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Electrical leakage currents in bipolar cell stacks

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A brief review of the origins of bipolar leakage currents, the means used for its measurement and calculation and the importance of minimizing the phenomenon, is followed by a novel means of computing leakage currents more accurately than hitherto possible, using a commercially available simulation program. This has the further advantage that the real i–V characteristics of an electrochemical cell can be used, there being no need to represent the cell itself as a zener diode which is a poor representation of real i–V cell characteristics.

1. Introduction

The bipolar cell stack is finding increasing favour in the electrochemical process industry, not only in the chlor-alkali field, which is tonnage-wise the most important, but also in electro-organic processing where it appears that all aqueous electro-organic processes (direct or indirect) now being carried out on a large scale make use of this type of cell.

A problem with such stacks is that of bipolar current leakage, sometimes also known as 'by-pass' or 'shunt current' leakage. This is current flowing from one cell to another not through the main electrodes but rather through the electrolyte feed and exhaust manifolds. Fig. 1 shows an analogue circuit representation of a bipolar cell stack where current can leak from cell 1 to cell 3, for example, through the manifold. If the cell components are metal, the current can pass through the manifold itself. More commonly the cell is made of insulating materials and the leakage current passes through the electrolyte. Various papers, some published [1–9, 11–13, 16] and others presented at meetings [10, 14, 15, 25] or as patents [17–20, 26, 27] have treated this subject. The purpose of the present paper is to summarize the field and to show how a recent commercially available computer simulation package can make calculation of such currents easier and more accurate than hitherto.

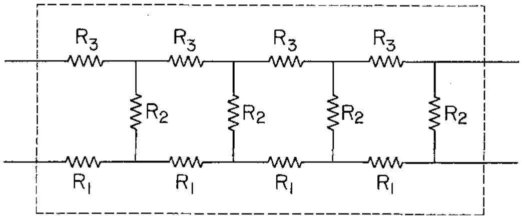

Fig. 1. Traditional, purely resistive, electrical analogue of a cell stack. R_1 represents the resistance of the cell, R_2 that of the feed-lines, R_3 that of the manifold. For the sake of clarity, only the cell stack and the anolyte inlets are represented here. Anolyte outlets and catholyte inlets and outlets can be similarly represented.

The origin of the leakage currents is shown in Fig. 1. In a cell stack where the end-to-end potential differences can easily be 100 V or more, it is seen that where the ohmic drop through the manifold and feed pipes across N cells is less than

$$(E_{\text{rev}} + \eta_a + \eta_c + iR)N$$

a viable path for current flow will be through the manifold pipes as well as serially through the main cell stack itself. The possible damage caused by leakage currents is threefold, namely: (a) current losses and inefficiency, (b) corrosion, and (c) explosive hazards.

(a) If current flows through the manifold rather than from cell to cell, the electrolysis will not take place in those cells that are by-passed, and there will be a resulting current inefficiency. It will be

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seen that this can be at least 1–4% of the total current.

(b) Bipolar leakage currents can result in a situation where a portion, at least, of an anode becomes cathodic and vice versa. This can result in corrosion taking place with consequent damage to the electrodes.

(c) The same effect can result in both anodic and cathodic products being simultaneously generated in the same electrode compartment. Since (in the case of chlor-alkali cells) as little as 4% of hydrogen in chlorine or vice versa constitutes an explosive mixture [18], there is a clear hazard as a result.

2. Calculation of leakage currents

It has long been recognized that a cell stack can be represented as an electrical network [1] and that the current flowing in various parts of the network can be calculated in the customary way using an analysis based on Kirchoff's laws. With a large stack, solution of such a problem is a time-consuming project. There are certain Russian papers [2–6, 8, 9, 12, 29] devoted to this problem, and also some in English [7, 10, 11, 13–16]. All represent the cell system as a purely resistive network, which it clearly is not. A major step forward is the work of Katz [16], who appears to have introduced the zener diode as a component into the network analogue of the cell system. Katz also used a computational solution to the problem, being apparently the first to do so (with the exception of [10]). Though the use of a zener diode analogue represents a great advance on earlier analogues, it is still some way short of a realistic model of a working electrochemical system.

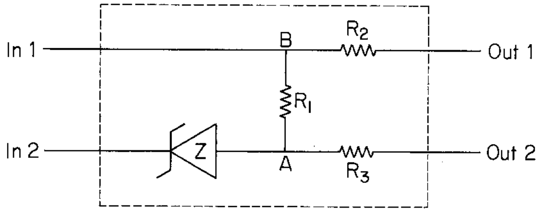

Fig. 2. Electrical representation of 'unit cell' forming the basis of the ASTAP model. The cell itself is represented as a 'zener diode', the current–voltage characteristics of which (not avalanche) can be chosen at will, or obtained from single cell data. Table 1 shows data used in this example; R_3 represents internal cell resistance, R_1 is feed-line, R_2 is manifold resistance.

Most of these papers are in qualitative agreement with one another in that they show the following picture. The *ionic shunt current*, that is to say the current flowing in an inlet or outlet manifold, is 'S'-shaped when plotted against cell number (Fig. 3); that is to say it is highest at one end of the cell, decreases to a value of zero in the ports at the centre of the stack and then increases once more, but with current flow of opposite sign, as one considers the cells in the other half of the stack. The *leakage current*, that is the shortfall between applied current to the stack and the current in individual cells, is smallest at the outermost cells and rises rapidly as one moves to the inner cells of the stack, being substantially constant in all but the outermost cells. This too is shown in Fig. 3. It is often said that there is a seeming paradox in this picture. However, further thought on the distribution of potential across the cell and manifolds leads to an understanding of this behaviour.

We have now found that there is a commercially available network simulation program (IBM's 'ASTAP') [21] which allows a more accurate representation of leakage currents.* The main feature of ASTAP is that not only does it allow any standard electrical component (*R*, *C*) to be modelled, but far more important, it allows the user to model any other component desired, by simply inserting into the program a table of values for that particular component. Thus, data was obtained for a typical industrial cell, and this data, cell current versus cell voltage for a single cell, was read into the ASTAP program. The simulation is made by labelling each 'node' in the circuit, and the values of components between each node. A typical cell stack was simulated by using the network shown in Fig. 2 as a 'unit cell'. A 20-cell stack was then postulated. The values of parameters and the results obtained are shown in Tables 1 and 2.

The resulting leakage currents are seen to be symmetrical about the centre cell in the stack, in agreement with all earlier analyses on the stack (see Fig. 3, quoted from [16]). The use of the ASTAP program allows instant calculation of

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* Other, though less powerful, programs are now becoming available, including some designed to run on microcomputers [24].

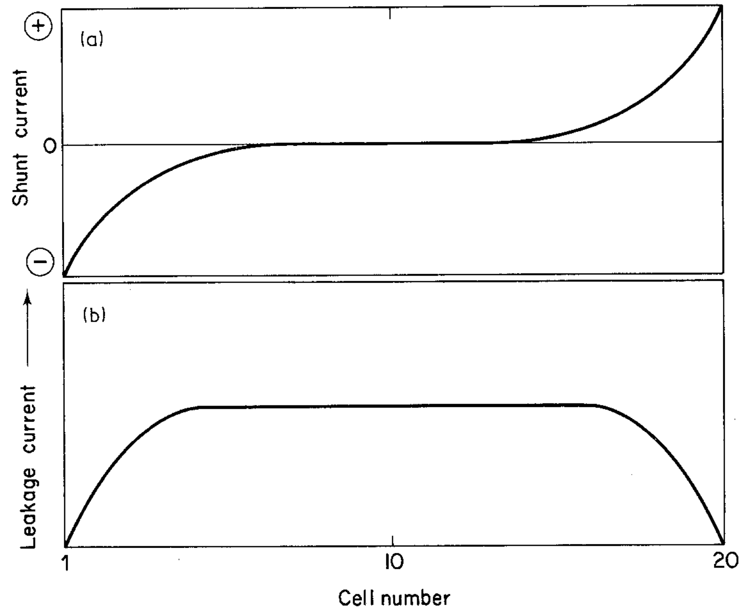

Fig. 3. Schematic representation of leakage currents (b) and shunt currents (a) in a cell stack. Abscissa shows cell number in stack series. Ordinate shows leakage current (b) and shunt current (a).

leakage currents as predicted for cells of various designs.

In the first simulation run, the value of R_3 (Fig. 2) was set at zero. In the second run, we assigned a value of $3 \times 10^{-3}\ \Omega$ to this resistance, thereby creating an analogue to the increasingly popular type of bipolar cells featuring a 'divided bipole' in which anode and cathode elements of the bipole are connected by conducting studs which pass through an insulating inter-cell wall. In this case, it is seen that substantial increase of leakage currents occurs, a finding not hitherto commented on and one of clear significance in cell design.

Table 1. 'Zener' characteristics of an electrochemical cell

Voltage (V)	*Current* (A)
0.00	0.00
2.90	0.00
2.95	1.00
3.00	100.00
3.05	1 000.00
3.10	5 000.00
3.15	10 000.00
3.20	10 000.00

It is very difficult to envisage any faster method of making such calculations. The technique of digital simulation, of which the IBM ASTAP program is a rather sophisticated example, is now so straightforward that there would not appear to be a case for analogue simulation of cell stacks; the accurate representation of the mixed logarithmic–linear current voltage response obtained in this technique is very hard to achieve by other methods.

3. Experimental measurement of leakage currents

The literature contains two main contributions to this. In one [8], an annular magnetic field detector is placed around the electrolyte feed or exhaust pipe. This requires a breaking of the hydraulic circuit, and the technique is not an easy one since it can be shown that the magnitude of the fields created by leakage currents is not greatly different from that of the earth's magnetic field. Add to this the stray fields always present close to heavy current-carrying busbars, and it is seen that the technique can only be used with great care. Rousar [11, 13] has adopted a different approach by insertion of platinized platinum probes into the feed pipes, in order to measure potential differences, which may in turn be related to current. This seems a more realistic approach.

Table 2. Currents in a bipolar cell stack (simulation) [Simulation conditions: total cell current = 2000 A; R_1 *(Fig. 2) = 9* Ω*;* R_2 *(Fig. 2) = 3* Ω*;* R_3 *(Fig. 2) = 0 (case A) 0.003* Ω *(case B)]*

Cell number	*Cell current*	*Shunt current*	*Leakage current*	
1	1999.1	(–) 0.862	A 0.86	B 2.55
2	1999.1	(–) 0.618	1.48	4.37
3	1998.5	(–) 0.442	1.92	5.67
4	1998.1	(–) 0.314	2.24	6.60
5	1997.8	(–) 0.223	2.46	7.26
6	1997.5	(–) 0.156	2.62	7.72
7	1997.4	(–) 0.106	2.72	8.03
8	1997.3	(–) 0.068	2.79	8.24
9	1997.2	(–) 0.038	2.83	8.35
10	1997.2	(–) 0.012	2.84	8.38
11	1997.2	0.012	2.83	9.35
12	1997.2	0.038	2.79	8.24
13	1997.2	0.068	2.72	8.04
14	1997.3	0.106	2.62	7.72
15	1997.4	0.156	2.46	7.26
16	1997.5	0.223	2.24	6.60
17	1997.8	0.314	1.92	5.67
18	1998.1	0.442	1.48	4.37
19	1998.5	0.617	0.86	2.55
20	1999.1	0.862	0.0	0.0

4. Impact of leakage current on industrial cell design

All modern patents on design of multi-cell bipolar electrolysers now recognize that the design must make provision for minimization of leakage currents, and long and thin feed pipes obviously achieve this. However the gain comes at the expense of extra pumping energy (to overcome their high hydraulic resistances). It is obvious that bipolar cells constructed on the plate and frame system, with the manifold built into the frame, will be more prone to leakage problems since the inter-cell path is shortest in this design. Cells have been disclosed [27] in which the feed pipes within the frame are deliberately made more tortuous, by leading the feed/exhaust pipes for some distance through or inside the frame. Alternatively, the frame can be much wider than purely mechanical conditions would dictate, in order to lengthen the lines. However this is wasteful of plastic construction material and also makes the cell volume much bulkier. This apart, a number of ideas recur in cell design aimed at minimizing or eliminating bipolar leakage currents. Most are based on means of (electrically) [26] breaking the circuit represented by the manifold. Thus electrolyte drainage in the form of droplets, or a spray, or a siphon pouring into a common gutter, all serve the common purpose of breaking electrical continuity. It has been pointed out that in gas-evolving cells, the 'plug-flow' mode, if this is created in the electrolyte exhaust, will greatly increase resistance, and a Japanese patent [19] quotes data for this. Presumably by means of gas-injection into the feed manifolds, leakage could likewise be reduced there, though this has not been suggested. The introduction of freely rotating, plastic 'water wheels' in a tightly fitting casing, would also serve to break long electrolyte lines into more or less insulated sections. Another idea is quoted in [28].

Some cell designers, rather than seeking to eliminate the leakage currents, have rather sought to control them. In a German patent [20] a small platinum wire is led through the frame of the cell, being spot-welded to the anode inside the frame and dipping into the electrolyte manifold outside the cell. Leakage current passes through this wire rather than in the electrolyte manifolds. The other consequence of leakage currents which both our own, and earlier models show, is that the shunt current in the Nth cell varies as N^2, where N is the total number of cells. Clearly such a power relationship must limit the maximum number of cells in a stack. However we believe that, with well-designed cells, this particular factor will never be the limiting factor governing the maximum number of cells in a stack, since legislation (though this varies from country to country) limits the maximum voltage to earth of any cell stack, and even if centre-tapping to earth allows cell voltages of double the legal limit, both this factor and the sheer size of a very large stack make it undesirable to aim for the largest possible number of cells. Increasingly there is an awareness that the slight additional economies of scale to be gained from having the largest possible unit are all too easily offset by the lack of flexibility when this, as opposed to two units of half the size, breaks down.

We have sought to cover briefly, the known literature on the subject of bipolar leakage currents, and to show how these may be more accurately calculated. A better understanding of them will avoid the sort of damage reported by Adamson, Lever and Stones [21] in their study on (undivided) bipolar hypochlorite cells. To this day, the cause of the catastrophic, explosive, failure of the bipolar cells at Ilford [23] is not known. However, the Inspector's report makes it clear that blocking of feed tubes by sludge was a perennial problem. Though it is not discussed in that report, it will be obvious from what has been said here, that a wholly or partially blocked cell will increase the ratio of $i_{\text{leak}} : i_{\text{total}}$ with obvious consequences in terms of corrosion and thus failure. Looking back, this seems as likely a cause of that explosion in which hundreds of children were at risk, as any other cause that comes to mind. The practical importance of this particular problem could not be more dramatically underlined.

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