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COMPARISON OF INTERCELL CONTACT BARS FOR ELECTROWINNING PLANTS

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Abstract

In normal practice, the design and sizing of intercell contact bars (ICCB) for electrowinning is based on previously used designs, empirical testwork, or rules of thumb, rather than from first principles. A major operating cost for electrowinning is power consumption. The ICCB is responsible for a portion of the power costs due to its electrical resistance, which comprises electrode contact resistances and the bulk resistance of the ICCB.

This paper presents the methods used to calculate the electrical resistances and the results for a number of different widely accepted ICCB designs currently used in electrowinning plants. The paper also makes comparisons between the systems on other key parameters for ICCB performance in nickel and cobalt tankhouses.

Introduction

Hatch has completed a study to compare a number of intercell contact bar designs currently available in the market for their use in electrowinning and electrorefining plants. The different designs have been compared on a number of bases to determine their ability to produce consistent product and minimize operating costs.

Operating costs are reduced when the power consumption per tonne of metal produced is reduced. It will be shown that a significant proportion of the power consumption is due to contact resistances and the ICCB resistive drop.

Better quality deposits and higher current efficiency result when each cathode in a cell has equal current meaning that current distribution is even. This is a key goal in an EW/ER plant design and specifically in ICCB design since the current distribution will be influenced by any variation in the contact system direct resistance values. In practice there will also be other factors that influence current distribution. These include:

- Dirty contacts or formation of oxide films.
- Damaged contact bars.
- Uneven electrode spacing.
- Different internal resistances of electrodes.

This paper presents the theory that governs calculation of resistive drop and power consumption for intercell contact bars and the electrode header bars that rest on them. A comparison is then made of the different contact systems to assess their relative efficiency with particular reference to nickel and cobalt plants. The systems are then also qualitatively compared on the basis of other practical considerations for ICCB design.

Background and Theory

Intercell Contact Bar Designs

The intercell contact systems considered in this paper include:

- Standard Walker intercell contact bar.
  - Triangular intercell contact bar.
  - Dog-bone intercell contact bar.
- Outotec's DoubleContact™ intercell bar.
- Cominco's spool contact bar.
- Notched contact bar.
- Freeport McMoRan double contact bar.

It is important that the different types of contacts used in all of these systems can be classified as either line contacts or point contacts according to the shape of the interface between the electrode header bar and the intercell contact bar.

A line contact occurs when the electrode header bar and intercell contact bar form a contact interface on an edge. This occurs when the flat surface of one member contacts the edge of the other. A point contact occurs when the two contacting items contact at a point. This can only occur when an edge from one member contacts the edge of another member or when an edge from one member contacts a convex surface of another member.

Intercell Bar – Standard Walker System. The Walker System uses continuous intercell contact bars which electrically connect adjacent cell electrodes in a parallel fashion. This system was patented in 1901 [1] and appears to be the basis of the more refined contact bar arrangements developed over time. The typical Walker system bars are generally of a dog-bone or triangular profile [2].

Triangular Intercell Bar. One of the most common profiles used when adopting the Walker System is the triangular profile [2]. It produces a line contact for both the cathode and anode.

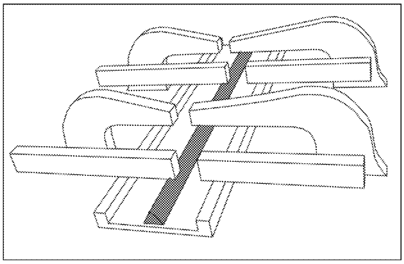


Figure 1. Triangular intercell bar system [3]

Dog Bone Intercell Bar. The other common profile used is the dog bone [2]. Similar to the triangular intercell bar, the cathode and anode each have separate line contacts but often on an edge formed by a radius, as opposed to a sharper edge formed by a triangular bar.

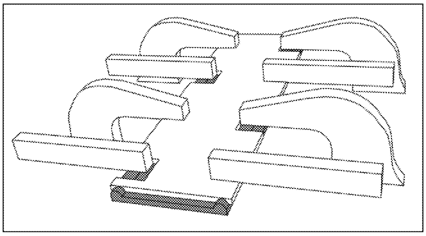


Figure 2. Dog Bone intercell contact bar system [3]

DoubleContact™ – Outotec. Outotec's DoubleContact™ intercell contact bar system is designed so that all electrodes have an electrical contact on each end. These electrical contacts are all line contacts. Outotec has claimed that the principal benefit of using the double contact system is a more even current distribution [4]. The basis of this design is that if there is a poor contact between an electrode and the contact bar, the electrode will still receive current from the contact on the other end of the electrode from the equalizer bar. Outotec claims that a more even current distribution is likely to reduce energy consumption and lead to better quality cathodes [4]. In this paper, the impact of the equalizer bars is not considered. This results in this system being considered as a simple dog-bone system.

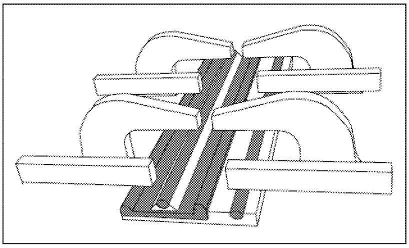


Figure 3. Double contact system [3]

Spool system – Cominco. The spool or sloping-tangent contact bar was developed in the 1970s by Cominco Ltd and utilizes a contact bar similar to that shown in Figure 4. This bar is claimed to provide excellent electrical contact via the notched portion of the header bars [5]. In theory this arrangement results in each electrode having four points of contact with the intercell contact bar.

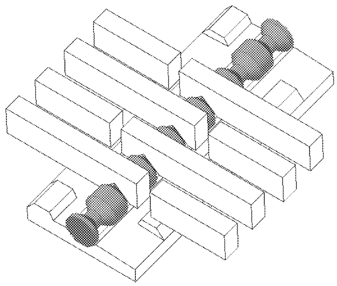


Figure 4. Illustration of a Cominco spool (developed from drawings in [5])

Notched Intercell Contact Bar. The notched intercell contact bar provides a double line contact for the cathode at the primary current transfer end as detailed in Figure 5.

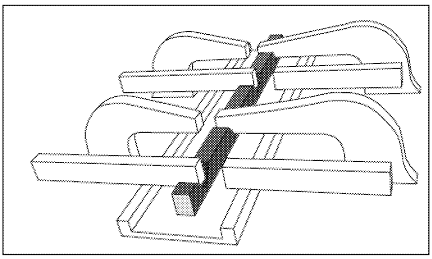


Figure 5. Notched contact bar system [3]

Freeport ICCB System. The Freeport ICCB system combines a double contact bar system with a notched contact bar generating a double line contact as shown in Figure 6, rather than the Outotec single line contact. As with the Outotec DoubleContact™ system, the equalizer bars are not considered in the calculations completed in this paper. This results in it being considered as a simple notched bar system.

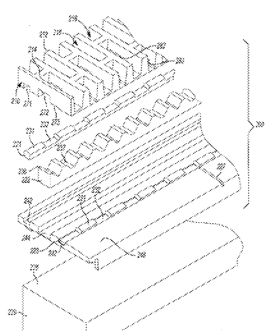


Figure 6. Freeport intercell contact bar [6]

Table I provides a summary of the intercell contact bars described above and their typical applications.

Table I. ICCB System Uses

ICCB	Type of Contact	Operation
Triangular	Line	Copper EW
Dog-Bone	Line	Copper ER, Cobalt, Nickel, Lead, Manganese
Outotec DoubleContact^{TM}	Line	Copper, Cobalt, Nickel, Lead, Manganese
Notched	Line	Zinc*, Manganese
Freeport McMoRan	Line	Copper
Spool	Point	Zinc

* may require watercooling

Methodology for Calculating Resistance

The total resistance of the intercell contact bar network is the sum of the 'contact' resistances between the electrodes and the intercell contact bar, and the bulk resistance, as shown in Figure 7.

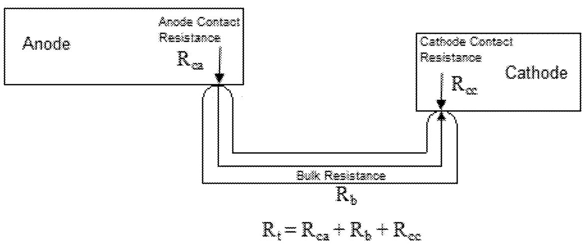


Figure 7. Resistances an in intercell bar network (dogbone configuration indicated)

Contact Resistance. To enable calculation of the cathode and anode contact resistances for each of the intercell contact bar systems, the equations presented in the literature have been assessed. For the case of two items being brought into contact, the area in apparent contact is much smaller than would be expected due to the microscopic high points (asperities) on each face. The resistance due to this smaller than expected area, is called the constriction resistance [7]. Additional resistance can occur due to thin films such as oxide deposits occurring on the contact surfaces. The sum of the constriction resistance and film resistance makes up the contact resistance for a particular contact.

According to Sawada et al. [8], the constriction resistance is dominant over film resistance when the loads exceed 10N (1kg) and when the film is thin. Due to the mass of electrowinning electrodes (>>1kg), it can be assumed that the film resistance is negligible, and hence, the contact resistance is equal to the constriction resistance. On this basis, the contact resistance is given by the following equation [9]:

$$R_c = \sqrt{\frac{\rho^2 \pi H}{4F}} \tag{1}$$

Where ρ = Electrical resistivity of material (ohm.m)
H = hardness of the material (Pa)
F = load normal to the contact bar surface (N)

It is important to note that based on Equation 1 the contact resistance is only dependent on the applied force and the hardness of the softer contact material, not on the apparent area of the contact. Due to this, whether the contact is a point or line, or the number of contacts per electrode, makes no difference to the electrode contact resistance by this theory.

However, Equation 1 assumes that the load is normal to the contact surface and for certain intercell contact bar designs this is not the case. Equation 1 can be re-arranged to take into consideration varying angles, and the mass of the electrode being split evenly on both sides of the cell.

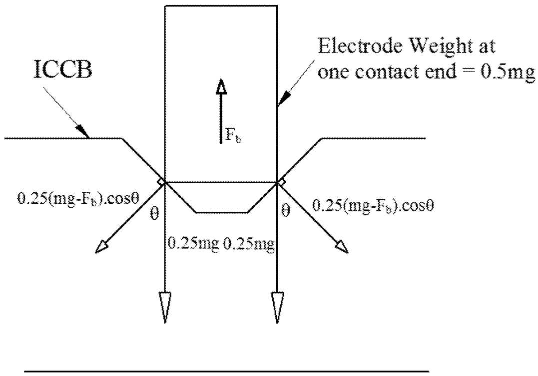
$$R_c = \sqrt{\frac{\rho^2 \pi H}{2mg\cos\theta}} \tag{2}$$

where m = mass of electrode (kg)
g = acceleration due to gravity (9.81 m/s^2)
θ = the contact angle between weight vector and normal force vector as shown in Figure 8.

Buoyancy effects result from electrolyte displacement by the electrodes and other submerged components attached to the electrodes. These effects are taken into account by modifying equation (2) as follows:

$$R_c = \sqrt{\frac{\rho^2 \pi H}{2(mg - F_b)\cos\theta}} \tag{3}$$

where F_b = buoyancy force (N)



$F = 0.5(mg-F_b).\cos\theta$

Figure 8. Contact force derivation

Buoyancy Effect of Bagged Anodes. Bagged anodes are utilized in nickel and often in cobalt electrowinning to keep acid generated at the anodes away from the cathodes where it can decrease current efficiency. The bags are generally supported and sealed on the anodes by a frame. The anode gas is collected in the bag and this gas displaces liquid in the bag volume and thus increases the buoyancy of the anode/bag/frame system.

Bulk Resistance. For a material of length L, with electrical resistivity ρ and constant cross-sectional area A, the resistance along the length of the material is given by the following equation:

$$R = \frac{\rho L}{A} \qquad (4)$$

Oxide Films on Copper. Oxide films are worthy of particular mention since thin oxide films are always formed on copper surfaces. When they are thin, these films do not lead to any significant increase in contact resistance [8]. However, the thickness of oxide films increases with time [10]. As the thickness increases, there is an increase in contact resistance [11] in the form of film resistance; hence, there is a need for regular contact bar cleaning in every plant. If sufficient cleaning is not carried out, the contact temperatures will increase due to this higher resistance and the rate of oxide formation will also increase since the rate of formation of oxide films is also known to increase with temperature [12]. The rate of oxide formation can become rapid if the temperature is allowed to continue to escalate [11].

In the extreme case, if the heat generated by current flow cannot escape an ICCB system fast enough then the system will overheat and will not sustain the required current flow. This has been seen to happen where the ICCB is undersized or where contact resistances are too high.

Some work has been done to find literature data on the impact of electrode weight or contact pressure on film resistance values but little information has been found. From the observations above and the personal experiences of one of the authors it appears that contact pressure may be an important factor when currents are high enough to make the contacts hot.

Heat removal from contact systems. The main method of heat removal from contact systems is conduction into the electrode header bars and into the electrolyte heat sink through the contact points. Other contributions are made through:

- Convection of heat from electrode header bars.
- Convection of heat from the exposed surfaces of the ICCB.
- Water cooling of ICCBs where this is employed.

The amount of heat rejected through convection is directly proportional to the amount of surface area exposed.

Results and Discussion

The resistance of the contacts and through the bulk of the ICCB is important because:

- Variations can lead to uneven current distribution.
- Power consumption can be affected.
- The amount of heat that needs to escape the ICCB system can be impacted.

The major components of the resistance and differences between their values for the various intercell contact bar types are reviewed below.

Bulk Resistance

To calculate the bulk resistance certain assumptions were made. These include:

- The current through each cathode was equal to 400A.
- The 'rule-of-thumb' $1A/mm^2$ was used to determine an initial cross-sectional area of the intercell contact bar – cross-sectional area was $400mm^2$.
- The distance between anode-cathode was 50mm.
- Electrical resistivity of ICCB material (copper) – $1.7x10^{-8}$ Ωm [7].
- No current was passing through the equalizer bar in the Outotec DoubleContact system or the Freeport McMoRan system.

With the above assumptions in place the bulk resistance is calculated by Equation 3 to be 2μΩ for all systems.

Contact Resistance

The contact resistances for each of the ICCB systems were calculated using the following assumptions and basis:

- Hardness of ICCB material (copper) – 500MPa [7].
- The contact angle, θ, for the spool contact bar is 45°.
- The contact angle, θ, for the notched contact bar is 30°.
- Thermal effects – temperature impacts on resistivity have not been considered.
- Film resistances were assumed to be negligible and contacts were assumed to be clean.
- Cathode mass at start and end of deposition cycle are 25kg and 85kg, respectively.
- Anode masses do not change during the deposition cycle. Two options were considered, a lead anode and a lightweight titanium catalytic anode. Their masses were 110kg and 20kg, respectively.
- Titanium anode dimensions and materials are taken from the conference paper by Sandoval et al. [13] which details the development of alternative anode technology.
- Bag contained volume is $0.07m^3$ and gas displacement of liquid in the bag is a maximum of 10% when cell is operating. This data has been taken from Hatch internal designs and calculations.
- Anode bags and frame materials have similar density to the electrolyte and thus assumed to have no impact on buoyancy.
- A typical nickel cell potential of 3.6V [14] is used.

Table II compares the different intercell contact bars mentioned, and displays the contact resistances that have been calculated for each ICCB system on the basis of no anode bags being used.

Table II. Calculated Contact Resistances and Total Maximum Resistance with No Anode Bags

ICCB	θ	Contact Resistances (μΩ)				R_t Pb Max (μΩ)	R_t Ti Max(μΩ)
		R_{ca} Pb	R_{ca} Ti	R_{cc} Start	R_{cc} End		
Triangular	0	15	35	33	18	50	70
Dog-bone	0	15	35	33	18	50	70
Notched	30°	16	38	35	19	53	75
Spool	45°	18	42	39	22	59	83

When the calculations are revised for the presence of anode bags the effective lead anode weight is decreased by 18% to 890N and titanium anode weight by 52% to 95N, at the maximum 10% gas hold up case. This would increase contact resistances by a maximum of 6% for bagged lead anodes and 50% for bagged titanium anodes.

There are several general observations from these results:

- The contact resistances are dominant over the bulk resistance of the intercell contact bar at between 95 and 98% of the total resistance.
- For unbagged lead anodes the total ICCB system resistance accounts for approximately 0.6% of the cell power consumption and for unbagged titanium catalytic anodes for approximately 0.9% of the cell power consumption.
- Cathode resistance changes from start to end of a deposition cycle as the weight of the electrode increases.
- There is a clear difference between the lead anodes and the catalytic titanium anodes – the titanium anodes have significantly higher contact resistance by approximately 20μΩ or 33% which equates to a power loss difference of 0.2% of the overall power consumption.
- It is interesting that unbagged titanium anode contact resistances are similar to the cathode resistances at the start of a cycle.
- Buoyancy effects are not substantial for the cathodes and both lead and titanium anodes at a maximum of 5% impact, when anode frames are not used.
- When anode bags/frames are used, the lead resistances are still low whereas titanium anode contact resistance increases dramatically. Unless bolted connections for bagged titanium anodes are used, resistive power loss will increase to 1.1% of the overall power consumption and heat generation will also increase significantly.

Comparative comments for the ICCB systems include:

- The triangular and dog-bone systems have lower contact resistance than the notched and spool bar systems. This difference is purely due to the difference in contact angle for the different systems. The steeper the contact angle the greater the contact resistance. The magnitude of the difference between the angled contacts and flat (contact angle of 0°) contacts is approximately 17%, which equates to a power loss difference of 0.1% of the overall power consumption which is minor from a power consumption perspective but generates more heat to be convected or conducted away from the ICCB.
- The difference between the Notched and Spool system results from the assumption made about the different contact angles and it should not be concluded that one is better than the other in practice.

<u>Other means of comparison</u>

Even electrode spacing. In Table III , the contact bar system methods of obtaining even electrode spacing are compared. It is expected that insulator blocks, notches and spool shape can provide similarly regular electrode spacing. Where the crane is relied upon to position the electrodes, the spacing reliability will depend upon the degree of automation of the crane and positive placement of the crane bale.

Table III. Electrode Spacing Mechanism

ICCB	Electrode spacing mechanism
Triangular	Insulator block or crane
Dog-Bone	Insulator block or crane
Outotec DoubleContact™	Insulator block
Notched	By notch
Freeport McMoRan	By notch and insulator block for equalizer bar
Spool	By spool shape

Heat removal. In Table IV, the systems are compared with respect to their ability to convect heat away from their surfaces. The approximate surface areas of one electrode pair ICCB section for the different geometries are calculated and presented.

Table IV. Surface Area for Heat Rejection

ICCB	Comparative surface area (no insulator block) [mm^2]	Comparative surface area (with insulator block) [mm^2]
Triangular	2000	800
Dog-Bone	5000	1500
Outotec DoubleContact™	5000	1500
Notched	3000	3000
Freeport McMoRan	3000	800
Spool	1000-3000	1000-3000

The following comments can be made:

- For the no insulator block case the dog-bone and Outotec DoubleContact™ arrangements allow for the largest amount of surface area.
- The notched, Freeport McMoran and Spool systems have the next highest amount of exposed surface area when no insulator blocks are used.
- The Spool system surface area is unclear because the exact dimensions have not been defined and significant reduction in spool bar diameter may be possible for this low current density system which could decrease surface area.
- When positioning insulator blocks are installed, the triangle bar and Freeport McMoRan systems have the smallest areas and the dog-bone and Outotec systems have the next smallest areas.
- The notched contact bar does not require insulator blocks for electrode spacing so would be expected to maintain the highest surface area.
- Where a crane is used for electrode positioning the dog-bone system may have highest surface area of all but this may introduce positioning errors and other issues.
- The importance of exposed surface area depends on the amount of convective heat removal from the ICCB compared to conductive heat removal through the header bars. This requires more work to assess.

Dirty contacts

In Table V, the type of contacts formed, and comments regarding redundancy, contact shear forces and contact pressure are made.

Table V. ICCB Design Considerations

ICCB	Type of Contact	Comments on contacts
Triangular	1 Line	No redundancy, no shear, low pressure
Dog-Bone	1 Line	No redundancy, no shear, low pressure
Outotec DoubleContact™	1 primary line, 1 equalizer bar line	Redundancy on equalizer bar, no shear, low pressure
Notched	2 Line	Redundancy, some shear, low pressure
Freeport McMoRan	2 primary lines, 1 equalizer bar line	Redundancy, some shear, low pressure
Spool	4 Point	Redundancy, some shear, high pressure

The following points can be made:

- Where there is a single line contact such as with triangular or dog-bone ICCB a dirty contact can significantly increase contact resistance.
- Multiple contacts provide some redundancy in the system so that if one contact is dirty the other(s) may still make good contact. It should be noted that the weight is distributed across the contacts so that if one contact is dirty the others will have higher voltage drop since each contact's resistance is higher than for a single contact system.
- The Freeport McMoran and Spool systems have redundancy at the main contact end whereas the Outotec system redundancy is provided on the equalizer bar. This equalizer bar contact will have low contact resistance since it carries full electrode weight but there will be an additional contact resistance and equalizer bar resistance needed to carry the current to that contact.
- Some shear between the header bar and contact system when the header bar is placed may provide benefits when contacts are dirty by self-cleaning the surfaces in contact. Regular contact cleaning is important for all contact systems but systems with shear may reduce the frequency required for this, or the criticality.
- The importance of film resistance is uncertain. Shear may cut through oxidation on the ICCB surface and reduce film resistance. In addition, contact pressure may be important and this will be highest for the point contacts on the Spool system. More work is required to investigate this factor.

Conclusion

This paper described the most common intercell contact bars currently available. These bars have been analyzed to determine how much electrical resistance can be expected due to the intercell contact bar system and have also been compared on the basis of other practical plant considerations. It was found that:

- The power consumption due to the ICCB system is between 0.5-1.1% of total power consumption.
- Increasing the load normal to the surface decreases the resistance of the ICCB such that a standard Walker bar results in a reduction in contact resistance, compared with the notched and spool bar alternatives for an impact of approximately 0.1-0.2% of power consumption.
- Lightweight anodes that are not bolted or otherwise positively fixed to the contact bar have higher electrical resistance than their lead based alternatives.
- The addition of anode bags increases the contact resistance due to buoyancy. This increase is minimal for lead anodes, but very significant for titanium anodes.

- Insulator blocks on ICCBs reduce the amount of surface area of ICCBs available for convecting heat away.
- A Notched ICCB appears the best configuration to reject heat through convection, whilst maintaining electrode positioning, where an accurate crane positioning system is not used.
- A subjective comparison has only been possible with respect to redundancy, contact shear and contact pressure but these warrant further investigation.

Further Work

This paper introduces the concept of determining the contact resistance of an intercell contact bar interface, and to use this information along with other parameters to develop the most efficient solution in the future. In future work the following additional aspects will be considered:

- Thermal effects need to be investigated in a more quantitative way to further improve understanding.
- In completing a thermal analysis, methods of bar cooling need to be examined to determine their cost effectiveness.
- More literature and practical testwork on film resistance and oxide film impacts is required particularly with respect to the importance of contact shear and contact weight/pressure.
- A detailed analysis of the equalizer bar concept to gain a better understanding as to whether they impact the overall resistance and hence power consumption.
- An assessment of cost impacts of the ICCB systems incorporating the differences in capital cost of the various systems as well as operating costs.
- Methods of reducing the contact resistance for titanium anodes.
- The presentation of the Hatch ICCB system being developed.

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