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THE HALL-HÉROULT CELL: SOME DESIGN
ALTERNATIVES EXAMINED BY A MATHEMATICAL MODEL

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ABSTRACT

A previously developed mathematical model was used to study the effect of various design or operating changes on the performance of the Hall-Héroult cell. Performance was judged from the flatness of the interface between the aluminum and molten salt electrolyte and from the current efficiency. The former was found to be particularly sensitive to horizontal currents in the aluminum and a novel cell design was suggested wherein the minimization of such currents leads to a nearly flat interface. Current efficiency was found to be relatively insensitive to the horizontal currents but to be dependent on riser design. Computations were carried out for end cells in potlines, for potlines of different spacings and for cells containing different levels of aluminum.

INTRODUCTION

In view of the large amounts of electrical energy consumed in the production of aluminum there is considerable incentive for improvement of the Hall-Héroult cell. The energy consumed per unit of aluminum produced may be decreased by reducing the distance from the carbon anode to the molten salt electrolyte-molten aluminum interface which forms the cathodic surface. Unfortunately this procedure is made difficult by the fact that electromagnetic forces within the cell distort the electrolyte-aluminum interface from its otherwise horizontal position and may, under some circumstances, cause an oscillation of this interface. These electromagnetic forces have a second impact on energy consumption by the cell in that they cause a circulation of both aluminum and electrolyte, predominantly in the horizontal direction, with velocities of the order of 10 cm/sec. The current efficiencies of typical commercial cells fall in the range 85-95% and it is generally accepted (1) that the inefficiency is due to a partial reoxidation of the aluminum into the electrolyte at the interface between the two, followed by transport of the dissolved aluminum to the anode region where reoxidation takes place. Such transport is effected by the flow of the electrolyte, in particular by the turbulence of this flow. In this way there is an effect of the electromagnetic fields of the cell on its current efficiency.

A mathematical model for the Hall-Héroult cell has recently been presented (2). In this model the current and voltage distribution within the cell are calculated. Then follows the calculation of the magnetic field within the cell due both to internal currents and to currents in surrounding cells and bus bars. The electromagnetic force distribution can

then be calculated leading to the computation of velocities and turbulence levels in the molten salt electrolyte (henceforth "cryolite") and aluminum. Pressure distributions in the cryolite and aluminum also result from these calculations and enable the calculation of the interface topology. Finally the turbulence level in the cryolite is used to calculate a mass flux of dissolved aluminum and consequently the current efficiency. Tarapore (3) has described a similar model although his model does not yield interface topography or current efficiency.

The objective of the present paper is to use the mathematical model to predict the effect of various changes in cell design or operating parameters on the performance of the cell, as measured by the current efficiency and the flatness of the cryolite-aluminum interface. It should be recognized at the outset that there is no significance to the absolute values of these predictions; while the model does not employ adjustable parameters, it does entail physical properties whose values are not precisely known. Nevertheless, it is believed that credibility can be attached to relative predicted performances and, as will be seen, it is possible to draw, from the computed results, generalizations that may lead to better cell designs.

THE MATHEMATICAL MODEL

The model employed here has been summarized above and described in detail in the previous paper (2). It was improved by the incorporation of the following modifications.

The original model employed an equation by Levich to predict the mass flux of aluminum across an interface (the cryolite-metal interface) damped by surface tension. Turbulence is also damped at such interfaces by the

effect of gravity (e.g. ref. (4)) and an allowance was made for such an effect in the updated model. In the prior version of the model it had been assumed (unrealistically) that aluminum transport occurred across this interface only in the areas beneath the anodes while in the revised version transport was permitted over the whole cryolite-aluminum interface.

The prior version of the model assumed that the anode surface was an isopotential surface, while in some of the results presented below computation of the current distribution within the anodes was carried out. Additional software changes included the incorporation of translation and reflection subroutines to facilitate the description of bus bars around several identical cells. Finally considerable graphics output software was developed for ready presentation of computed results.

COMPUTED RESULTS AND DISCUSSION

The basic cell employed in the computation was one of 185 k amps. measuring 4.2 m. by 8.5 m. by 1.2 m. high (steel shell dimensions) equipped with eighteen prebaked anodes. A variety of bus bar and collector bar arrangements were tested and compared to a "base case" which is the "quarter riser" design depicted in Fig. 1. This figure shows the conductors around six cells in two potlines (cathode and anode buses, anode rods and risers) with other cell components left out for clarity. The current efficiency is computed to be 92.7% and the cryolite-metal interface is depicted in Fig. 2 with a trough to peak distance of 8.9 cm. The cell for which the computations are carried out is the one marked with an arrow in Fig. 1. The interface is more distorted than is observed in most cells which is probably a consequence of the fact that the potlines are closer

(12.0 m. center to center) than is usual practice. Figs. 3-6 present the current density distribution, horizontal forces in the cryolite, velocities in the cryolite and velocities in the aluminum for this base case.

Fig. 3 shows the current density vectors in a vertical plane through the cell (the cell is symmetric and therefore only half of the cross section is depicted). The large horizontal currents in the aluminum should be noted. These horizontal currents interact strongly with vertical magnetic field components in the aluminum to cause horizontal forces which are responsible for deformation of the aluminum-cryolite interface and circulation of the aluminum. These vertical magnetic field components are produced by horizontal currents in and around the cell, notably the collector bar current, the current in the aluminum itself, the currents in anode and cathode buses of the cell in question and its neighbors. In contrast, the current flow in the cryolite is predominantly downward and at much lower current density. Horizontal forces in the cryolite are therefore the result of horizontal magnetic fields arising from vertical current flows (notably those in the anode rods and risers) and horizontal current flows (notably those in the aluminum pool and collector bars).

The effect of spreading the potlines apart (to a center to center distance of 14 m.) is depicted in Fig. 7. The current efficiency is essentially unchanged but the deformation of the interface is less with a trough to peak distance of 6.8 cm. An effect on the interface deformation without a corresponding effect on the current efficiency may at first seem paradoxical since both are functions of the electromagnetic forces. However, the interface shape is determined by absolute values of the forces whereas flow of the cryolite (and consequently its turbulence and the aluminum

reoxidation flux) is determined by variations in the forces, or, in mathematical terms the curl of the forces. The (relatively) distant adjacent potline makes little contribution to the variation of the forces i.e. there is little difference from one end of the cell to the other in the magnetic fields due to currents in the adjacent potline, compared to large variations in magnetic fields within the cell due to risers or internal currents. However, the adjacent potline does have an effect on the absolute value of the magnetic field in a cell and thereby on the trough to peak distance.

The effect of spreading apart the individual pots in a potline (larger separation in y direction) is practically zero. On spreading the pots from a center to center spacing of 7 m. in the base case to a spacing of 8 m. the current efficiency fell from 92.7% to 92.5% (a negligible amount) and the trough to peak distance changed slightly from 8.9 to 9.1 cm. This is to be expected since for a particular cell magnetic fields due to currents in an "upstream" cell are largely cancelled out by corresponding currents in the "downstream" cell. The result may have economic significance; substantial additional bus bar costs are associated with more separated cells and it is seen that there is no advantage to such separation beyond the point where there is sufficient clearance for cell operation.

Fig. 8 depicts the effect of operating the cell with less aluminum in the pot, 12.4 cm. versus the base case depth of 16.4 cm. The computed current efficiency is 92.8% (essentially unchanged) while the interface is more distorted with the trough to peak distance increasing from 8.9 to 11.0 cm. As discussed in connection with Fig. 3 the major part of the cell current flows horizontally in the aluminum pool. This is true also in the case of the reduced aluminum depth, but now because of the shallower pool the current

density in the aluminum is higher resulting in stronger electromagnetic forces in the aluminum and more interface deformation.

Fig. 9 depicts a quarter riser cell where the two sections of the anode bus are more widely spaced (1.428 m. versus 1.028 m. for the cell of Fig. 1). The anode rods are now offset with respect to the center of gravity of the anodes which may pose operating difficulties but the interface deformation is thereby reduced to 7.0 cm at a small price in current efficiency (90% versus 92.7%). The explanation is that the region of horizontal current flow in the aluminum is much diminished, as can be seen by comparing Fig. 10 with Fig. 3. As stressed already, these horizontal currents are a major cause of forces on the aluminum. It should be recognized that in practice the connection between the anode rod and the anode is made via several anode stubs, but the more accurate representation of the current flow through such a connection would be likely to make only minor differences to the computed results. An offset of the anode rods in the other direction, such that the two anode buses were separated by 0.628 m. resulted, as expected, in a greater interface deformation (9.6 cm. trough to peak).

At the end of a potline there is no "balancing" of an upstream pot by a downstream pot and such pots can therefore be expected to display a poorer performance than pots within the line. This is consistent with the computer predictions, as can be seen from Figs. 11-14. The effect on trough to peak distance is much more marked than the effect on current efficiency again indicating that the latter is largely determined by currents within the cell and in its immediate vicinity, while the former is also affected by adjacent cells or potlines.

The other common design is the end riser cell and one such design is

depicted in Fig. 15. The low current efficiency is at first paradoxical. The design appears to have a greater symmetry (e.g. in the currents in the anode bus) than the quarter riser design, and therefore superior performance might be expected. A closer examination of the end riser cell with the quarter riser cell of Fig. 1 reveals the following deficiencies in the former. In the quarter riser design the vertical currents in the risers bringing the current to a cell are approximately balanced by vertical currents in the risers downstream from the cell. No such compensation exists for the end riser design and in this design the risers generate strong horizontal fields which, interacting with the vertical currents in the cryolite, cause strong forces and considerable motion in the cryolite, thereby diminishing current efficiency. Another detrimental feature of the end riser design is the horizontal section of the bus bar from the cathode bus of the upstream cell to the vertical section of the riser. Part of this section runs alongside the cell in close proximity to the aluminum and cryolite pools and contributes significantly to magnetic fields in these pools. There is no corresponding horizontal current in the quarter riser design. As might be expected, the end riser cell also shows a severely distorted interface, as depicted in Fig. 16.

Quite small changes in the design of end risers appear to be able to overcome the difficulties mentioned above, as can be seen in Fig. 17. By incorporation of an inclined section into the riser (presumably at some saving in bus bar costs) the current efficiency is significantly increased. The corresponding computed trough to peak distance is a low 5.1 cm. The success of these small changes may be ascribed to the fact that the vertical components of the currents in the risers bringing current to a cell are now partially balanced by those in the downstream cell. Furthermore, the

horizontal (y direction) current component in the riser close to the cell is now effectively well above the level of the melts and partly balanced by the current in the y direction in the cathode bus.

Fig. 18 depicts cells with multiple risers. The corresponding computed trough to peak difference is 9.1 cm and neither this distance nor the current efficiency are significantly different from those of the quarter riser cell. At first these results appear surprising since it was expected that using four, rather than two, risers per cell would yield smaller and more uniform magnetic fields within the cell. The explanation is that for the quarter riser cell of Fig. 1 the risers on the upstream side of the cell are in balance with those on the downstream side and therefore increasing their number has little effect. The pots depicted in Fig. 18 are in line with each other i.e. they have common center planes. The effect of offsetting the pots in one line such that their center planes fell between those of the adjacent potline. Negligible changes in current efficiency and interface deformation resulted. This indicates that although a cell is affected by the adjacent potline, even at the relatively close potline spacing used in these calculations, the detailed geometry of the adjacent potline is not significant.

An additional computation carried out for the multiple riser design was one where the length of the anode rods was increased from 1.81 m. to 2.31 m. with concomitant increase in riser length and anode bus height. The current efficiency decreased somewhat (to 91.2%) which can be rationalized as follows. Forces, and resultant flow, in the cryolite are due to vertical currents and horizontal magnetic fields. If the risers are well-balanced around the cell, the latter are due primarily to horizontal currents in the aluminum and

collector bars, and vertical currents in the anodes, carbon lining and anode rods. Only the last named contribution is effected by lengthening the anode rods and the effect is likely to be small, as computed. However, the computed effect on the interface is large, resulting in a trough to peak distance of 12.2 cm. A rationalization of this effect has so far escaped the authors.

Numerous other riser designs were tried, including some with substantial asymmetry. None proved better than the quarter riser or modified end riser designs discussed above and designs with asymmetric risers proved significantly worse.

The discussion above has made much of the fact that deformation of the cryolite-aluminum interface is greatly effected by horizontal currents in the aluminum. It follows that cell designs which minimize such currents should yield flat interfaces. One such cell design is depicted in Fig. 19 with the corresponding cell current densities depicted in Fig. 20. The cell employs horizontal collector bars akin to those of the conventional cell; connection to the collector bars is, however, not made at the ends of the bars but rather by means of two vertical steel pieces projecting from the bottom of the cell. As depicted in Fig. 20, horizontal current components in the aluminum are substantially reduced from those of Fig. 3. Furthermore, horizontal currents in the collector bars are reduced and now so directed as to cause partial cancellation of the fields therefrom. The computed interface shape (Fig. 20) is now quite flat with a trough to peak distance of 1.8 cm. The current efficiency of this novel design is computed as 92.2%, not significantly better than many of the alternative designs studied above. This is a consequence of the fact that horizontal currents in the aluminum contribute much to horizontal forces acting on the cryolite but little to

their variation (and consequently cryolite circulation and current efficiency). The calculated cryolite velocities in the novel cell are depicted in Fig. 22 and are seen to be comparable in magnitude to those in Fig. 5. An ability to control interface shape and cryolite circulation independently is significant. While cryolite circulation adversely effects current efficiency, it is the mechanism by which dissolved alumina is brought into the interpolar gap. Consequently a cell with no circulation, if this could be achieved, is likely to be inoperable. The calculations reveal that a nearly flat interface is possible without jeopardizing alumina distribution within the cell.

CONCLUDING REMARKS

The results presented in this paper are likely to be inexact. Within the Hall-Héroult cell there are many complex phenomena taking place some of which are ignored or poorly represented in mathematical models available at present. In addition our knowledge of the physico-chemical properties required in the mathematical models is presently uncertain.

Notwithstanding these difficulties, mathematical models can be a valuable adjunct to more traditional methods of cell development, and it is believed that relative or semi-quantitative information can be obtained from such modeling. In the present case the modeling has pointed to the very significant role played by horizontal currents in the aluminum and collector bars, on the bowing of the aluminum in the cell. An alternative cell design is suggested that does not appear impractical and wherein such bowing is substantially reduced.

Such horizontal currents appear to have little effect on circulation of the cryolite and current efficiency. It is more difficult to make generaliza-

tions concerning cryolite circulation since these arise from variations in electromagnetic forces and these are less clearly perceived than the forces themselves. It does appear, however, that cryolite circulation and current efficiency are effected by riser designs lacking the "balance" of multiple or quarter risers.

The mathematical model has indicated that more widely separated potlines may be beneficial but that separating cells within a potline will have little effect on cell performance. The model successfully predicts the inferior performance of cells at the end of potlines and suggests that performance of a cell would be impaired by a practice that minimizes the amount of aluminum in the pot.

It is hoped that the use of this or similar mathematical models will contribute to the development of cells consuming less electrical energy per unit of aluminum produced. The computer programs, having been produced with public funds, are available to interested parties.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

- 1 Six 185kA quarter riser cells in two potlines. Only the anode and cathode bus, risers and anode rods for each cell are shown. Subsequent calculations are for the cell marked with an arrow and take account of the currents in all the conductors shown. The drawing is to scale.
- 2 The interface between aluminum and cryolite computed for the cell indicated in Fig. 1. Straight lines indicate a horizontal plane. The vertical scale is exaggerated by a factor of 40. Current flow in the potline is from upper right to lower left.
- 3 Current densities within a half section of the cell depicted in Fig. 1. Units are A/m^2 .
- 4 Horizontal electromagnetic forces acting on the cryolite in the cell of Fig. 1 as seen from above. The direction of the potline current is from top to bottom of the picture. Units are N/m^3 .
- 5 Velocities in the cryolite in the cell of Fig. 1 as seen from above.
- 6 Velocities in the aluminum in the cell of Fig. 1 as seen from above.
- 7 Computed current efficiency for the case where the potlines are more widely separated (14 m center to center versus 12 m in Fig. 1).
- 8 Computed shape of the cryolite-aluminum interface for the cell indicated in Fig. 1 but with less aluminum in the pot (average depth of 12.4 cm versus 16.4 cm in the case of Fig. 2).
- 9 A quarter riser design employing a larger y direction spacing between anode rods.
- 10 Current density vectors for the cell of Fig. 9. Units are A/m^2 .
- 11 Current efficiency computed for the end cell in a potline (indicated by the arrow).
- 12 Computed interface shape for the cell of Fig. 11.
- 13 Current efficiency computed for the other end cell in a potline (indicated by the arrow).
- 14 Computed interface shape for the cell of Fig. 13.
- 15 An end riser cell design and the current efficiency computed for the cell indicated by the arrow.
- 16 Interface shape for the end riser cell of Fig. 15.

- 17 A modified end riser design.
- 18 A multiple riser cell design and the current efficiency computed for the cell indicated by the arrow.
- 19 A novel cell design (wherein current is taken out through the bottom of the cell) and the current efficiency computed for the cell indicated by the arrow.
- 20 The computed current density distribution for the cell indicated in Fig. 19. Units are A/m^2 .
- 21 The computed interface shape for the cell indicated in Fig. 19.
- 22 The computed cryolite velocities for the cell indicated in Fig. 19.

92.7% EFFICIENT

IFETCH08,TAPE13=PARCE20/VERS2/XQUART,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART,34612.11

8338103

Fig. 1: Six 185kV quarter riser cells in two potlines. Only the anode and cathode bus, risers and anode rods for each cell are shown. Subsequent calculations are for the cell marked with an arrow and take account of the currents in all the conductors shown. The drawing is to scale.

TROUGH-PEAK DISTANCE = 8.9 CM.
 INTERFACE TOPOLOGY

IFETCH08,TAPE13=PARCE20/VERS2/XQUART,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART,34612.11

8338103

Fig. 2: The interface between aluminum and cryolite computed for the cell indicated in Fig. 1. Straight lines indicate a horizontal plane. The vertical scale is exaggerated by a factor of 40. Current flow in the potline is from upper right to lower left.

IFETCH08,TAPE13=FARCE20/VERS2/XQUART,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART,34612.11

8338103

Fig. 3: Current densities within a half section of the cell depicted in Fig. 1. Units are A/m^2 .

IFETCH08,TAPE13=FARCE20/VERS2/XQUART,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART,34612.11

8338103

Fig. 4: Horizontal electromagnetic forces acting on the cryolite in the cell of Fig. 1 as seen from above. The direction of the potline current is from top to bottom of the picture. Units are N/m^3 .

IFETCH08,TAPE13=PARCE20/VER82/XQUART,34612.11
L IFETCH08,TAPE14=TACT20/VER82/XQUART,34612.11

8338103

Fig. 5: Velocities in the cryolite in the cell of Fig. 1 as seen from above.

IFETCH08,TAPE13=PARCE20/VER82/XQUART,34612.11
L IFETCH08,TAPE14=TACT20/VER82/XQUART,34612.11

8338103

Fig. 6: Velocities in the aluminum in the cell of Fig. 1 as seen from above.

92.6% EFFICIENT

1:FETCHOS,TAPE13=FARCE20/VERS2/GFIRC11,34612.11
 1:FETCHOS,TAPE14=TACT20/VERS2/GFIRC11,34612.11

GFIRC11
 0021001

Fig. 7: Computed current efficiency for the case where the potlines are more widely separated (14 m center to center versus 12 m in Fig. 1).

TROUGH-PEAK DISTANCE = 11.0 CM.
 INTERFACE TOPOLOGY

1:FETCHOS,TAPE13=FARCE20/VERS2/ALQUART,34612.11
 1:FETCHOS,TAPE14=TACT20/VERS2/ALQUART,34612.11

8338104

Fig. 8: Computed shape of the cryolite-aluminum interface for the cell indicated in Fig. 1 but with less aluminum in the pot (average depth of 12.4 cm versus 16.4 cm in the case of Fig. 2).

90.0% EFFICIENT

IFETCH08,TAPE13=FACE20/VERS2/XQUART2,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART2,34612.11

8338108

Fig. 9: A quarter riser design employing a larger y direction spacing between anode rods.

IFETCH08,TAPE13=FACE20/VERS2/XQUART2,34612.11
 IFETCH08,TAPE14=TACT20/VERS2/XQUART2,34612.11

8338108

Fig. 10: Current density vectors for the cell of Fig. 9. Units are A/m^2 .

91.3% EFFICIENT

IFETCHOS,TAPE13=PARCE20/VERB2/XFIRCE1,34612.11
 IFETCHOS,TAPE14=TACT20/VERB2/XFIRCE1,34612.11

X3B1008

Fig. 11: Current efficiency computed for the end cell in a potline (indicated by the arrow).

TROUGH-PEAK DISTANCE = 13.5 CM.
 INTERFACE TOPOLOGY

IFETCHOS,TAPE13=PARCE20/VERB2/XFIRCE1,34612.11
 IFETCHOS,TAPE14=TACT20/VERB2/XFIRCE1,34612.11

X3B1008

Fig. 12: Computed interface shape for the cell of Fig. 11.

92.7% EFFICIENT

```

;FETCHOS,TAPE13=FARCE20/VERS2/XFIRCE2,34612.1;
;FETCHOS,TAPE14=TACT20/VERS2/XFIRCE2,34612.1;

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XFIRCE2
X3B1G08

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Fig. 13: Current efficiency computed for the other end cell in a potline (indicated by the arrow).

TROUGH-PEAK DISTANCE = 12.4 CM.
INTERFACE TOPOLOGY

```

;FETCHOS,TAPE13=FARCE20/VERS2/XFIRCE2,34612.1;
;FETCHOS,TAPE14=TACT20/VERS2/XFIRCE2,34612.1;

```

```

X3B1G08

```

Fig. 14: Computed interface shape for the cell of Fig. 13.

84.4% EFFICIENT

```

:FETCHGS,TAPE13=FARCE20/VERS2/XMEND,34612.;;
L:FETCHOS,TAPE14=TACT20/VERS2/XMEND,34612.;;

```

S33B101

Fig. 15: An end riser cell design and the current efficiency computed for the cell indicated by the arrow.

TROUGH-PEAK DISTANCE = 10.9 CM.
INTERFACE TOPOLOGY

```

:FETCHOS,TAPE13=FARCE20/VERS2/XMEND,34612.;;
L:FETCHOS,TAPE14=TACT20/VERS2/XMEND,34612.;;

```

S33B101

Fig. 16: Interface shape for the end riser cell of Fig. 15.

87.2% EFFICIENT

```

;FETCHGS,TAPE13=PARCE20/VERS2/XM2END,34612.;;
L ;FETCHGS,TAPE14=TACT20/VERS2/XM2END,34612.;;

```

6338103

Fig. 17: A modified end riser design.

92.3% EFFICIENT

```

;FETCHGS,TAPE13=PARCE20/VERS2/XM4NEW,34612.;;
L ;FETCHGS,TAPE14=TACT20/VERS2/XM4NEW,34612.;;

```

6338100

Fig. 13: A multiple riser cell design and the current efficiency computed for the cell indicated by the arrow.

92.2% EFFICIENT

IFETCHGS,TAPE13=FARCE20/VER52/NIVEL3,J4612.11
 IFETCHGS,TAPE14=TACT20/VER52/NIVEL3,J4612.11

NIVEL3
 XJB1006

Fig. 10: A novel cell design (wherein current is taken out through the bottom of the cell) and the current efficiency computed for the cell indicated by the arrow.

IFETCHGS,TAPE13=FARCE20/VER52/NIVEL3,J4612.11
 IFETCHGS,TAPE14=TACT20/VER52/NIVEL3,J4612.11

XJB1006

Fig. 20: The computed current density distribution for the cell indicated in Fig. 10. Units are A/m^2

TRough-PEAK DISTANCE = 1.8 CM.
INTERFACE TOPOLOGY

```
IFETCH08,TAPE13=FARCE20/VERS2/NIVEL3,34612.11
IFETCH08,TAPE14=TACT20/VERS2/NIVEL3,34612.11
```

X3B1C06

Fig. 21: The computed interface shape for the cell indicated in Fig. 12.

```
IFETCH08,TAPE13=FARCE20/VERS2/NIVEL3,34612.11
IFETCH08,TAPE14=TACT20/VERS2/NIVEL3,34612.11
```

X3B1C06

Fig. 22: The computed cryolite velocities for the cell indicated in Fig. 12.

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