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ESTIMATION OF FROZEN BATH SHAPE IN AN ALUMINUM REDUCTION CELL BY COMPUTER SIMULATION

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Heat transfer from electrolyte and liquid metal to the side wall freeze was studied by measuring frozen bath shape and temperature distribution in a cathode pot. Heat flux entering freeze from liquid metal, in spite of its larger thermal conductivity, was fairly small in comparison with the reasonable value of the heat flux in the electrolyte zone. It suggests that the heat transfer mechanism at freeze surface may be different in these two melts. The shape of freeze was simulated by computer for several cases in solving the differential equation for heat balance considering the freeze surface as a moving boundary.

Introduction

In an aluminum reduction cell, a frozen bath layer (freeze) protects the side wall of the cathode from corrosive electrolyte. This freeze also reduces heat loss from the cathode, and works as a heat sink when the extra power is supplied to the cell. However, when the freeze widely covers the cathode surface, horizontal current arises in the metal layer. The electro-magnetic force due to this current causes strong convection of the metal, which induces its surface oscillation (1) (2) (3). Thus, the freeze profile influences the cell voltage stability and current efficiency (4) (5) in the commercial cells. It is essential for stable cell operation to keep a good freeze profile.

In order to investigate the factors that decide the freeze profile, the measurement of accurate heat transfer coefficients from melts to freeze would be indispensable. These coefficients obtained by several researchers (6) (7) (8) were roughly identical and reasonable in the electrolyte zone. However, the coefficients from metal to freeze did not agree in each work.

In the present investigation, the effective coefficients were determined from the observation of the freeze profile and the temperature distribution in the actual cell. Thus, the mechanism of heat transfer from metal to freeze was clarified, which gave an explanation of the disagreement in the values of the metal zone. By using these results, it became possible to estimate precisely the freeze shape by computer simulation, in which the freeze and the cathode parts were treated by finite difference method, regarding the interface of the melts-freeze as a moving boundary. The automatic determination of the profile could give us more useful informations about the varing cell condition than the studies depending on the fixed freeze profile (9).

Mechanism of heat transfer at freeze surface

Principle

The schematic model of heat transfer from melts to freeze through the boundary layer is shown in Figure 1. As existing fluid flow is very strong in the cell, the temperature is uniform in the bulk and drops in the boundary layer up to liquidus temperature of bath. Thus, the amount of heat entering freeze from these melts can be expressed by the following equations:

$$q_b = h_b(T_b - T_l) = K_f\left(\frac{\partial T}{\partial n}\right)_i \qquad (1)$$

$$q_m = h_m(T_m - T_l) = K_f\left(\frac{\partial T}{\partial n}\right)_i \qquad (2)$$

where q_b, q_m : heat flux density entering freeze from bath or metal
h_b, h_m : heat transfer coefficient from bath or metal to freeze
T_b, T_m : temperature of bath or metal
T_l : liquidus temperature of bath
K_f : thermal conductivity of freeze
n : unit normal, outward is positive
i : point on the interface.

Therefore, the heat transfer coefficients can be determined by knowing the temperature difference between melts and freeze, and the gradients at the boundary. The mechanism of heat transfer can be clarified by comparing the observed coefficient in the actual cell with the value obtained from dimensionless analysis of fluid.

Estimation of heat transfer coefficients

Heat transfer coefficients, h_b and h_m, are expressed as follows from the equations 1 and 2:

$$h_b = \frac{q_b}{T_b - T_l} = \frac{K_f(\frac{\partial T}{\partial n})_i}{\Delta T_b} \qquad (1')$$

$$h_m = \frac{q_m}{T_m - T_l} = \frac{K_f(\frac{\partial T}{\partial n})_i}{\Delta T_m} \qquad (2')$$

Temperature of both melts, T_b and T_m, can be measured in the actual cell. Liquidus temperature, T_l, is estimated from the bath composition. However, these temperatures vary with changing cell condition. So, in the present work, mean temperature difference over extended periods of cell operation, 15°C, was appropriately adopted as ΔT_b and ΔT_m. The temperature gradient at the boundary was obtained from the calculation of temperature distribution by finite element method. The necessary boundary conditions, such as freeze profile and boundary temperature, were obtained from the measurements. The freeze surface was regarded as liquidus temperature of bath. Figure 2 shows the freeze divided into triangular elements and temperature distribution for three cases. The heat transfer coefficients were calculated with respects to each element along the freeze surface as shown in Figure 3. The coefficients obtained for the bath zone are almost constant along the freeze surface and roughly equal for three cases. However, in the metal zone, in spite of its larger thermal conductivity, the coefficients are fairly small in comparison with that in the bath zone and vary along the freeze surface. These coefficients are compared with the values by other investigators (6) (7) in Table I. The agreement of the values is good for the bath zone, but extremely poor for the metal zone.

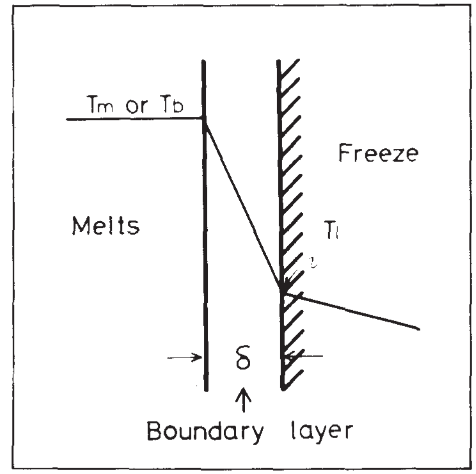
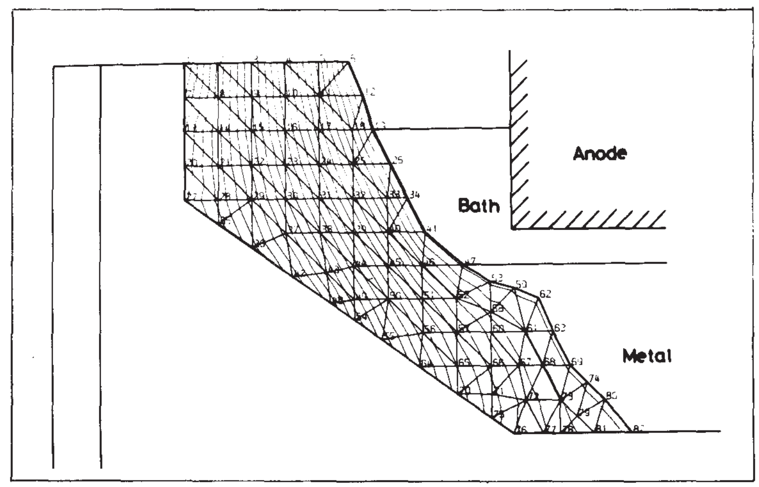


Figure 1. Heat transfer from melts(bath and metal) to freeze



2. Freeze profile divided into triangular elements and temperature distribution for three cases, (a) (b) (c).
Isotherms are taken as 25 °C intervals.

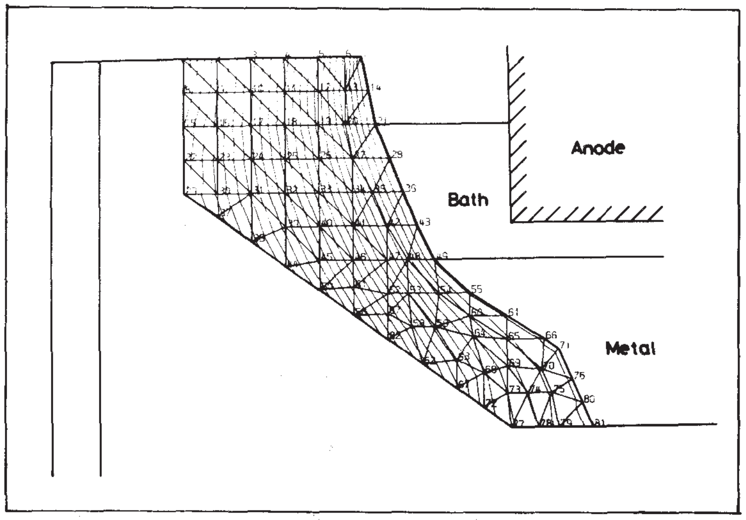


Figure 2-b.

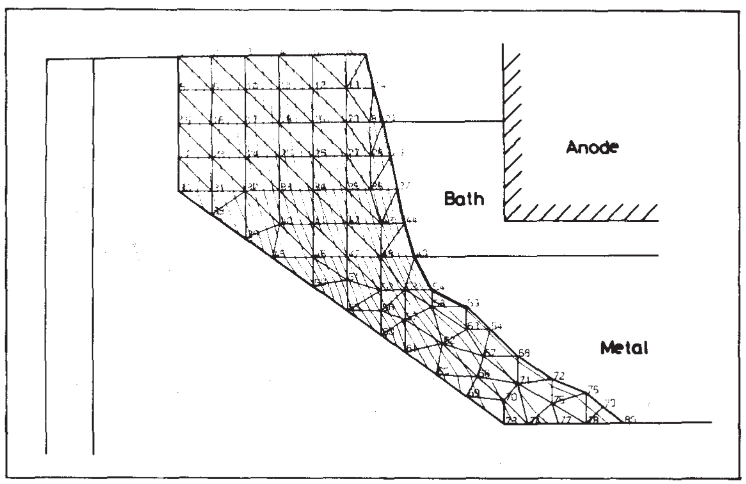


Figure 2-c

Figure 2. Freeze profile divided into triangular elements and temperature distribution for three cases (a) (b) (c). Isotherms are taken as 25 °C intervals.

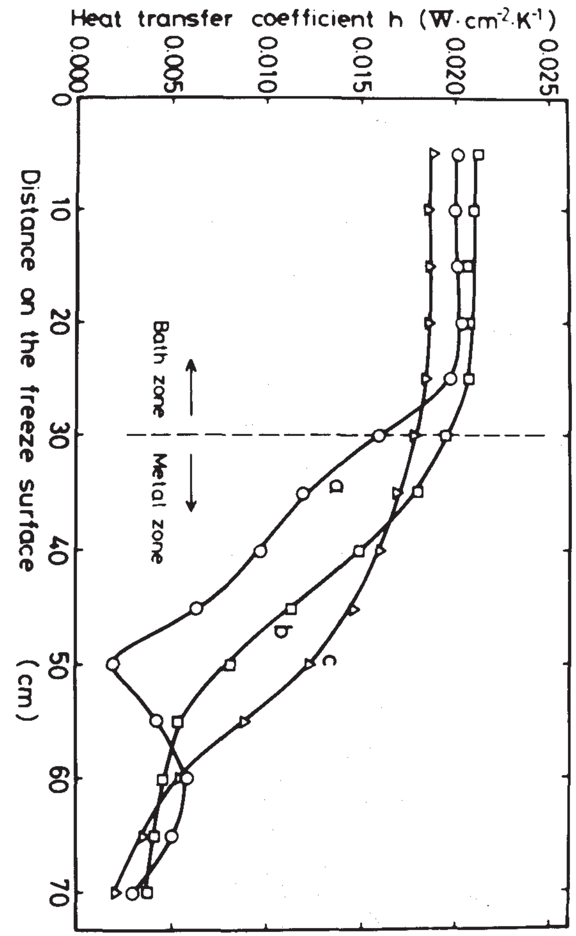


Figure 3. Heat transfer coefficients from melts to freeze surface calculated along its surface in the side feed cell.

Table I Heat transfer coefficients from melts to freeze

($W\ cm^{-2}\ K^{-1}$)

	h_b	h_m
Present work	2.0×10^{-2}	$2.0 \times 10^{-3} - 1.5 \times 10^{-2}$ *1 4.0×10^{-2} *2
Haupin (6)	3.7×10^{-2} *3,4	1.5×10^{-1} *3 1.1×10^{-1} *4
Arai (7)	$1.7 - 2.9 \times 10^{-2}$	$1.2 - 2.3 \times 10^{-2}$

*1 The value of effective heat transfer coefficient obtained in the side feed cell.
*2 The value of true heat transfer coefficient.
*3 The value calculated from dimensionless equation.
*4 The value obtained from the measurement in the cell.

Heat transfer at metal-freeze interface

The heat transfer through the metal boundary layer was characterized by its extremely small coefficient and the dependence on the location. The former should be attributed to the small heat flux, the amount of which, however, is thought to be correct because of its strict estimation. While, as regards the coefficient itself, it is difficult to think that the large value obtained from theoretical order estimation is quite incorrect. The introduction of the bath film between metal and freeze by Haupin (6) can never explain the large difference. Therefore, it is reasonable to consider that the actual ΔT_m is far smaller than the value taken in the estimation. The temperature of freeze surface should be nearly equal to the metal temperature. An explanation is as follows.

When the large amount of alumina is fed into the bath by side breaking, undissolved alumina would become freeze or sludge in the metal pad (8), and the freeze in the metal zone comes to contain 15-30 % alumina. The equilibrium between the freeze and the bath film on it should be treated as the binary system of cryolite and alumina (10) shown in Figure 4. If the temperature of the freeze surface is equal to T_l, the bath film in contact with that should have the composition of C_l. When much amount of heat flux due to large coefficient, h_m, melts the surface, alumina content of this composition increases along the liquidus curve under the condition that the renewal of the bath film with bulk is very slow. Thus, T_l rises to T_l', nearly equal to the metal temperature of T_m. T_l' may be a certain value depending on the alumina concentration. As a result, heat flux goes down and stable profile is

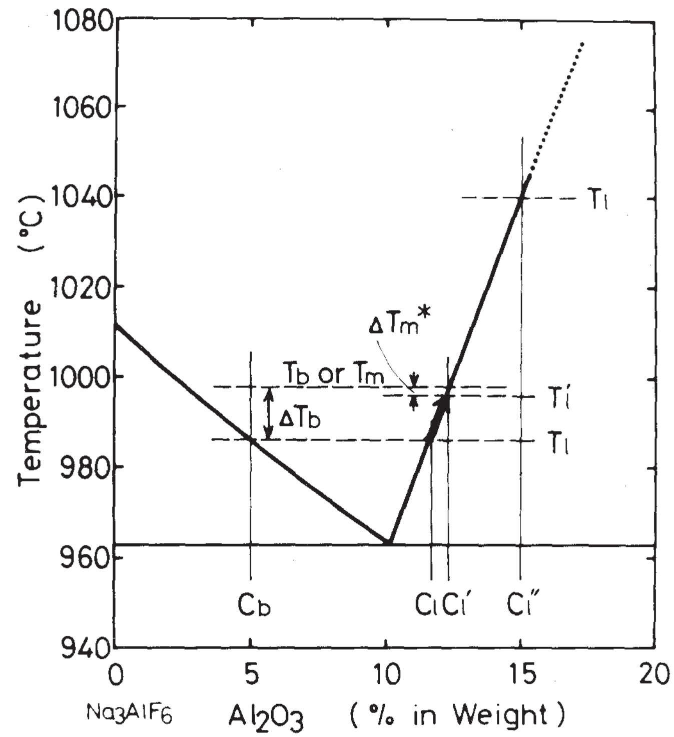


Figure 4. The phase diagram of Na_3ALF_6 - AL_2O_3 (10):

C_b, C_l'' : the composition of bath and freeze
C_l : the composition of bath film which should be held, if the freeze surface is kept at T_l
C_l' : the actual composition in the bath film between metal and freeze
T_l, T_l' : the liquidus temperature of bath and bath film
ΔT_b : the temperature difference between bath and freeze
ΔT_m^* : the actual temperature difference between metal and freeze.

attained in the metal zone. It is, therefore, sure that the freeze profile in the metal layer depends essentialy on the alumina feed system. The small coefficient from metal to freeze obtained for side feed cell is hereafter referred to as effective heat transfer coefficient with the sign of h_m^*.

The similar analysis for freeze under the condition that no alumina is fed on its surface was carried out to get the true coefficient, h_m. The value of h_m, obtained as 0.04 ($W\ cm^{-2}\ K^{-1}$) from that experiment, was still small in comparison with that calculated from dimensionless equation as shown in Table I (6). The reason may be due to the thermal resistance of the bath film between metal and freeze. Its thickness estimated from that value is about 1 mm.

Computer simulation of freeze profile

Treatment of metal-freeze boundary and application of heat transfer coefficient

It has become obvious that the freeze in the metal zone is not in the state of thermal and mass equilibrium for side feed cells. Nevertheless, it is necessary and reasonable to use the effective heat transfer coefficient, h_m^*, instead of the small temperature difference, ΔT_m^*, for simulating the actual heat flux and the correct profile. The value of h_m^* can be selected from the range of about 0.002-0.015 ($W\ cm^{-2}\ K^{-1}$) at each metal level. In case of simulating the freeze plofile under the condition that alumina is fed from the center surface of the cell, the true coefficient, h_m, can be chosen, and the value is 0.04 ($W\ cm^{-2}\ K^{-1}$).

Computer program

In steady state, electrical potential and temperature in a cathode can be obtained from the following two basic equations:

$$\mathrm{div}\ \mathbf{i} = 0 \tag{3}$$

$$\mathrm{div}\ \varphi + q_j = 0 \tag{4}$$

where $\mathbf{i}$: current density vector
φ : heat flux vector
q_j : Joule heat.

Boundary condition becomes as follows:

Melts(bath and metal)-freeze interface are treated in equation 1, 2.

Boundary where melts directly contact with cathode carbon:

$$q_b' = h_b(T_b - T_s) \tag{5}$$

$$q_m' = h_m(T_m - T_s) \tag{6}$$

where q_b', q_m' : heat flux density entering cathode from melts
T_s : temperature of cathode carbon surface.

Radiative and convective boundary:

$$q_w=1.16\times10^{-4}a(T_w-T_a)^{1.25}+5.66\times10^{-12}k((T_w+273)^4-(T_a+273)^4) \tag{7}$$

where q_w : heat flux density dispersing from cathode shell
T_w : temperature of cathode shell
T_a : ambient temperature
a : convection coefficient
k : emissivity.

These equations were solved by the finite difference method. The accuracy of the simulation depends on the number of the lattice points in a given area. However, calculation time is approximately proportional to the square of the number of the points. So, the program was separately constructed for freeze and cathode to decrease the total number of the points; that is, more fine division was applied to freeze section. These two programs were alternately solved. The flow chart of the program is shown in Figure 5. The freeze surface was modified by the program to become the liquidus temperature of bath. The calculation was repeated until the movement of freeze surface and the temperature fluctuation of the points in freeze and cathode became sufficiently small.

Application

The simulation was tried on two cases for the same type cathode. The heat transfer coefficient, h_b, was taken as 0.02 ($W\ cm^{-2}\ K^{-1}$). The liquidus temperature of bath was 955°C, and the temperature of bath and metal were 970 °C. First is the case using the effective small coefficient, h_m^*= 0.003 ($W\ cm^{-2}\ K^{-1}$), in the metal layer as shown in Figure 6. The resulted profile is satisfactory, which corresponds to the side feed cell. In the second case, the true coefficient, h_m= 0.04 ($W\ cm^{-2}\ K^{-1}$), was employed as shown in Figure 7. The freeze is not formed in the metal zone. From these results, it can be understood that the freeze in the metal zone disappears and the heat loss from the cathode markedly increases, unless the alumina is fed on it. Thus, it is concluded that the heat design of the cell is highly dependent on the alumina feed system.

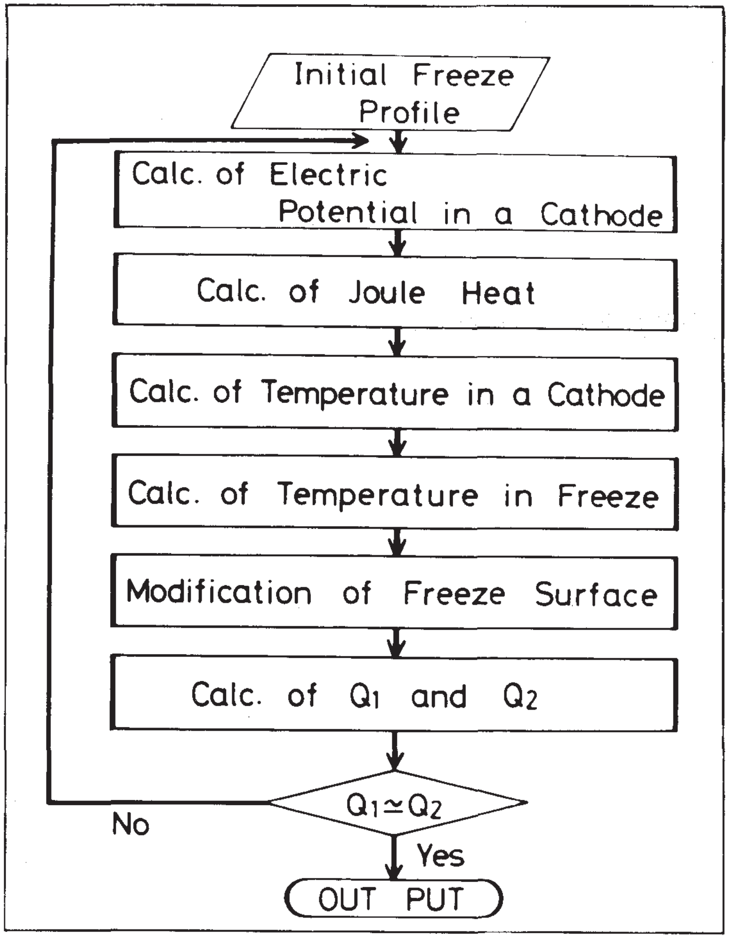
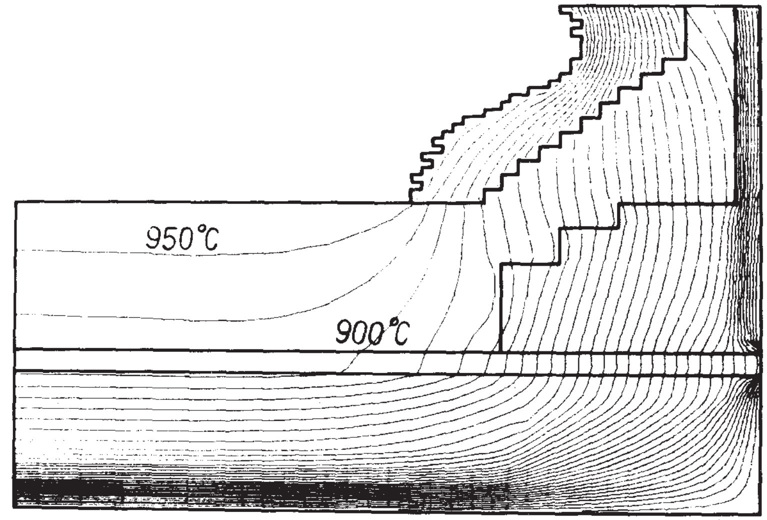
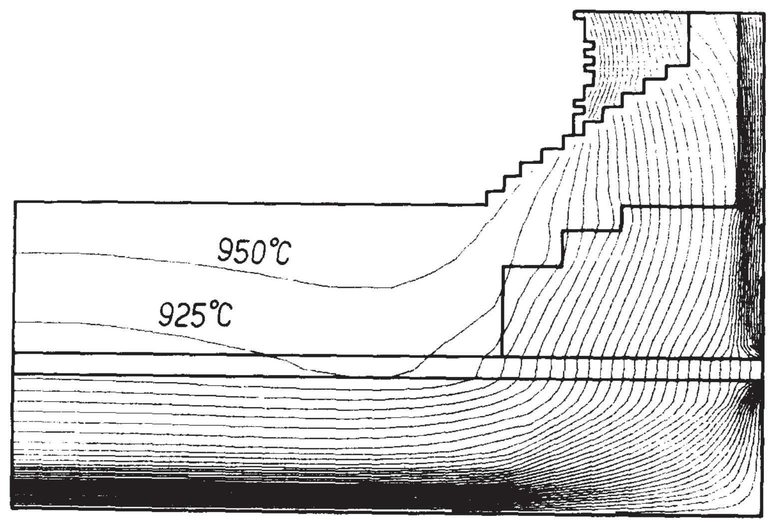


Figure 5. The flow chart of the program for freeze profile simulation.
Q_1, Q_2 show the heat flux entering freeze and cathode from melts, and dispersing from cathode shell, respectively.



6. The freeze profile and temperature distribution in a cathode, when the effective heat transfer coefficient, h_m^*, is used.
T_b, T_m= 970 °C T_1= 955 °C



7. The freeze profile and temperature distribution in a cathode, when the true heat transfer coefficient, h_m, is used.
T_b, T_m= 970°C T_1= 955 °C

Summary

From the observation of heat transfer at metal-freeze interface and computer simulation for freeze profile, the following conclusions were given.

In the side feed cell, the freeze in the metal zone is formed by alumina feed and remains stable because of its slow dissolution to the bulk bath. The metal-freeze interface may be under the situation that the dissolution is restricted due to slow renewal of the bath film and alumina rich freeze which raises the liquidus temperature of the film. That is the reason why the measurement gives the extremely small heat transfer coefficient, h_m^*, in the metal zone. The coefficient, h_m, measured without the disturbance of alumina feed showed a resonable value larger than h_m^*.

We succeeded in simulating the freeze profile, regarding its surface as a moving boundary. For the above purpose, it was proper to use the different heat transfer coefficient in the metal zone, corresponding to the various alumina feed systems. The program made a great cotribution to the cell design and the study of cell operation parameters.

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