

**METAL PAD VELOCITY MEASUREMENTS IN PREBAKE  
AND SODERBERG REDUCTION CELLS**

A. T. Tabereaux and R. B. Hester

Reduction Laboratory  
Reynolds Metals Company  
P.O. Box 1200  
Sheffield, Alabama 35660

Calibration curves have been established for the relationship between measured weight loss per unit length of iron rod immersed and rotated in molten aluminum metal over the practical range of velocities experienced in aluminum reduction cells. The effect of metal temperature, iron content, alloy content of the iron rod, and rod size on the rate of dissolution have been determined. The rate of dissolution of the iron rod can be related directly to an empirical convection mass transfer equation.

Results of measurements for prebake and Soderberg reduction cells suggest basic information and relationships between flow patterns, metal pad velocities, and cell design.

Introduction

The method of measuring metal velocities in aluminum reduction cells developed by Johnson (1) in which iron rods are inserted vertically into the metal pad has proven to be a valuable research technique. The method yields both the magnitude and direction of metal flow at each rod location.

However, the empirically derived relationship used to calculate metal pad velocities in aluminum reduction cells was based on calibrations made in the temperature range 758 to 843°C in metal tapping crucibles, well below those found in reduction cells. The mass transfer relationship has been refined with metal calibration temperatures in the range 950 to 965°C.

Experimental Procedure

Metal calibration experiments were conducted in a gas fired Hausfeld furnace with temperature controller. The furnace has a suspended clay-graphite crucible of the dimensions, 16 inches ID by 26 inches deep. The furnace contained about 200 pounds of aluminum metal at  $\pm 3^\circ\text{C}$  during calibration experiments.

The stirring apparatus shown in Figure 1 consisted of a rotating arm or spindle with two iron rods attached at different radii. The spindle rotated 3/8-inch diameter rods at a specified diameter by a 1/4-hp motor with a variable speed controller. The rotation speed was checked during each calibration run with a digital contact tachometer. To ensure that the metal pool in the crucible was not moving and affecting the calibration results, metal rods were often suspended stationary in the metal pool during the stirring experiments. Results from these stationary rods indicated the metal pool was not being stirred, however more recent data, Figure 13, where rods were rotated individually at a larger radius do indicate stirring of the metal pool was occurring at velocities above 14 cm/sec, Figure 2.

After each set of calibration runs, the iron rods were cleaned of adhering aluminum metal by immersion in a caustic solution for over 24 hours. A uniform section of each rod below the metal immersion line was cut and weighed to determine the weight loss.

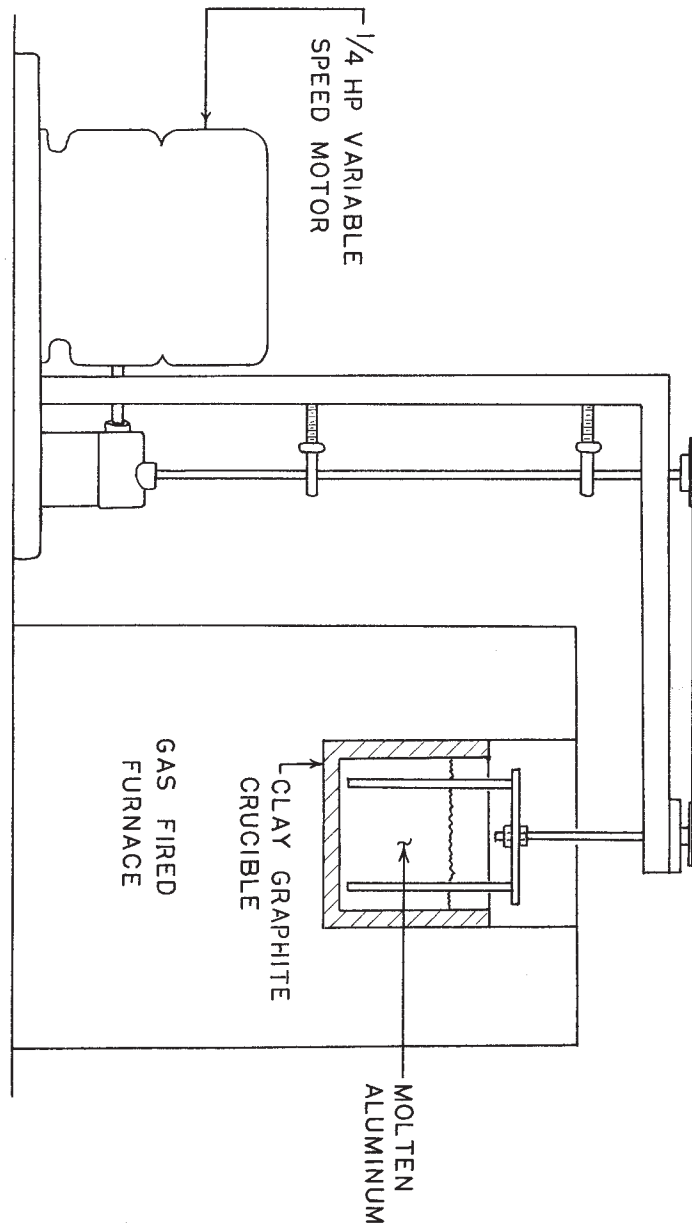
The chemistry of the iron rods used for the calibration experiments was determined by spectrographic analysis by an independent metallurgical laboratory.

Equation of Mass Transfer

The correlative equation of mass transfer for 3/8-inch diameter vertical iron rods placed in a stream of molten aluminum established by Johnson has the general form (1):

$$\text{Nu} = A + B \text{Re}^n \text{Sc}^m \quad (1)$$

FIGURE 1. CALIBRATION APPARATUS FOR METAL VELOCITIES.



where:

$$Nu = \text{Nusselt number for mass transfer} = \frac{k\bar{d}}{D}$$

$$Re = \text{Reynolds number} = \frac{\rho U \bar{d}}{\mu}$$

$$Sc = \text{Schmidt number} = \frac{\mu}{\rho D}$$

A, B, n, m = Constants

and,

k = mass transfer coefficient (cm/sec)

$\bar{d}$  = average rod diameter (cm)

D = diffusivity of iron in aluminum (cm<sup>2</sup>/sec)

$\rho$  = density of molten aluminum (g/cm<sup>3</sup>)

$\mu$  = kinematic viscosity of molten aluminum (g/cm-sec)

U = metal velocity (cm/sec)

Assuming that the dissolution of solid metal is controlled by mass transfer in molten metal, the mass transfer coefficient, k, is defined by the expression:

$$k = \frac{D_0 - D_f}{2t \ln \left[ 1 + \frac{x_0 - x_b}{1 - x_0} \right]} \quad (2)$$

where:  $D_0$  = initial rod diameter (cm).

$D_f$  = final rod diameter (cm).

t = time of immersion in metal pad (sec).

$x_0$  = equilibrium mole fraction of iron in molten aluminum at rod surface.

$x_b$  = mole fraction of iron in bulk metal.

The final rod diameter,  $D_f$ , is calculated from the final rod weight,  $W_f$ :

$$D_f = 2 \sqrt{\frac{W_f}{\rho L}} \quad (3)$$

where:  $W_f$  = final rod weight (gm).

$\rho$  = density of iron rod (gm/cm<sup>3</sup>).

L = Length of rod immersion in metal (cm).

The constants B, n, and m in equation (1) were determined by a computer linear regression analysis (SAS General Linear Model Procedure) from calibration experiments. Zero velocity metal flow data were used to determine the constant A. The mass transfer correlation with redefined constants for calibration data measured within the temperature range of 950-965°C is:

$$Nu = 3.57 + 2.8 \times 10^{-6} Re^{1.06} Sc^{2.87} \quad (4)$$

The results of the iron rod measurements used to define the velocity, U, as a function of the mass transfer coefficient, k, are shown in Figures 2 and 13. These are several interesting trends apparent from these results:

- There is a linear relationship between metal velocity and the mass transfer coefficient.
- The slope of the velocity - mass transfer relationship is about 2.6 times higher than reported by Johnson.
- The apparent change in slope above 14 cm/sec in Figure 2 is attributed to stirring of the metal pool. More recent data, Figure 13, where rods were rotated individually at larger radius to minimize stirring, indicate the slope is uniform over the entire range of measurable velocities.
- At velocities above 24 cm/sec, the iron rod immersed in the metal was completely dissolved within the 10-minute test period.

The drag force (coefficient) on the cylinder, pressure resulting from a low pressure region on the rear of the cylinder, is of the same magnitude at Reynolds' numbers in the range of  $10^3$  to  $10^5$ . At Reynolds' numbers greater than  $10^5$ , the boundary-layer flow becomes completely turbulent with a change in the drag coefficient curve (2). However, the calibration velocities have Reynolds' numbers shown in Table I which are well below that point.

Table I. Metal Velocity-Reynolds' Number Relationship

Velocity cm/sec	Reynolds' Number	Velocity cm/sec	Reynolds' Number
4.0	1041	12.8	2952
5.0	1273	14.0	3169
5.9	1477	14.6	3056
6.9	1704	16.0	3613
8.0	1957	17.0	3608
9.0	2115	18.4	4173
9.7	2204	20.0	4371
12.0	2771		

Basic Relationships

The effects of several experimental parameters were investigated to determine their effect on the measured metal flow velocity-mass transfer relationship.

Iron Alloy Rods

Increased levels of iron alloy in the rods were studied. The chemical compositions of the various iron rods used in the calibration experiments at 950°C are shown in Table II.

Table II. Iron Rod Chemical Composition

	Pure*	1008	1010	1018	4150
Carbon, %	0.02	0.06	0.11	0.24	0.48
Silicon, %	0.024	0.12	0.06	0.06	0.23
Manganese, %	0.17	0.32	0.39	0.66	0.89
Phosphorus, %	0.002	0.004	0.009	0.003	0.007
Sulphur, %	0.013	0.017	0.026	0.017	0.075
Nickel, %	0.08	0.07	0.07	0.04	0.20
Chromium, %	0.04	0.02	0.04	0.04	0.96
Copper, %	0.06	0.14	0.12	0.05	0.15
Molybdenum, %	NA	0.02	0.02	0.02	0.20

\*Commercially pure unalloyed iron.

The results of the calibration tests with various iron alloys are shown in Table III. The presence of any alloy content above that present in the commercially pure iron has a dramatic impact on the dissolution of the iron rod in molten aluminum. Iron rods with increased levels of carbon, silicon, and manganese produced poor results. The dissolution of the alloyed rods was not uniform and exhibited excessive pitting. Only commercially pure unalloyed iron rods with low carbon content, less than 0.02%, can provide the reproducibility necessary for metal flow experiments.

The dissolution of the iron alloy rods in molten aluminum is controlled by the chemical reaction process at iron/alloy layer interface or diffusion process of iron in an alloy layer (3).

Table III. Weight Loss Per Unit Length Iron Alloy Rods

Iron Rod	Velocity cm/sec	Weight Loss, g/cm	Velocity cm/sec	Weight Loss, g/cm	Velocity cm/sec	Weight Loss, g/cm
Pure*	5.1	2.60	15.95	3.86	23.94	5.39
1008	5.1	0.08	15.95	1.38	23.94	0.70
1010	5.1	NA	15.95	2.30	23.94	2.43
1018	5.1	1.39	15.95	2.44	23.94	NA
1020	5.1	1.28	15.95	NA	23.94	2.25
4150	5.1	0	15.95	NA	23.94	0

\* Commercially pure unalloyed iron.

Rod Diameter Size

Iron rods of diameter sizes 3/8, 1/2, and 5/8 inches were investigated in calibration experiments to determine the effect of rod diameter size on the mass transfer correlation. The results for 1/2-inch diameter rods are shown in Figure 3. Similarly to the 3/8-inch rods, the 1/2-inch rods also exhibit a linear relationship between metal velocity and mass transfer coefficient and can be calibrated for plant measurements in operating reduction cells. Test results with 5/8-inch rods indicate that they can also be calibrated for metal velocity measurements.

Iron Content

The iron content in the 200 pounds aluminum metal in the calibration furnace increased after each run. The effect of the higher iron levels in the metal upon the mass transfer correlation is shown in Figure 4. There is a 0.02-0.04 x 10<sup>-3</sup> cm/sec decrease in the mass transfer coefficient per 0.1 w/o increase in the iron content. The iron content in the metal pad of most aluminum reduction cells is in the range of 0.05 to 0.15 w/o.

Rod Immersion Time

An important parameter in both laboratory and plant tests is the rod immersion time in the metal flow. Figure 5 shows the increase in the mass transfer coefficient with respect to the rod immersion time. The mass transfer coefficient increases at a rate of 12 to 19 x 10<sup>-3</sup> cm/sec per minute immersion time. It is necessary to use the same immersion time in plant test as established during the calibration runs.

Metal Temperature

The results of varying the metal temperature on the mass transfer correlation are shown in Figure 6. The mass transfer coefficient was found to increase at a linear rate of 89 to 127 x 10<sup>-3</sup> cm/sec per 100 degree centigrade increase in metal temperature during calibration tests. It is evident that the metal temperature has a significant impact on the metal

FIGURE 2. EXPERIMENTAL DATA FOR CORRELATION BETWEEN MASS TRANSFER COEFFICIENT AND VELOCITY FOR 3/8 IN. DIA. RODS.

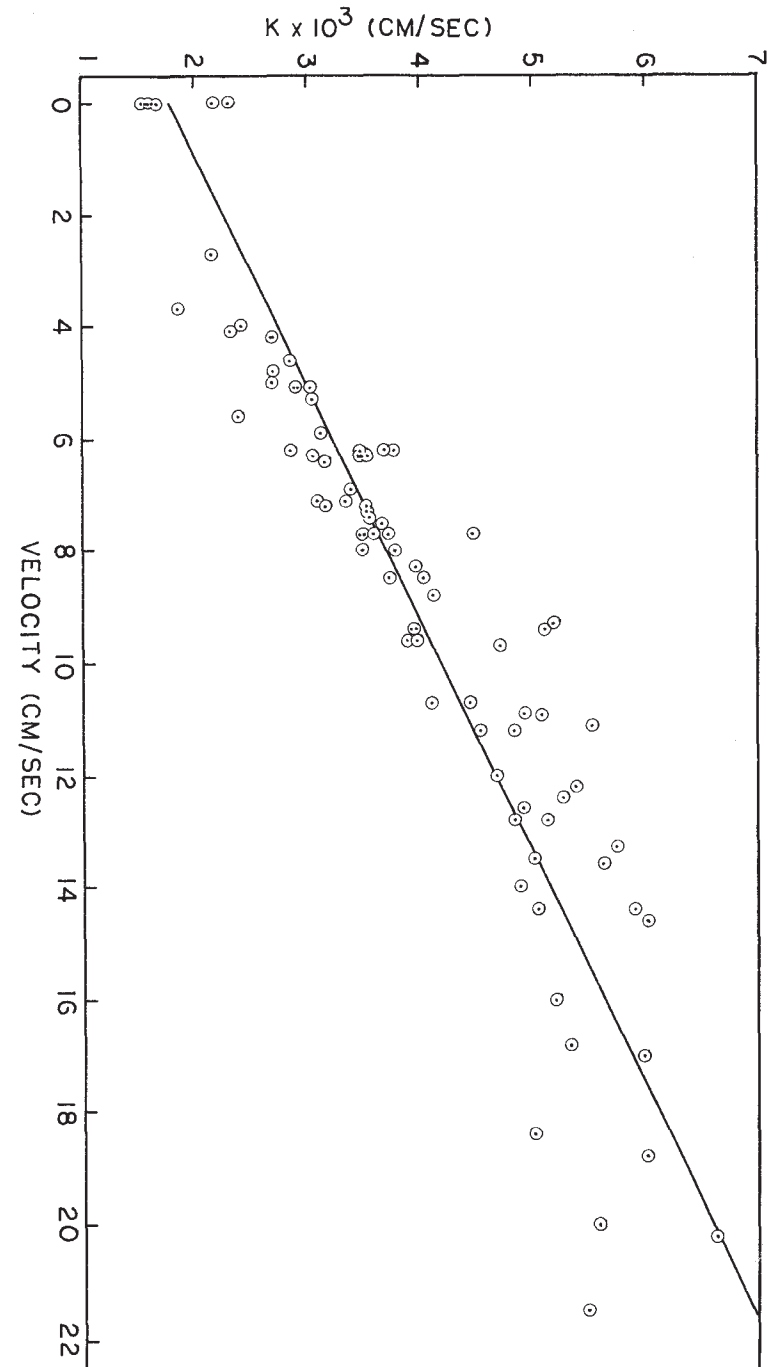


FIGURE 3. EXPERIMENTAL DATA FOR CORRELATION BETWEEN MASS TRANSFER COEFFICIENT AND VELOCITY FOR 1/2 IN. DIA. RODS.

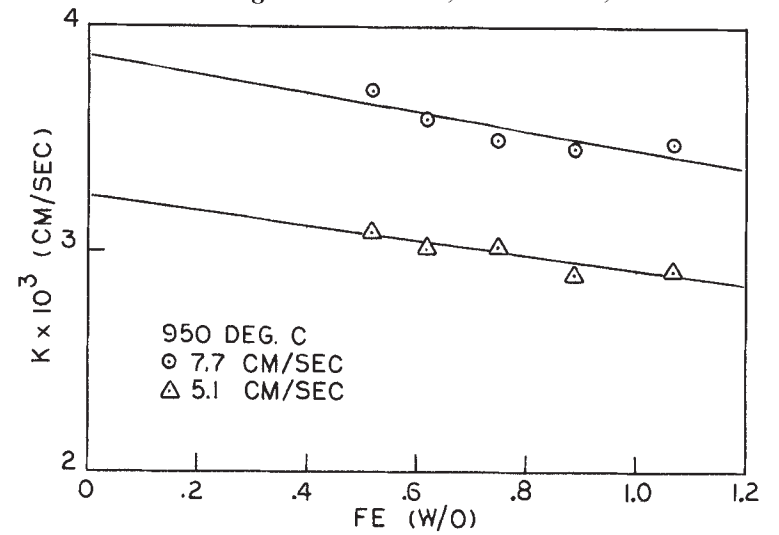
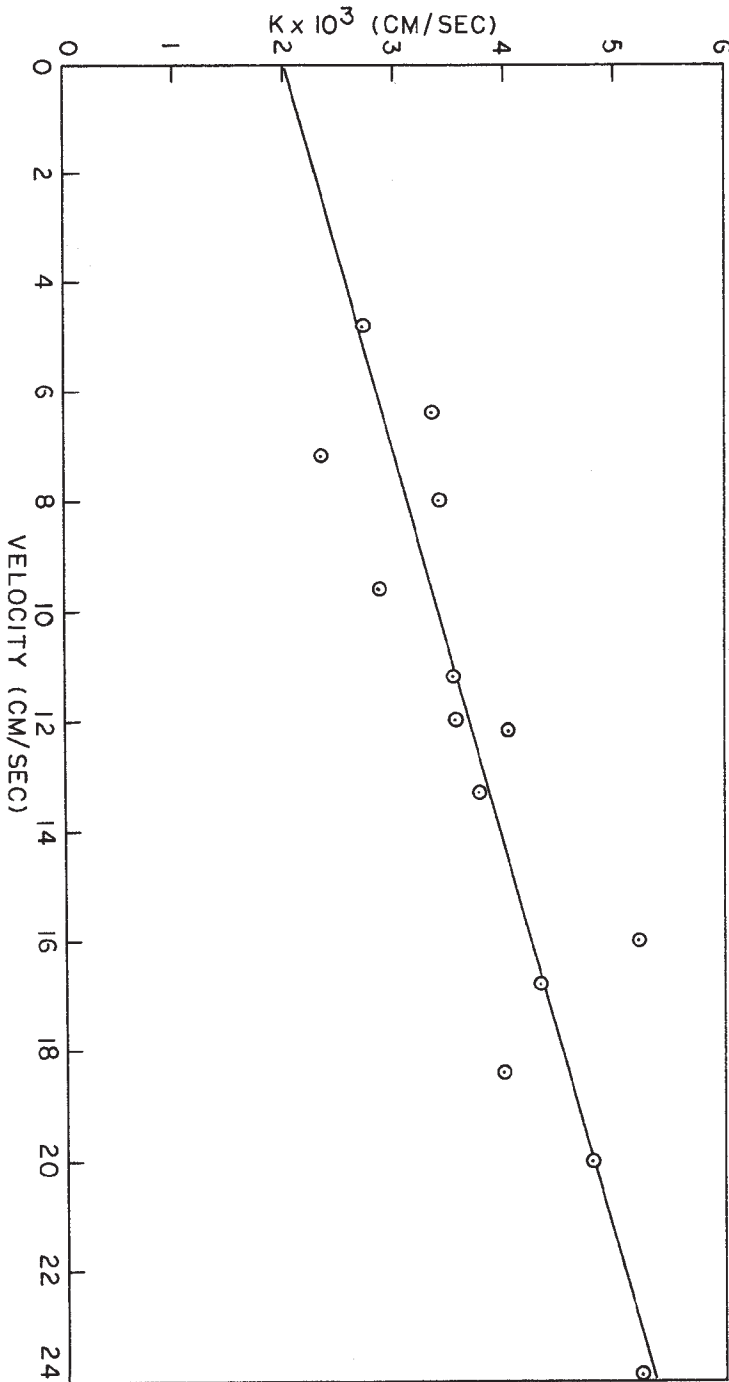


FIG. 4. MASS TRANSFER COEFFICIENT VS. IRON CONTENT IN THE ALUMINUM.

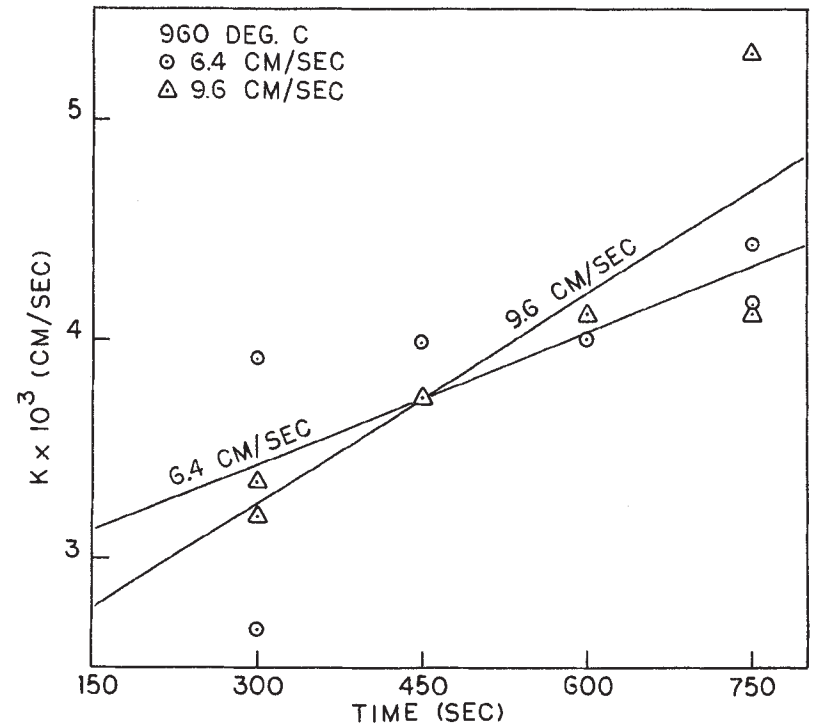


FIG. 5. MASS TRANSFER COEFFICIENT VS. IMMERSION TIME.

FIGURE 6. MASS TRANSFER COEFFICIENT VS. TEMPERATURE .

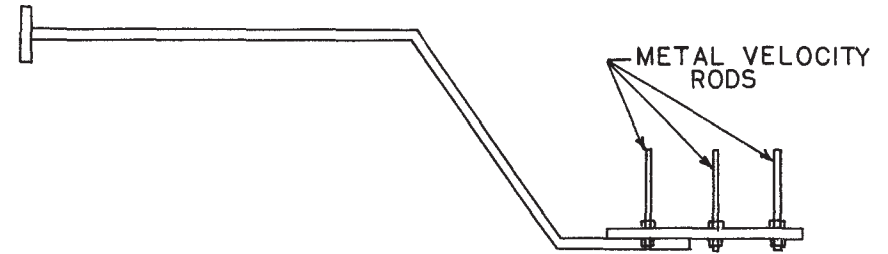
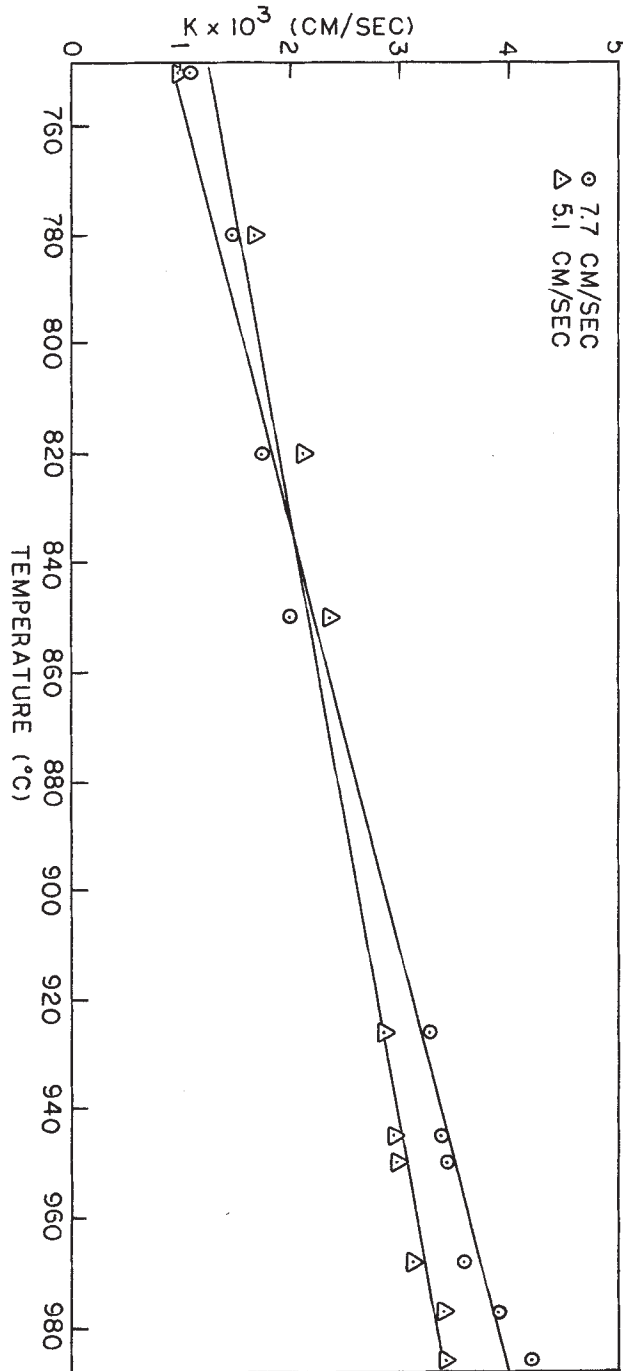


FIGURE 7. SPECIAL METAL ROD HOLDER.

dissolution rate. Metal velocity calibration runs should be conducted at the same temperature range as measured in the reduction cell metal pad.

Reduction Cell Measurements

A number of metal velocity measurements have been made in both Soderberg and prebake reduction cells. The rods were inserted consecutively through small holes in the crust and left in the metal for 10 minutes. The rods were removed in the reverse order. Prebake cell measurements were generally made at locations between the anodes and the cell sidewall and at the ends of the cell. At times measurements were also made through holes drilled in the anodes.

Metal velocity measurements in Soderberg cells were found to be more difficult due to the frozen side ledges and muck near the periphery of the anode. A special rod holder made to measure metal pad velocities simultaneous at three locations under the Soderberg anode is shown in Figure 7. Three rods were inserted into holes in a plate welded to the rod holder and attached with bolts. The rod holder with three rods attached is maneuvered into position under the anode with the plate resting on the cathode cavity floor and the rods pointing upward in the metal pad. Upon removal from the cell metal pad an orientation mark is made on the three rods and they are cut off near the plate with a bolt cutter. It worked especially well in measurements in VS Soderberg cells.

VS Soderberg Cell

Results of metal pad velocity measurements in a 110 kA VS Soderberg cell (end-to-end) are shown in Figure 8. The special Soderberg rod holder was used to obtain measurements at six locations around the anode and three points at each location. The following trends in metal pad circulation pattern are evident:

- One large clockwise metal flow pool.
- Metal velocities were very uniform near the center of the cell.
- The highest and lowest metal velocities occurred near the corners of the cell.

HS Soderberg Cell

Metal pad velocities measured at various locations in a 100 kA HS Soderberg cell (end-to-end) are shown in Figure 9. The following trends in the metal pad circulation pattern are evident:

- Confirmed by metal velocity measurements in other cells, there is one major counterclockwise metal flow pool.
- Anomalies or differing metal flows at some locations were thought to be caused by an excessive accumulation of muck in the cathode cavity of the cell.

End Riser Prebake Cells

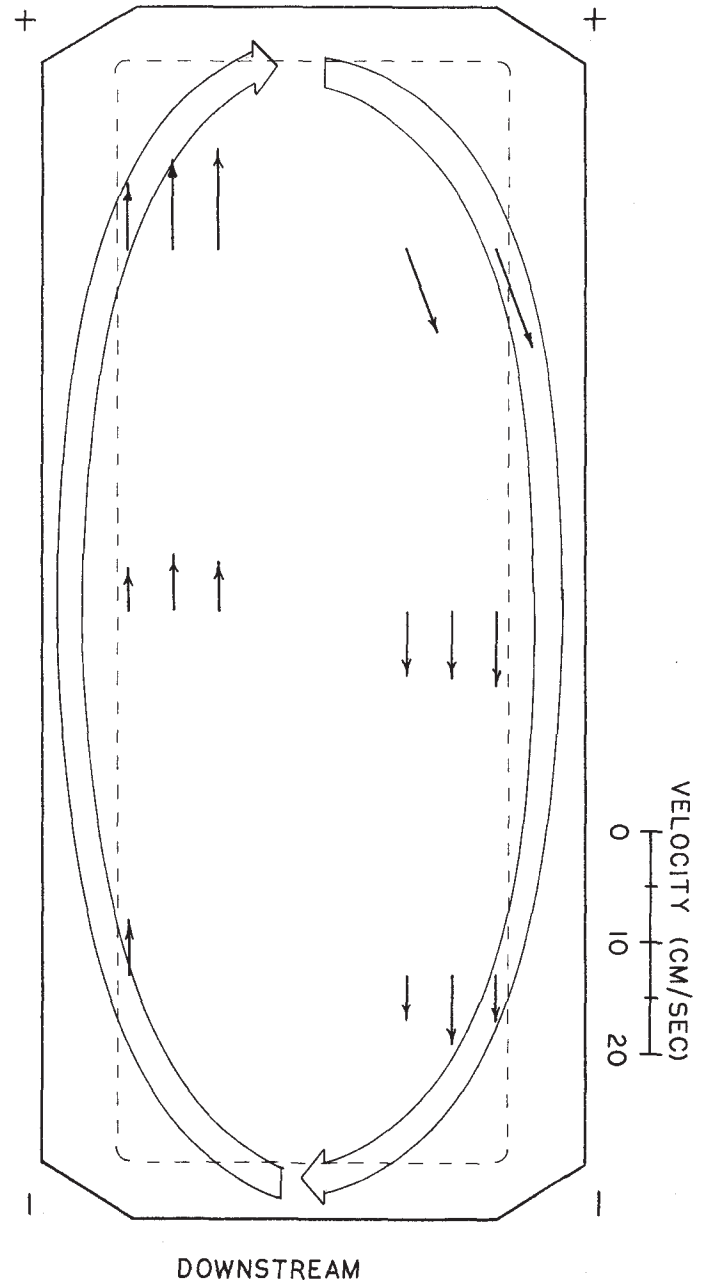
150 kA Prebake Cell. Results of metal velocity measurements in a 150 kA prebake cell with end anode riser bus are shown in Figure 10. The following trends in metal pad circulation patterns are evident:

- Two major metal circulation pools. The metal flows from the center of the cell toward the ends of the cell on the downstream side of the cell. The metal circulates around the ends of the cell toward sidewall on the upstream side of the cell.
- The highest metal pad velocities are generally found on the upstream side of the cell as the metal approaches the sidewall after passing around the ends of the cells. The lowest metal pad velocities are generally found in the center of the cell as the two metal pools converge.

76 kA Prebake Cell. Results of metal velocity measurements in a 76 kA prebake cell with end anode riser bus are shown in Figure 11. The following trends in metal pad circulation patterns are evident:

- Four major metal circulation pools. In the center work area of the cell, the metal flows to both ends of the cell. At the ends of the cell, the metal circulates around the ends toward the center of the cell on both the upstream and downstream sides of the cell.

FIGURE 8. METAL FLOW VELOCITIES IN 110 KA V.S. SODERBERG CELL.



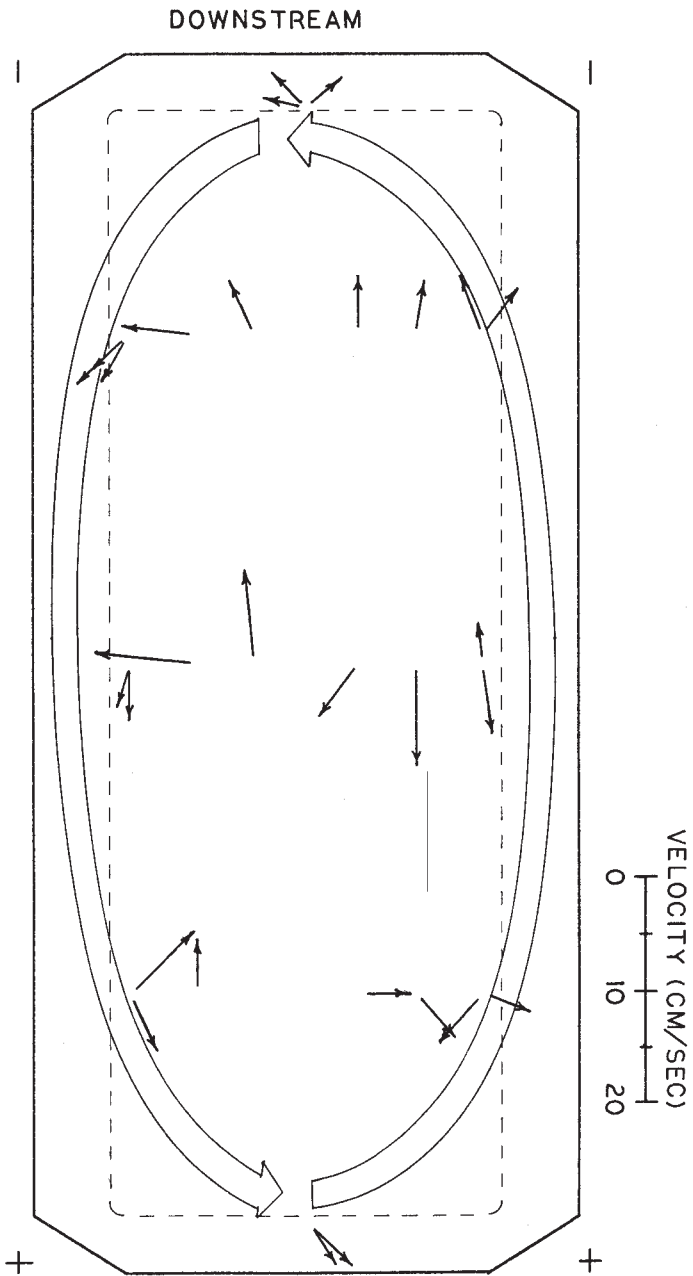


FIGURE 9. METAL FLOW VELOCITIES IN 100 KA H.S. SODERBERG CELL.

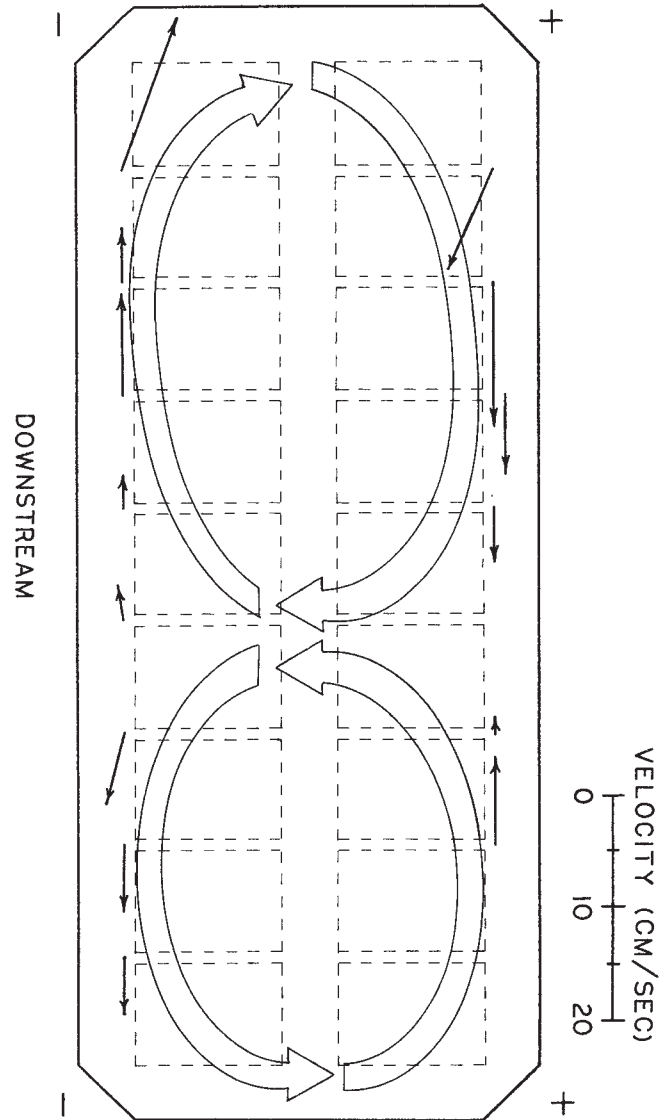


FIGURE 10. METAL FLOW VELOCITIES IN 150 KA END RISER PREBAKE CELL.



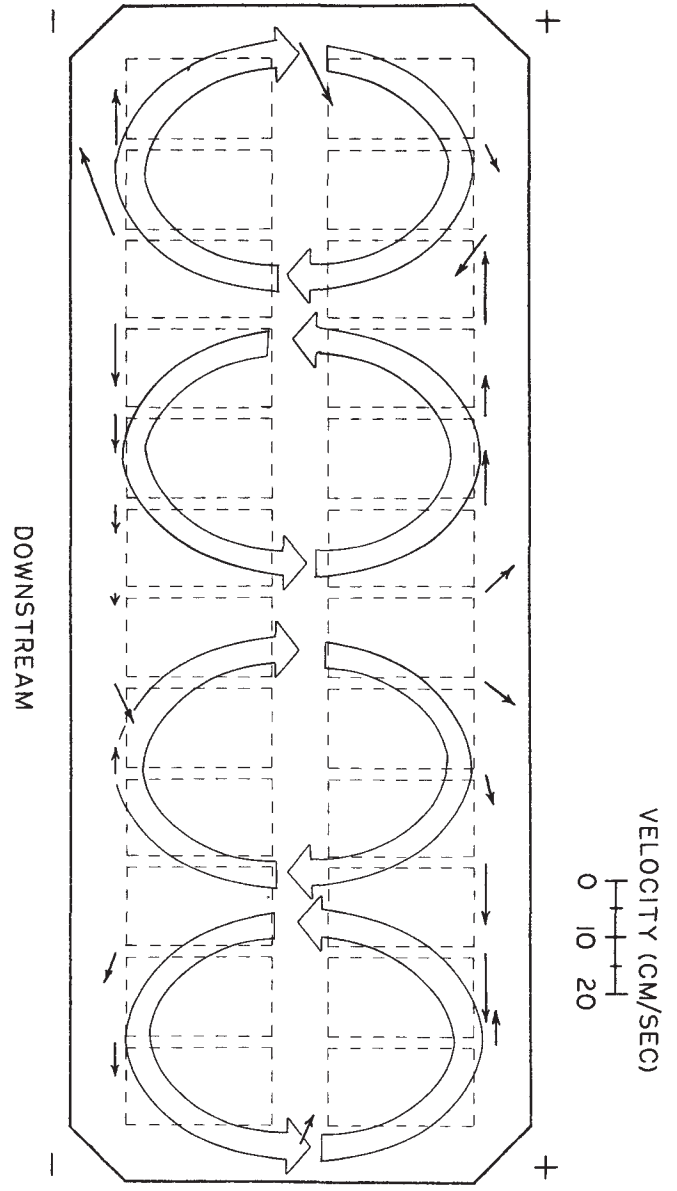


FIGURE 12. METAL FLOW VELOCITIES IN 150 KA QUARTER RISER CELL.

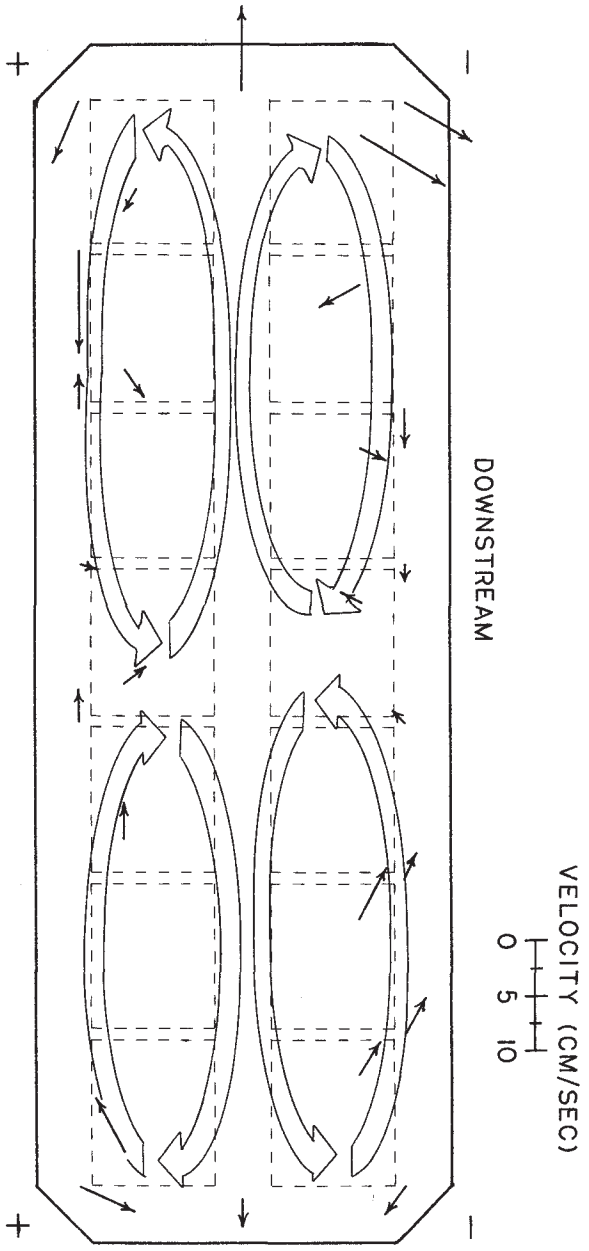
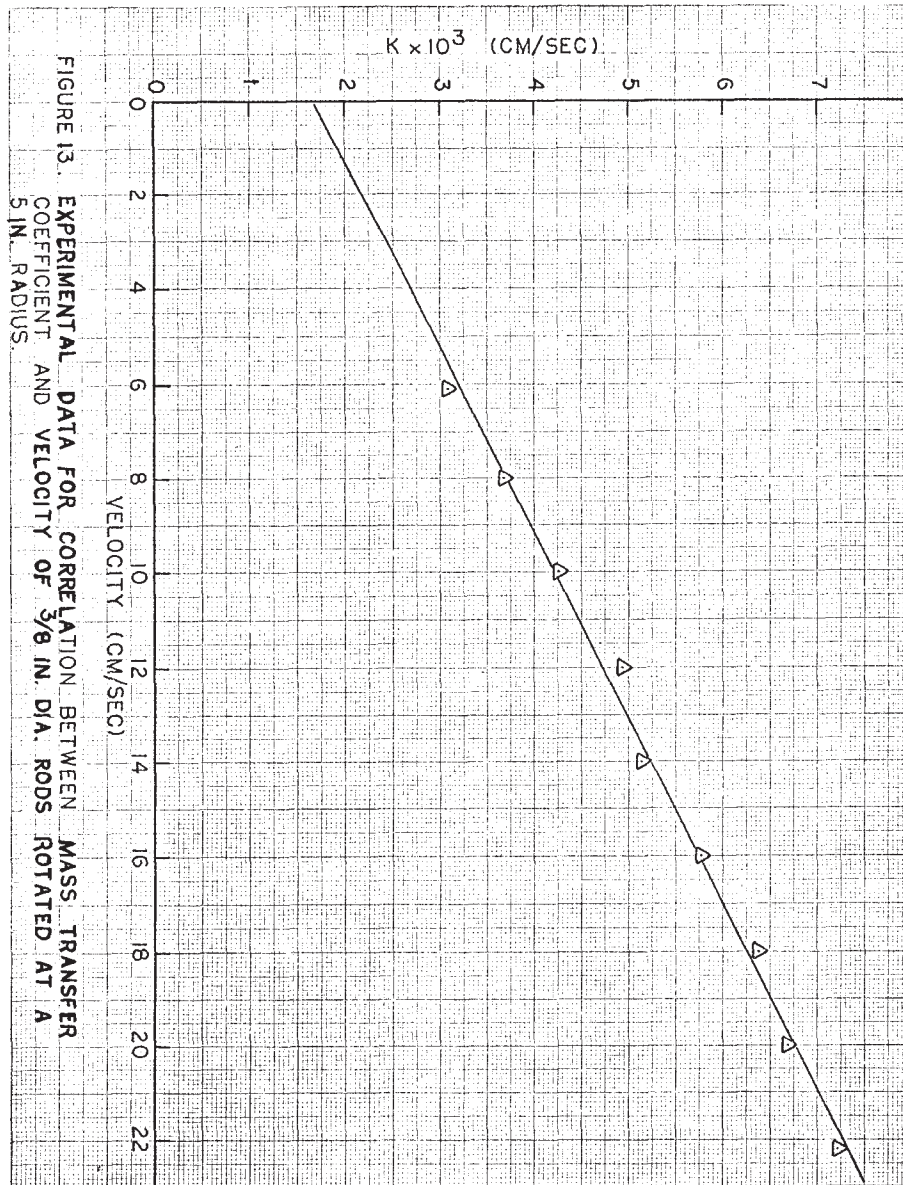


FIGURE 11. METAL FLOW VELOCITIES IN 76 KA PREBAKE CELL.



- The highest metal pad velocities are generally found near the ends of the cell as the metal approaches the sidewall after passing the ends of the cell. The lowest metal velocities are found near the center of the cell as the metal pools converge.

Quarter Riser Prebake Cells

150 kA Prebake Cell. Metal velocity measurements in a 150 kA prebake cell with quarter anode riser bus are shown in Figure 12. The following trends in metal pad circulation patterns are evident:

- Four major metal circulation pools. In the center of the cell, the metal flows across the cell from downstream to upstream side of the cell. On the upstream side of the cell, the metal flows from the center toward the quarter riser where the metal flows across the cell from upstream to downstream sides of the cell. The metal flows around the ends downstream to upstream sides of the cell.
- The highest metal velocities are generally found along the upstream side of the cell and lowest velocities are found on the downstream side of the cell.

Repetitive measurements of metal velocities and flow patterns in each cell have shown that although some variations in metal flow directions and/or velocities occur, the overall average metal flow patterns and velocity trends continue to persist.

From these metal velocity measurements in different reduction cell designs several definite trends are apparent:

- Although there are variations in the direction of metal flow, the overall metal flow circulation pools and/or patterns for each cell are fairly constant.
- Each design of reduction cell had a different and distinctive metal circulation pattern.
- Variation in metal flow directions and/or velocities at some locations can be influenced by cell conditions that can be variable: excessive muck, ledges, or anode changes.
- The highest metal velocities are found near the sidewalls at the ends of the cells where the highest sidewall erosion is generally found.
- The lowest metal pad velocities are found near the center of the cells where the metal pools generally converge.
- Increased metal pad stability may be indicated by a lower average metal velocity and a lower standard deviation of metal velocities.

#### Conclusions

It has been demonstrated that the empirically derived mass transfer expression established by Johnson for iron rods in aluminum metal flow is valid for the reduction cell metal pad temperature range 950-965°C, but required that the mass transfer constants be redefined. Other findings from the study included that:

- Only commercially pure iron rods can provide reproducible results necessary for metal velocity measurements.
- Rod with larger diameters, 1/2 and 5/8 inches, as well as 3/8-inch rod can be used for metal velocity measurements.
- Relationships between mass transfer coefficient, iron content, immersion time, and metal temperature were determined.
- Metal velocity measurements in reduction cell metal pads provide important information relating metal circulation patterns and cell bus design.

#### Acknowledgements

The authors are grateful to Charles Bunt and Michael Grisham for their contribution in conducting the experimental work, and to Beth Barnett for her invaluable assistance with the SAS General Linear Model Procedure.

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