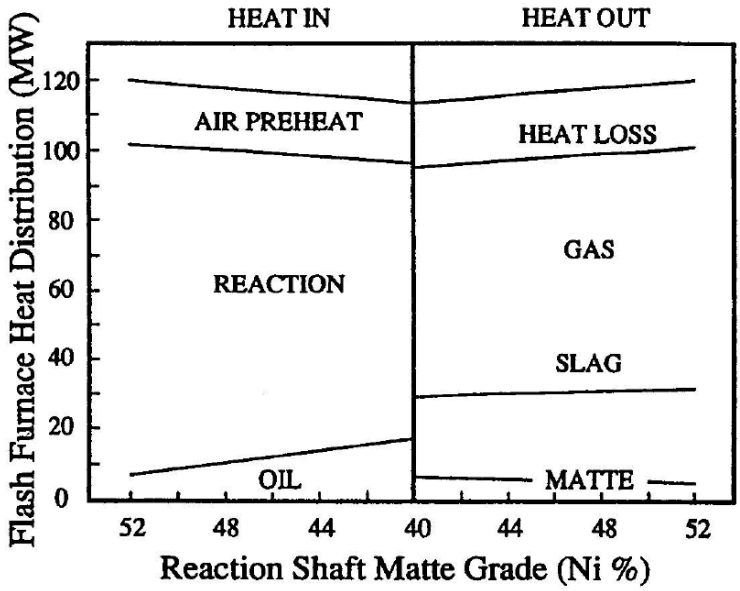

Fig. 3: The distribution of heat in the flash smelting of nickel at a constant feed rate of 72 tonnes/hr of concentrate.

As the matte grade increases (to the left), the heat of reaction increases and less compensating heat is required from the burning of oil. Practical constraints, such as the waste gas handling capacity, limit the matte grade to under 48 percent nickel. The right side of the figure shows the distribution of available heat amongst the outputs, namely, the unit heat loss, the matte, slag and gas, where the latter contains the majority of the heat. As the matte grade increases (to the right), the heat content of slag and gas increase as their respective masses increase, whereas the heat content of the matte decreases as its mass decreases. In practice, the gas, matte and slag represent intermediate streams which are not, in reality, accessible, since they are diluted with streams emanating from the appendage end of the furnace. However, it is necessary to be able to predict the reaction shaft matte grade, as this ultimately controls the tapped grade and slag losses.

The nickel content of so-called low grade (LG) or flash furnace matte which is charged to the converter has an effect on the heat balance of the converter, as shown in figure 4. The output or target matte is called high grade (HG) matte. The left side of the figure shows that the available heat from the converting reaction decreases with increase in LG matte grade. However, the heat carried away in the gas and slag also decreases, since the respective masses decrease with increase in LG matte grade. The process remains autogenous and the main effect of an increase in LG matte grade is a shorter blowing time.

The model developed for the KNS flowsheet can be easily modified to allow for investigation of a variety of process parameters. As an example of this, the sensitivity of the process to the fluctuation in concentrate feed rate and the effect on matte grade was investigated. The flash furnace module was modified to accommodate this problem. The feedback controllers for the process air, oil and flux were removed, and the respective flows fixed at the required level for a feed rate of 62 tonne/hr of concentrate. The feed

rate then was varied from 59 to 67 tonne/hr so that the resultant effect on the matte grade could be evaluated. The results of this investigation are shown in figure 5, where a ±3% change in feed rate corresponds to a significant matte grade variation from 41 to 50 percent nickel. Such a variation also will significantly affect the process heat balance, as indicated in figure 2.

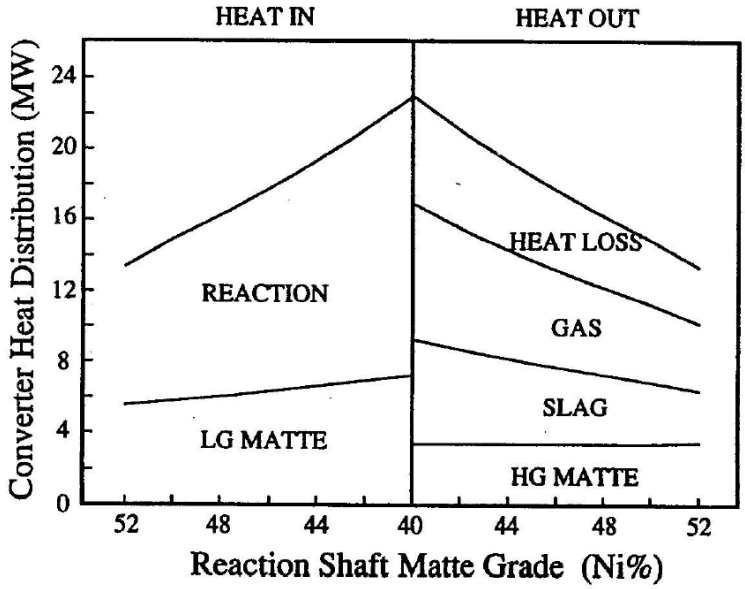

Fig. 4: The distribution of heat in the converting of nickel matte.

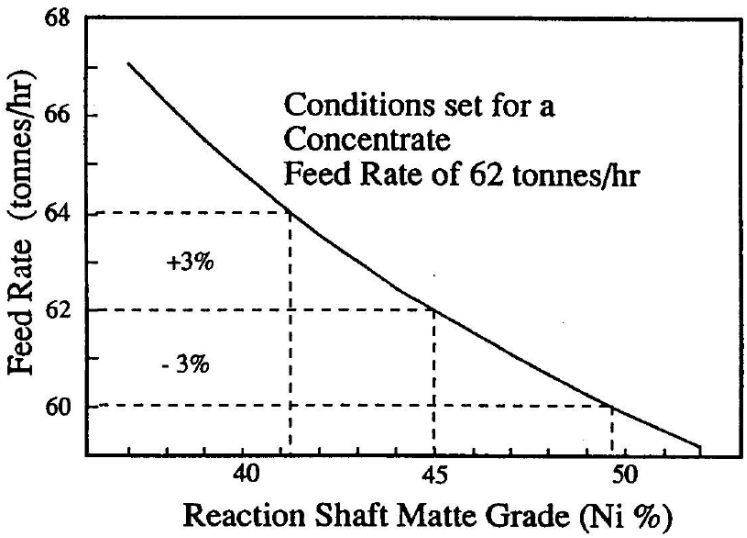

Fig. 5: The sensitivity of matte grade to variations in feed rate, with conditions set for a concentrate flow rate of 62 tonnes/hr of concentrate.

CONCLUSIONS

The commercial software METSIM has been used to develop a complete steady state heat and mass balance profile of the Western Mining Kalgoorlie Nickel Smelter (KNS) flowsheet . The simulation can be used to investigate the global interaction of most of the important process parameters, and easily can be altered to extend the simulation to

sensitivity analyses. The refinement of the KNS simulation will continue and its applications extended.

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