

The 1972 Extractive Metallurgy Lecture

The Metallurgical Society of AIME

Techniques of Process Analysis in Extractive Metallurgy

NICKOLAS J. THEMELIS



The study of process metallurgy should include the theory of heat, mass, and momentum transfer and also the techniques of process analysis and design which have made chemical engineering an indispensable partner of the chemical science. The analytical tools which can be used in a particular situation depend entirely on the ingenuity of the metallurgist and his willingness to adapt and utilize the existing methodology. Various techniques of process analysis are exemplified in this paper.

THE study of extractive metallurgy can be divided into two major areas: *chemical metallurgy*, which is concerned with thermodynamics, chemical kinetics, and diffusion, and *process metallurgy*, which examines the interaction of the above with the physical phenomena of momentum, heat, and mass transfer in industrial furnaces or other types of reactors.

In the past, the growth of knowledge in the domain of process metallurgy has been very slow, probably due to the fact that metallurgical processes were developed and operated empirically and, therefore, there was little incentive for training specialists in this area.

The stagnation of process metallurgy as a science might have continued if it were not for the increased

competition in the metal industry and the need to produce metals more efficiently and with the least possible waste and effect on the environment. There are now concrete examples of the successful application of scientific principles in the design and operation of metal extraction processes; the myth that metallurgical furnaces are too large or too hot to be subjected to systematic analysis and simulation, is gradually dying out.

Most extractive reaction systems are heterogeneous and, therefore, are controlled by the transport phenomena in the reactor. Failure to appreciate this fact has in the past resulted in many laboratory studies which were of little practical use to industrial metallurgists,

N. J. THEMELIS was born in Athens, Greece, in 1933 and obtained his Chemical Engineering degree at McGill University, Montreal, Canada, in 1956. After a brief stay with the Pulp and Paper Research Institute of Canada, he returned to McGill for his Ph.D. thesis on iron reduction which steered him to the metallurgical field. In the years 1960-62 he worked for the Strategic Materials Corporation in Niagara Falls and in 1962 he joined the newly formed Noranda Research Centre where he became manager of the Engineering Division. In February 1972, he joined the Metal Mining Division of Kennecott Copper Corporation as Vice President, Research and Engineering. He is the author of many technical papers and patents in the area of metal proces-

sing, including the Noranda Process for the continuous smelting and converting of copper concentrates. In collaboration with Prof. Julian Szekeley, Dr. Themelis published recently the textbook *Rate Phenomena in Process Metallurgy* (John Wiley and Sons, 1971). He is an active member of AIME, past recipient of the Extractive Metallurgy Award for best paper published (1968), and 1972 Extractive Metallurgy Division Lecturer. He has been Secretary-Treasurer of the Metallurgical Society of C.I.M. (1966-68), and Director of the Canadian Soc. of Chemical Engineers (1968-71).

The 1972 Extractive Metallurgy Lecture was delivered on Feb. 22, at the AIME annual meeting in San Francisco.

since they could not be related to the "real" world of the plant.

Thus, the principal role of process metallurgy is to bridge the existing gap between the chemical metallurgist and the plant engineer, by showing to the former the range of conditions which should be included in his study, and presenting the latter with design correlations which tie the bench results to the industrial plant. For example, a laboratory study on iron reduction *must* be carried out under well-defined flow and heat transfer conditions; a reliable mass transfer correlation is then necessary to relate the laboratory results to a fluidized bed or rotary kiln reactor.

In order for process metallurgy to fulfill this role, it is necessary to determine the phenomena occurring in a particular reactor and then describe them in terms which are sufficiently quantitative to be readily usable by the design engineer and the plant operator. For instance, the ideal process metallurgist should be prepared to work his way through the packed bed of a blast furnace, examining the path of gases through the charge, noting the temperature profiles and collecting all sorts of useful information which will allow him to analyze the process and guide the design and operating engineers accordingly.

On another occasion, the ideal process metallurgist is injected bodily into a copper converter through a tuyere and emerges in the bath where he obtains first-hand information on the trajectory of the air jet and its physical and chemical interaction with the matte. Such a herculean effort would certainly be worthy of a doctorate degree, irrespective of the results obtained.

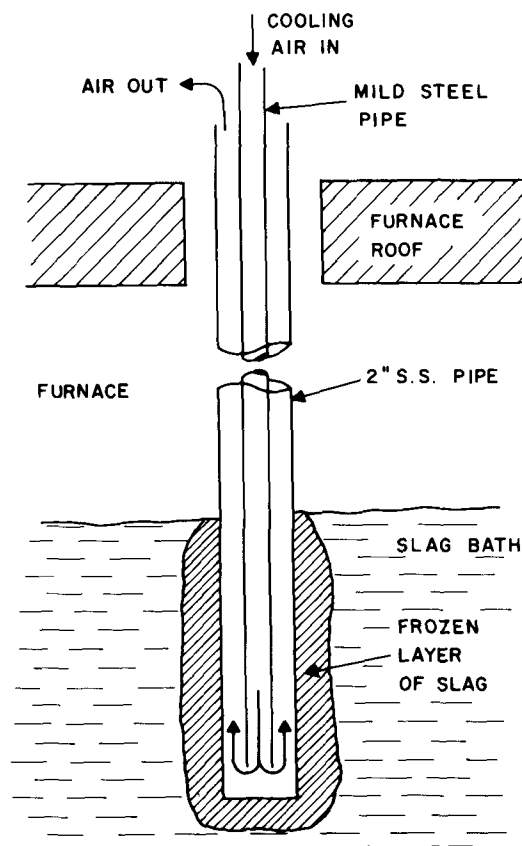


Fig. 1—Air-cooled probe for sampling reverberatory furnace bath.

Naturally, there will not be many ideal process metallurgists to volunteer for such demanding jobs but the principle remains the same: how to obtain the maximum amount of "inside" information about an existing or envisaged process by means of actual measurements, pilot plants and physical and mathematical models which simulate the process. Collectively, these tools may be called *techniques of process analysis*. Several examples of their application will be described in this paper. For a more comprehensive treatise of this subject, the reader is referred to a recent addition to the metallurgical literature.¹

With respect to the question what constitutes an "adequate" quantitative description of a phenomenon, the answer is that this depends on the complexity of the system and the ingenuity of the researcher. It may range from a theoretical derivation to a semiempirical or empirical correlation. For instance, the flow in a glass melting furnace may be defined adequately from the first principles of transport theory; on the other hand, the mixing conditions in an open hearth furnace are so intense that one may have to resort to an empirical *eddy diffusivity* by assuming that bulk flow in the bath follows the laws of diffusion. The success of an analytical method does not depend on the amount of theory which it incorporates but on its reliability as a mirror of reality.

Various techniques of process analysis are discussed in the following sections.

MEASUREMENTS IN AN EXISTING PROCESS

a) Concentration and Temperature Profiles

Useful information on an existing process can be obtained by measuring the temperature and concentration profiles in the reactor proper. An example of this technique is a study carried out on a calcine-smelting reverberatory furnace at the Noranda smelter. The objective was to determine the composition and origin of a "mushy" layer which had been observed by the operators to exist in the bath above the matte layer.

In order to obtain representative samples of the slag at various locations and levels, a sampling probe was devised which could be lowered into the bath through an opening in the furnace roof, Fig. 1. The design of the probe was simple but very effective. It consisted of two concentric steel pipes which were cooled by air flowing first through the inner pipe and then through the annulus.

In the operation, the probe was first lowered into the furnace atmosphere and allowed to heat up to the bath temperature, without any air flow. After a few seconds, it was lowered further, into the slag layer and, once in place, the air flow was started. In a few minutes, the air cooling resulted in the solidification around the probe of a slag layer which was representative of the slag composition at various levels. The probe was then withdrawn from the furnace and the sample was divided into sections.

This method of sampling was reliable and allowed sampling of the entire slag layer. The results of the analysis showed that the "blanket" consisted of precipitated crystals of chromite, Fig. 2, and was due to a relatively large input of chromium oxide in the charge. An intensive effort was made to eliminate some of this

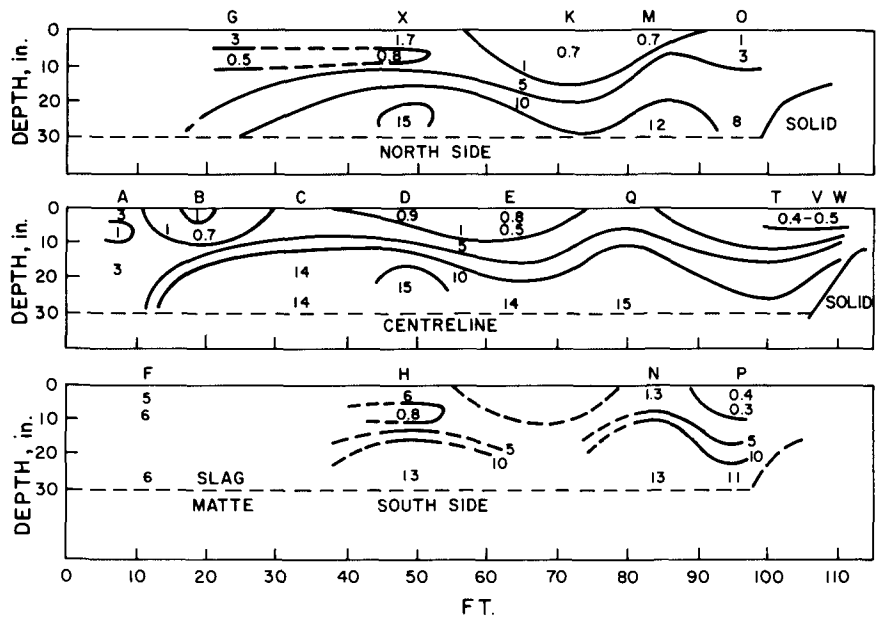


Fig. 2—Concentration profiles of Cr_2O_3 in reverberatory slag, as a function of slag depth and distance from fire-end wall.

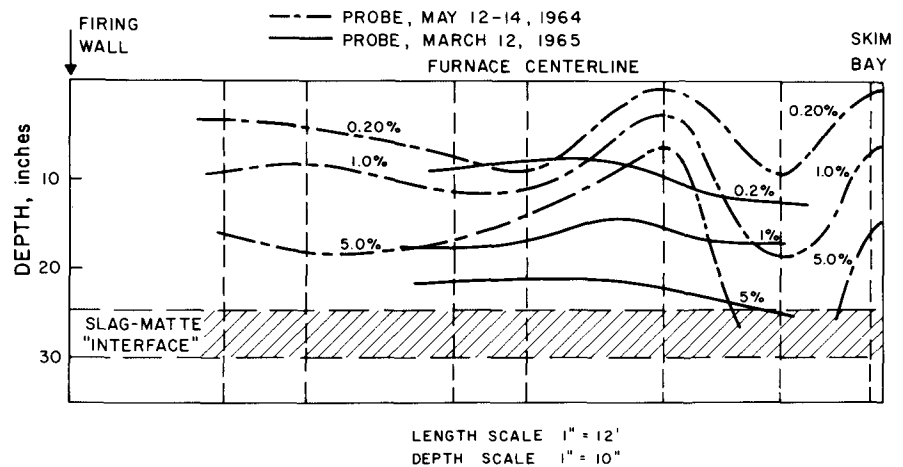


Fig. 3—Results of steam-blowing campaign on Cr_2O_3 concentration in reverberatory slag.

“sandy” material by blowing the bath with air lances and thus entraining some of the chromite crystals in the skimmed slag. Further sampling of the slag layer after this work showed that some of the blanket had been eliminated, Fig. 3.

During the same period, extensive temperature measurements were made in the furnace bath, Fig. 4. These were related to a study of the flow phenomena in the reverberatory furnace which has been published² and will be discussed briefly in the next section.

b) Tracer Techniques

The *average* residence time of a fluid in a continuous flow reactor, *e.g.* converter slag through a reverberatory furnace, can be calculated by dividing the volume of the bath by the volumetric flow rate of the fluid. This ideal condition would prevail in a *plug flow* reactor where all the fluid is involved in the flow, *i.e.*, there are no dead volume regions. In practice, dead volume regions invariably exist and there is a certain degree of mixing so that fluid elements spend different time periods in the reactor.

The effect of mixing conditions on the performance of a continuous flow reactor can be visualized by con-

sidering the behavior of a first-order leaching reaction, where the leaching rate is proportional to the acid concentration in the solution.

Let us assume that in a batch reactor the required time for the acid concentration to decrease from the initial concentration, C_i , to the final, C_f is t_b . In the continuous plug flow reactor, the acid concentration is altered only by chemical reaction and, therefore, the required residence time is still t_b . However, in the presence of backmixing, the acid concentration at any point is diluted by fluid elements from downstream; consequently the rate of leaching is decreased and the required residence time is now greater than t_b , Fig. 5.

In the extreme case where the continuous flow reactor behaves as a perfect mixer, as in the case of fluidized roasting, the entire reactor volume is at the exit concentration C_f , the concentration driving force is at its minimum, and therefore the required residence time is much greater than in a batch reactor.

A convenient method for determining the mixing and flow conditions in a metallurgical furnace is by means of radioactive tracer tests.¹ As an example, in a study of copper losses in slag,² a few grams of radioactive copper were added in a ladle of converter slag which was transferred to a reverberatory furnace. Samples

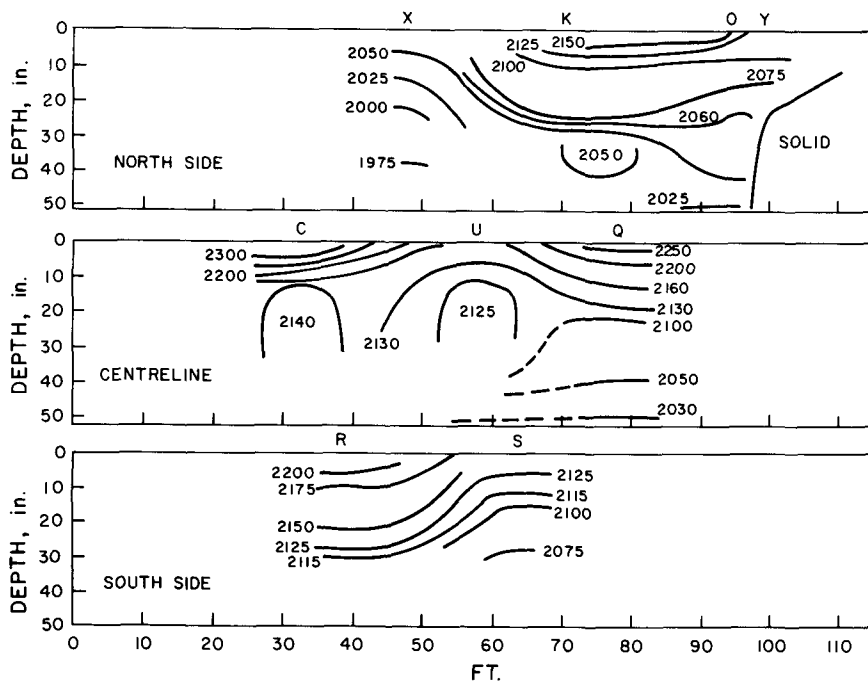


Fig. 4—Temperature profiles in reverberatory slag as a function of slag depth and distance from fire-end wall.

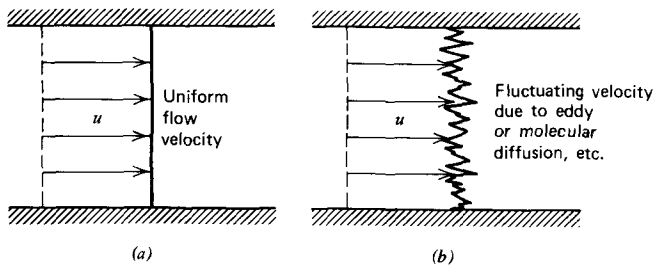


Fig. 5—Effect of backmixing on the flow through a reactor.

of the skimmed reverberatory slag were then collected at regular intervals and analyzed for radioactivity.

The results were plotted in the form of a concentration-time curve, Fig. 6, which revealed that a large portion of the slag layer, 86 pct, behaved as a dead volume region, due to the presence of a "blanket" of precipitated chromite and magnetite crystals. A campaign was then undertaken to entrain some of this blanket into the moving slag by blowing the bath with air lances. A second tracer test, made after this campaign, showed, Fig. 6, that the active volume of the slag layer had been nearly doubled and the dead volume region was reduced to 76 pct. In Fig. 6, V represents the total volume of the slag in the furnace, and V_p , V_m , V_d the volume fractions behaving as plug flow, backmix, and "deadwater" regions, respectively.

The radioactive tracer technique has also been used by the Noranda Research Center in the analysis of flow of materials in an industrial mill producing zinc concentrates.³ At a later stage, the "tagged" concentrates were used to determine the residence time in an industrial fluidized bed roaster.

c) Plant Tests

One of the most common methods of developing an existing process is by altering slightly the operating conditions and then standing by, with a certain amount

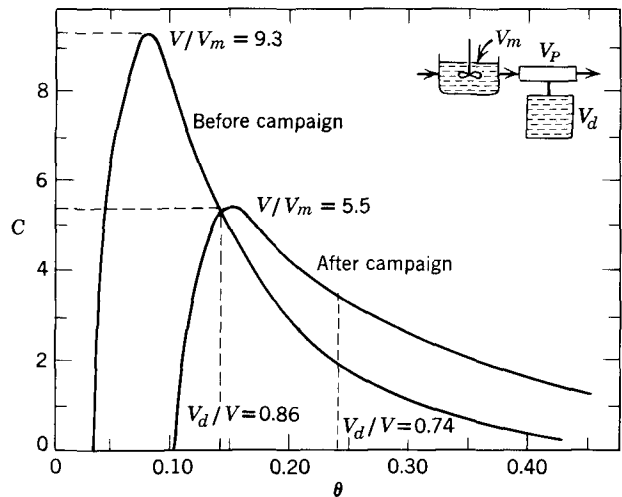


Fig. 6—Concentration vs time plots for radioactive tracer tests in reverberatory furnace.

of apprehension, to observe the results. Under proper planning, this technique may also be used to obtain valuable information as to the workings of a process.

A good example of this application is some work conducted by the author on the generation and distribution of heat in a three-electrode ferro alloy electric furnace.⁴ In the case of submerged arc operation, where the electrodes are surrounded by the solid charge, most of the heat is generated in the arc striking between the electrode and the charge. However, in the semi-industrial furnace under study the charge was fed around the periphery of the furnace and therefore the bath surface around the electrodes was exposed.

The question was whether most of the heat was being generated in the slag layer bridging the electrodes or at the periphery of the electrodes which were in contact with the slag. The answer would have an important bearing on the electrode spacing and diameter required for scaling up the process to a larger furnace. To

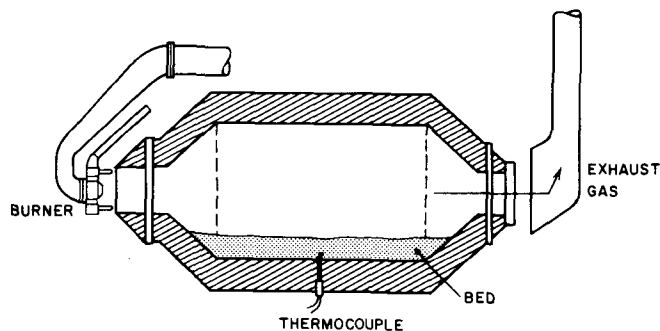


Fig. 7—Rotary batch furnace used as a section model of iron reduction rotary kiln.

resolve this problem, the depth of immersion of the electrodes in the slag layer was increased progressively, at constant voltage. The resulting current-voltage relationship was analyzed by considering the alternative paths of electricity through the bath.

The results of this analysis showed that the resistance per electrode was inversely proportional to the surface area of the electrode in contact with the slag. This finding signified that the major resistance step was at the electrode-slag interface and was probably due to the "corona" effect of a film of ionized gas. Further confirmation was obtained by measuring the temperature of the slag layer by means of consumable platinum thermocouples; the highest recorded bath temperature was invariably adjacent to the electrodes.⁴

An excellent example of a simple but very ingenious industrial test is that carried out by Prof. Kellogg⁵ on a Cominco zinc-fuming furnace and later on at the El Paso furnace of ASARCO. For a few minutes the coal supply through the tuyeres was interrupted while still blowing with air. The resulting changes in the FeO and Fe_3O_4 content of the slag bath provided a valuable insight into the mechanism of the zinc-fuming process.

PILOT PLANTS AND MODELS

In order to construct a pilot plant of a process on a scientific basis, it is necessary to observe four states of similarity between the prototype and its model: geometric, mechanical, thermal, and chemical similarity. In general, a *pilot plant* is designed to encompass all these states, while a *model* simulates only certain aspects of the process.

Thus, a rotary batch furnace, Fig. 7, can be utilized as a *section model* of a rotary kiln by using the same charge, loading, and temperature and by relating its speed of rotation to the prototype.

Usually there are two stages of pilot plants in the development of metallurgical processes. The first "small pilot plant" stage determines whether the process is technically feasible and also provides some idea as to its economic potential. The second "semi-industrial pilot plant" stage is to prove the economic feasibility of the process and, possibly, to produce large quantities of the product for market tests.

Undoubtedly, the semi-industrial pilot plant should be a near replica of the prototype. However, the same is not necessarily true of the first-stage small pilot plant. In the past, large amounts of money and effort have been expended in building "soup-to-nuts" minia-

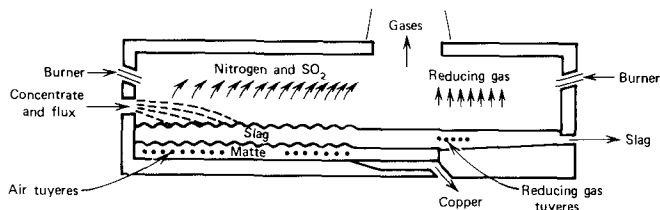


Fig. 8—Initial concept of the Noranda Process for the continuous smelting and converting of copper.¹

ture plants of a new process and attempting, usually against the odds, to operate them continuously. Thus valuable energy which could have been directed towards the understanding of the phenomena in the reactor proper, was wasted in operating and maintaining an array of miniature auxiliary equipment.

In the alternate school of thought, the process under study is analyzed into its components, which are then examined individually in the light of the existing knowledge. It is possible that some of these components have already been proven, either experimentally or in industrial operation. Consequently, they need not be included in the first stage pilot plant which is designed to concentrate on the remaining unknown factors.

An illustration of this principle is the development of the Noranda Process,^{6,7} Fig. 8. Despite the fact that since its initial conception the process had been based on the use of a cylindrical furnace and tuyeres, the first-stage piloting was done in a small reverberatory furnace using lances which were lowered into the bath through the ceiling of the furnace, Fig. 9. It was reasoned that the problems of operating small-diameter tuyeres would outweigh their advantages; also, the performance of tuyeres in converting was well established from the operation of the Pierce Smith converters.

Thus the bulk of the first-stage piloting of the Noranda Process was directed towards the principal question of whether it was possible to smelt concentrates and produce metallic copper simultaneously in the same furnace. This was established by actual smelting-converting tests in the small reverberatory furnace and by measurements of the mixing conditions in a flow model of the Noranda Process reactor.

Other components of the process, such as the smelting capacity per unit surface area of the bath, the recovery of copper from the slag by milling or pyrometallurgically, and the processing of the copper produced to anode copper were studied in various pieces of equipment, including a small experimental converter. The final synthesis of all these data indicated that the process was technically feasible and led to the decision to build a 100 TPD semi-industrial pilot plant.

It should be mentioned that radioactive tracer tests on this reactor (7 ft diam) showed that despite the extensive effort on flow models and in the pilot reverberatory furnace, the mixing conditions in the large vessel had been underestimated. This did not affect the smelting and converting functions of the reactor but prevented the production of a low-copper slag, without increasing the slag settling zone appreciably. However, provision had been made in the original plans for the alternative treatment of the slag by milling.

It can be seen that the design of metallurgical processes is not as yet a precise science.

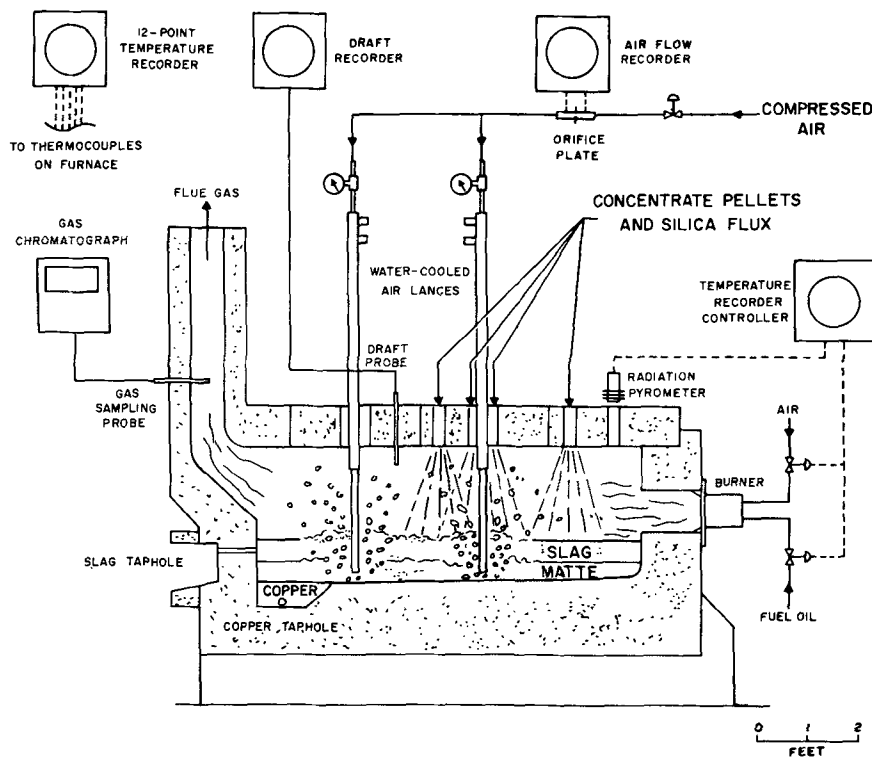


Fig. 9—Pilot furnace used in first-stage development of Noranda Process.⁶

MATHEMATICAL MODELS

As mentioned earlier, the task of the process metallurgist is to combine the available chemical and transport theory with his experimental results and develop mathematical models which are readily usable by design and operating engineers. These models may be in the form of an equation, a plot, or a tabulation and may range from the highly theoretical to the fully empirical, provided that they represent reality with a certain degree of accuracy.

Naturally, those models which have a basis on scientific theory are bound to have a wider range of application. For instance, let us assume that a researcher discovers that the pressure drop through a pipe is a function of the velocity of the fluid flowing through it; he therefore plots a curve of pressure drop against velocity and this is an empirical model which is fairly adequate for anyone working with the same pipe diameter, fluid, and range of velocities. However, someone else who is more enterprising takes these same results, combines them with the equations of continuity and motion, and constructs a model which involves a friction factor and is usable over a much wider range of operating conditions.

Mathematical models should be defined in terms of the minimum possible number of variables. This can be achieved through the use of the *dimensionless numbers* which are groups of properties in a system that are independent of the unity of measurements and can be used as criteria of similarity.

The dimensionless numbers can be derived either by means of the dimensional analysis technique¹ or on the basis of the dimensional homogeneity of the equations which represent the system. As an illustration, let us consider the case of unidirectional mass transfer by diffusion and bulk flow. The equation of motion under steady-state conditions and in the presence of natural

convection is:

$$\rho u \frac{\partial u}{\partial x} = \mu \frac{\partial^2 u}{\partial x^2} + g\beta\rho T \quad [1]$$

where

ρ : fluid density

μ : fluid viscosity

u : flow velocity in direction x

g : acceleration due to gravity

β : thermal coefficient of volume expansion

T : temperature above a certain reference datum

x : distance in the direction of flow

Also, the equation expressing the conservation of mass yields:

$$u \frac{\partial c}{\partial x} = D \frac{\partial^2 c}{\partial x^2} \quad [2]$$

where

c : concentration

D : diffusion coefficient

Let us now consider a model of properties ρ_1, u_1, x_1 , and so forth, and a prototype of properties ρ_2, u_2, x_2 , and so forth. In order for similarity to exist, each property of the prototype must be proportional to the corresponding property of the model, *i.e.*

$$\rho_2 = C_\rho \rho_1 \quad (1)$$

$$u_2 = C_u u_1 \quad (2)$$

$$x_2 = C_L x_1 \quad (3) \quad [3]$$

where C_ρ, C_u, C_L are the proportionality constants.

Since all terms in an equation must be dimensionally

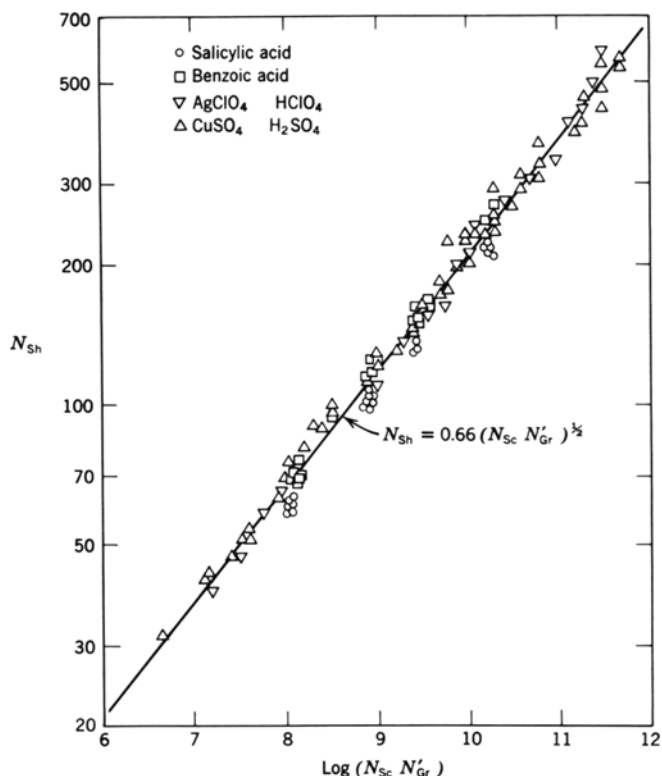


Fig. 10—The Wilke correlation for mass transfer between a liquid and a vertical plate by natural convection.⁸

homogeneous, it can be shown easily from Eqs. [1] and [2] that the following identities exist:

$$\frac{C_\rho C_u^2}{C_L} \equiv \frac{C_\mu C_u}{C_L^2} \equiv C_g C_\beta C_\rho C_T \quad [4]$$

and

$$\frac{C_u C_c}{C_L} \equiv \frac{C_D C_c}{C_L^2} \quad [5]$$

Rearrangement of Eqs. [4] and [5] yields the following dimensionless relationships:

$$\frac{C_L C_u C_\rho}{C_\mu} = 1; \text{ i.e., } \frac{X_1 u_1 \rho_1}{\mu_1} = \frac{X_2 u_2 \rho_2}{\mu_2} \equiv N_{Re} \quad [6]$$

$$\begin{aligned} \frac{C_g C_\beta C_\rho C_L^3 C_T}{C_\mu^2} &= 1; \text{ i.e., } \frac{g_1 \beta_1 \rho_1 x_1^3 T_1}{\mu_1^2} \\ &= \frac{g_2 \beta_2 \rho_2 x_2^3 T_2}{\mu_2^2} = N_{Gr} \end{aligned} \quad [7]$$

$$\frac{C_\mu}{C_\rho C_D} = 1; \text{ i.e., } \frac{\mu_1}{\rho_1 D_1} = \frac{\mu_2}{\rho_2 D_2} = N_{Sc} \quad [8]$$

Therefore, this simple analysis has yielded three of the most important dimensionless numbers, namely the Reynolds, the Grashof, and the Schmidt number. These three variables are the similarity criteria for the system represented by Eqs. [1] and [2], which incorporated nine variables.

Two well known dimensionless groups are the Arrhenius number, in chemical thermodynamics, and the Mach number in high velocity motion. The principal use of these numbers is in the development of generalized correlations which express an important

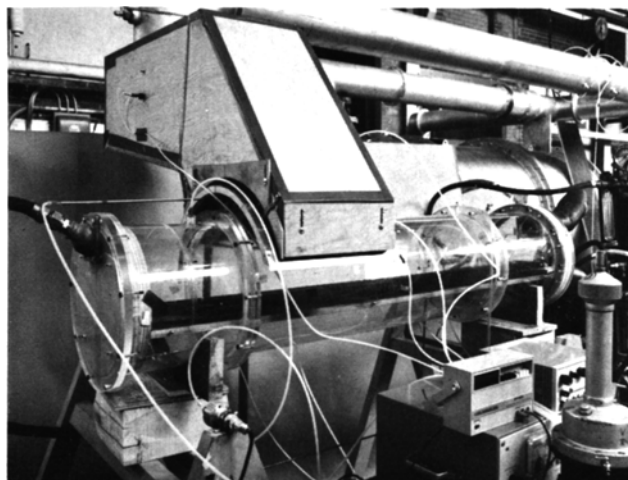


Fig. 11—Model of gas flow in Noranda Process Reactor.⁹

characteristic, e.g. mass transfer rate, to the intrinsic and extrinsic properties of the system. A "library" of such correlations is gradually being built by researchers in the metallurgical field and constitutes a major tool for process analysis and design.

As an example, the following correlation was developed by Wilke and his coworkers^{8,9} for representing the mass transfer rate from vertical plates, under natural convection, Fig. 10.

$$N_{Sh} = 0.66 (N_{Gr}' N_{Sc})^{0.25} \quad [9]$$

where N_{Sc} is the Sherwood number

$$N_{Sc} : \text{Sherwood number} = \frac{k_d L}{D}$$

N_{Gr}' : Grashof number

k_d : mass transfer coefficient

L : height of plate

D : diffusion coefficient

In the case of copper electrorefining, it has been shown¹ that Eq. [9] can be used to predict accurately the limiting current density at which electrodeposition is controlled by mass transfer through the boundary layer over the electrode. The realization of the importance of the flow phenomena in electrorefining has led to a search for new designs of cells where the flow of electrolyte past the electrode may be controlled by forced rather than natural convection.

For systems where there are no available correlations, the dimensionless numbers may still be used as criteria of similarity between a prototype system and its model. For instance, during the design of the first industrial plant of the Noranda Process, Fig. 8, it became necessary to estimate the pattern of pressure distribution in the atmosphere above the bath. The objective was to design the reactor and hood system to provide for a slight negative pressure (draft) at the feed port so as to minimize the infiltration of air, while at the same time avoiding "blowbacks" of hot gases which might damage the feeding mechanism.

In view of the complexity of the system it was virtually impossible to calculate the pressure distribution from first principles. Consequently, Dudgeon¹⁰ undertook to experiment with an air-flow model of the re-

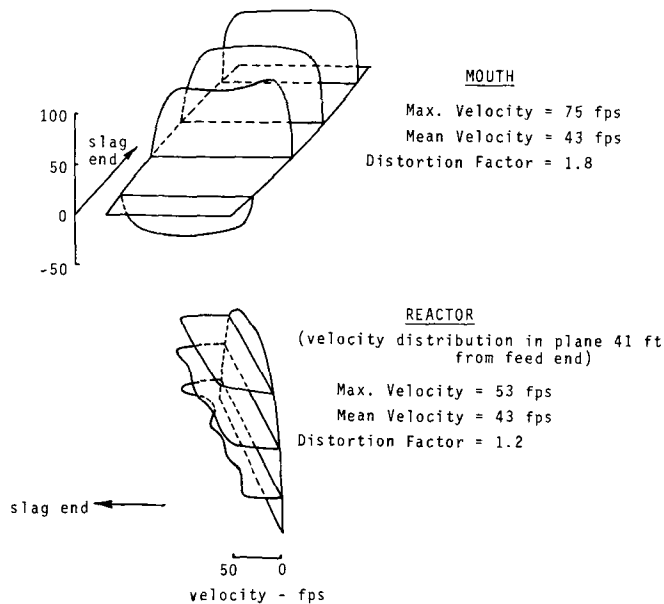


Fig. 12—Velocity profiles in Noranda Process reactor, as per flow model.⁹

actor, Fig. 11. The model was geometrically similar to the Noranda Process reactor and also provided for dynamic similarity of the gas flow by maintaining the same Reynolds number ($N_{Re} = 56,000$) and introducing part of the air flow ("tuyere air") through a horizontal grid in the "converting zone" of the model. The results of these tests led to some changes in the design of the prototype reactor; an example of the velocity profiles measured with a hot wire anemometer is shown in Fig. 12.

As another illustration of the use of dimensionless numbers in simulating a process, let us assume that we want to reproduce the vortex configuration of an industrial leaching tank in a model, Fig. 13. The important similarity criteria in this case are the Reynolds number, which represents the ratio of inertial to viscous forces, and the Froude number, which is the ratio of inertial to gravity forces:

$$N_{Re} = \frac{d^2 N \rho}{\mu} \quad [10]$$

$$N_{Fr} = \frac{d N^2}{g} \quad [11]$$

where

d : impeller diameter

N : speed of rotation of impeller

ρ, μ : density and viscosity of fluid

Eq. [11] shows that the model and prototype will have the same Froude number if:

$$\frac{N_m}{N_p} = \left(\frac{d_p}{d_m} \right)^{\frac{1}{2}} \quad [12]$$

where the subscripts m and p signify properties of the model and prototype, respectively.

Also, by substituting from Eq. [12] in the definition of the Reynolds number, Eq. [10], we obtain:

$$\left(\frac{\mu}{\rho} \right)_m = \left(\frac{\mu}{\rho} \right)_p \left(\frac{d_m}{d_p} \right)^{\frac{3}{2}} \quad [13]$$

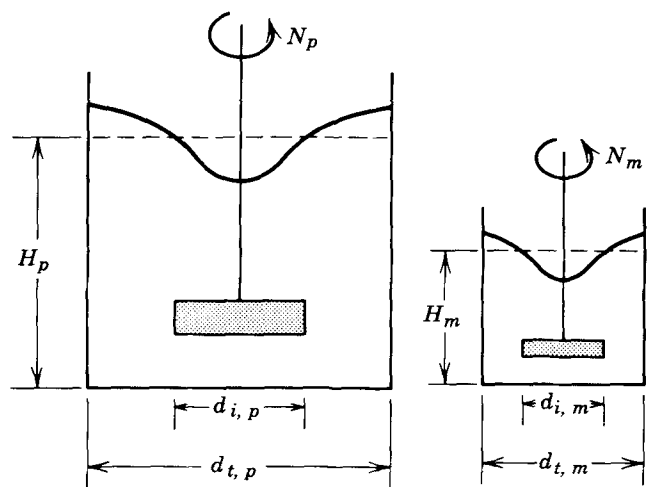


Fig. 13—Modeling of the vortex configuration in a leaching tank.

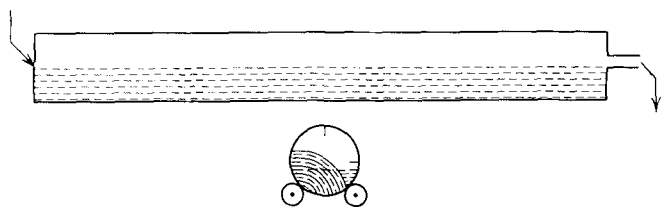


Fig. 14—Model of the continuous-flow reactor for the precipitation of tellurium.

Equation [13] indicates that the fluid used in the model must have a lower kinematic viscosity (μ/ρ) than the leaching solution in the prototype.

Mathematical models which are to be used for design purposes should take into account both the chemical and physical characteristics of the system. Such a model was used in the development of a new process for the treatment of copper refinery slimes.¹¹

One of the important steps in this process was the precipitation of cuprous telluride from the leach solution, by means of metallic copper. Experimental work had shown that the continuance of this reaction depended on the removal of the telluride layer from the surface of the copper particles; this could be achieved by using a rotary drum reactor so that the tumbling of the copper shot bed would be self cleaning.

Chemical rate studies in a rotary batch reactor showed that the precipitation reaction was of first order:

$$\frac{dc}{dt} = k_r c \quad [13]$$

where

c : concentration of tellurium in solution

t : time of reaction

k_r : specific rate constant

For practical reasons, it was decided to use a continuous flow reactor for carrying out the precipitation at the industrial plant. It was therefore necessary to estimate the mixing conditions in such a reactor; as noted earlier, the degree of mixing affects the required residence time of the solution in the reactor.

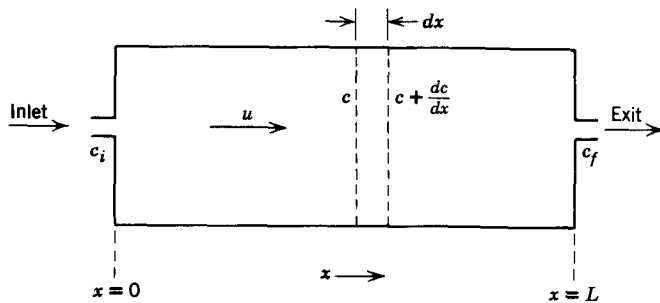


Fig. 15—Material balance over a section of a continuous flow reactor.

To this effect, tracer tests were conducted in a flow model, Fig. 14, under conditions of copper loading, flow, and speed of rotation which simulated the industrial reactor. The concentration-time plots obtained from these tests yielded the value of the Peclet number ($N_{Pe} = 5$) which is a measure of the mixing conditions and is defined as follows:

$$N_{Pe} = \frac{uL}{D_e} \quad [14]$$

where

u : fluid velocity

L : length of reactor

D_e : eddy diffusion coefficient

The mathematical model for the system could be now constructed by expressing the material balance for tellurium in solution over a section element in the reactor, Fig. 15, as follows:

$$D_e \frac{\partial^2 c}{\partial x^2} - u \frac{dc}{dx} = k_r c \quad [15]$$

$$\left[\begin{array}{l} \text{net material} \\ \text{transfer due} \\ \text{to eddy diffusion} \end{array} \right] - \left[\begin{array}{l} \text{net material} \\ \text{transfer due} \\ \text{to bulk flow} \end{array} \right] = \left[\begin{array}{l} \text{material con-} \\ \text{sumed by chemical} \\ \text{reaction} \end{array} \right]$$

The solution of this equation is represented graphically in Fig. 16.¹² The results are plotted in the form of reactor volume required to obtain a certain fractional conversion (x -axis) at different values of chemical rate constant and eddy diffusivity. The solid lines are drawn for various values of the Peclet number while the dotted lines represent the product (chemical rate constant) \times (mean residence time).

In our example, this plot was used to calculate the required volume of reactor and residence time, on the basis of the known values of rate constant, Peclet number, and fractional precipitation of tellurium (as final concentration/initial concentration).

CONCLUSION

It has been attempted to show that the design and development of metallurgical processes need not be done by the trial and error methods of the past. Many

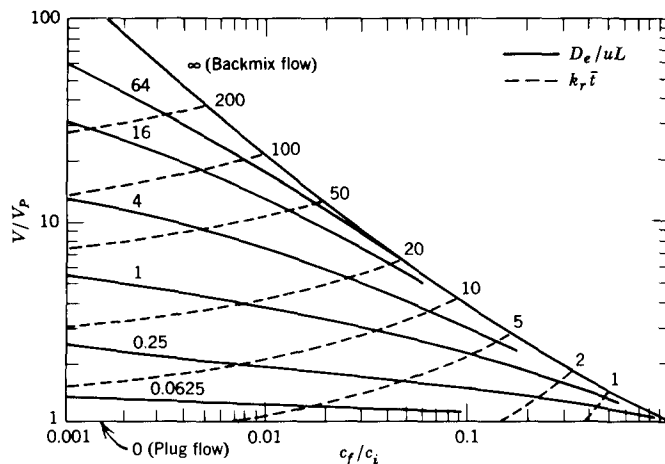


Fig. 16—Comparison of required volumes of real, V and plug flow, V_p , reactors for first-order reactions.¹²

analytical tools have become available through the work of metallurgical and chemical engineers. These tools will be used more extensively as the credibility gap between researchers and operating metallurgists narrows.

It is interesting to note that engineers who trust their lives into the mass of instrumentation of a passenger jet plane, become highly skeptical when a slight degree of sophistication is suggested for their furnaces. On the other hand, this attitude is not helped by researchers who are unwilling to venture to the roof of a reverberatory furnace and see for themselves the problems of installing and maintaining a pyrometer.

The emergence of process metallurgy in the curricula of many metallurgical schools is a welcome sign that the gap is being bridged and that extractive metallurgy is gradually changing from an art to a science.

REFERENCES

1. J. Szekely and N. J. Themelis: *Rate Phenomena in Process Metallurgy*, John Wiley and Sons, N. Y., 1971.
2. N. J. Themelis and P. Spira: *Trans. TMS-AIME*, 1966, vol. 236, p. 821.
3. P. Spira: Noranda Research Centre, private communication, 1968.
4. N. J. Themelis: Strategic Materials Corp. Internal Report, private communication, 1962.
5. H. H. Kellogg: *Trans. TMS-AIME*, 1967, vol. 239, p. 1439.
6. N. J. Themelis and G. C. McKerrow: *Symp. on Advances in Extractive Metallurgy*, Inst. Mining Met., London, Oct. 1971.
7. N. J. Themelis, G. C. McKerrow, P. Tarassoff, and G. D. Hallett: *J. Metals*, 1972, p. 25.
8. C. R. Wilke, M. Eisenberg, and C. W. Tobias: *J. Electrochem. Soc.*, 1953, vol. 100, S13.
9. C. R. Wilke, C. W. Tobias and M. Eisenberg: *Chem. Eng. Prog.*, 1953, vol. 49 p. 663.
10. E. H. Dudgeon, I. R. G. Lowe, Model of the Aerodynamics of the Noranda Process Reactor, Div. of Mech. Eng., National Research Council of Canada, Report No. LTR-GD-11, Dec. 1971.
11. P. H. Jennings, N. J. Themelis, and E. S. Stratigakos: *Can. Met. Quart.*, 1969, vol. 8, p. 281.
12. O. Levenspiel and K. B. Bischoff: *Ind. Eng. Chem.*, 1959, vol 51, p. 1431; 1961, vol. 53, p. 313.