AL19 - The Continuous Prebaked Anode Cell – a Pathway to Carbon Capture in Aluminium Production

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Abstract

The routine replacement of spent anodes is the major impediment to achieving process continuity and stability in aluminium electrowinning. It is the root cause of significant process inefficiencies such as complex gas scrubbing systems, and equipment for reprocessing and recycle of the anode butts. These systems add significant capital and operating cost to the process, while adding no value to the metal produced. Further, anode replacement is the major cause of fugitive emissions to the environment, of potentially hazardous interfaces between operator and process, and of contamination of the aluminium product by iron. A continuous anode, where replenishment is achieved without disruption or opening of the process to the atmosphere, offers tremendous advantages on all these dimensions. The continuous anode concept is not new however. As an in-situ, self-baking anode monolith the Soderberg cell won no friends for its environmental credentials but it does provide directions for what is needed to establish a viable, continuous prebaked anode (CPA) technology. Specifically, the key technical challenges are just two – an effective glue to join prebaked carbon blocks, and a robust and efficient electrical contact and support system that can match the inherent design efficiency of the conventional anode rod and stub assembly. The industry has been surprisingly slow to take these challenges on – but may be forced to in the future should the inert anode not succeed. CPA technology is the enabler for more efficient sealing of the cell, which in turn enables viable carbon capture from a more concentrated cell off-gas. This paper describes work conducted by the authors more than a decade ago to define a viable electrical contact and superstructure design for a CPA cell. The technology awaits proving at an industrial scale for those who see value in this ‘diamond in the rough’.

Keywords: Continuous prebaked anode, CPA, carbon capture, electrical contact system.

1. Introduction

The development pathway for reduction cell technology over many decades now has been singularly focused on higher productivity from each cell, this being the key driver of both the investment cost and the operating cost of a smelter. Over the past 50 years we have seen cell current increase approximately four-fold from around 150 kA to 600 kA, with productivity increases of a similar magnitude. There have been important enabling technologies along the way, including automated control of cell resistance and alumina feeding via distributed microcomputers, improved cell designs supported by computer modelling, dry scrubbing and recycle of cell emissions, and increasing levels of sophistication in automation of cell tending and anode processing operations. These improvements have not only underpinned new cell designs, but have also been retrofitted to existing smelters enabling extension of their viable economic life through current creep and improved environmental performance.

There are now indications that the productivity improvement pathway via increasing current, and increasing current density in particular, has run its course. In recent years we see Faraday efficiency, cathode life and net carbon consumption in decline in our modern smelters where current density has been maximised at the expense of other important physical aspects of the process such as electrolyte volume, uniformity of current distribution, and electrode polarisation [1].

At the same time, a new paradigm is emerging to challenge the direction of technology development for the aluminium industry– how to reduce the CO_2 emission from the process (both direct and indirect Scope 2&3 emissions) in the context of a substantial cost that is likely to apply to this emission in future? The Elysis consortium including Alcoa and Rio Tinto are taking on the 'holy grail' challenge of the inert (oxygen-evolving) anode development [2], while Hydro Aluminium are revisiting the chloride electrolysis route [3] which was piloted by Alcoa more than 50 years ago. These are benchmark projects in the industry's quest for a net zero primary aluminium production, but with potentially long and high-risk pathways to commercialisation.

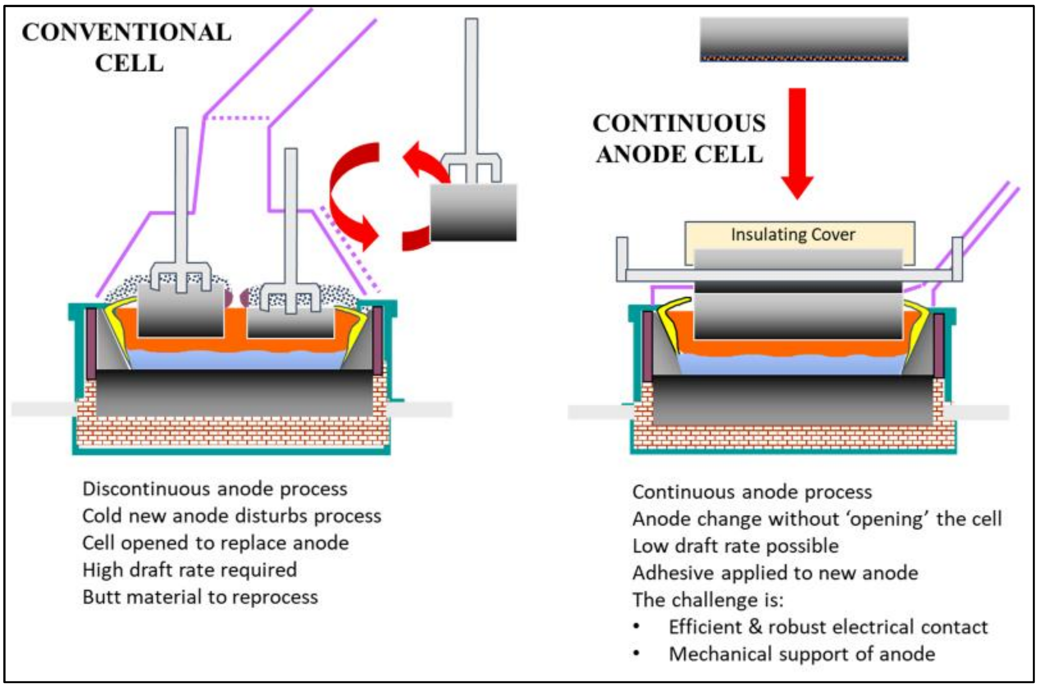
The continuous prebaked anode (CPA) technology offers a different route to net zero CO_2 emission, in addition to its *many* other advantages over conventional prebaked anodes. Specifically, it offers:

- Elimination of the anode butt recycle requirement, reducing the anode baking fuel consumption by 20-25 % (Scope 2 emission).
- Reduction in the net consumption ratio (Scope 1 emission) by around 5% through improvement in anode reactivity as a result of elimination of the butt component.
- Much tighter sealing of the cell from the atmosphere, increasing the off-gas CO_2 concentration to a level where carbon capture becomes economically viable.
- Retrofit capability to existing smelters.

In contrast to the inert anode and chloride electrolysis processes which require significant breakthroughs in materials and /or process engineering, the CPA technology is primarily a challenge for cost-effective mechanical engineering employing conventional materials and processes. It is the 'diamond in the rough' that these authors believe is ready to be polished!
The Urban Dictionary – Diamond in the Rough: "Someone (or something) that has hidden exceptional characteristics and/or future potential, but currently lacks the final touches that would make them (or it) truly stand out from the crowd."

2. The Continuous Prebaked Anode – Concept & Fundamental Challenges

A conceptual comparison of the conventional prebaked anode cell and the CPA cell is shown in Figure 1. In the CPA cell, the consumable anode is replenished without any interruption to the process. As the cell is sealed with off-gas being contained below the upper surface of the anode stack, there is no need to break the seal or open the cell for anode replacement. The new anode is glued to the anode below on which it rests, and the glue is cured when the anode reaches a targeted temperature. The anode stack can be covered for thermal insulation purposes and for protection from oxidation (airburn).



Discontinuous anode process
Cold new anode disturbs process
Cell opened to replace anode
High draft rate required
Butt material to reprocess

Continuous anode process
Anode change without ‘opening’ the cell
Low draft rate possible
Adhesive applied to new anode
The challenge is:

- Efficient & robust electrical contact
- Mechanical support of anode

Figure 1. Conceptual comparison of conventional and CPA cells.

The key design challenges for a successful CPA technology are:

- ***An efficient and robust electrical contact system***. The electrical contact may be stationary with respect to the anode surface, and moved upward periodically with the anode busbar (analogous to the anode beam raising operation in conventional cells), or alternatively it may be at a fixed location with the anode moving through the contact in response to its consumption (analogous to a carbon brush contact).
- ***A robust mechanical support system for the anodes***, which is optionally integral with the electrical contact system. The mechanical support system must accommodate the demanding temperatures, stresses, and corrosion characteristics of the service environment. The anodes may optionally span the full width of the cell (as shown in Figure 1) or preferably be contained in cassettes enabling use of smaller anodes offering more efficient anode gas release.
- ***An effective gluing material***, which must be electrically conductive in the cured state and have sufficient strength to resist stresses across the working temperature range. It must also resist the stresses imposed by the support frame and contact system when the glued anode joint moves past them.
- ***Operability aspects*** including thermal balance adjustment for the tall anode stack, avoidance of airburn potentially induced by ‘chimney effect’ in the gaps between anodes, removal and replacement capability for defective anodes, cell preheating process etc which would be refined through operating experience.

3. Comment on the Energy Requirement for a CPA Cell

It is important to note that the conventional prebaked anode assembly is inherently very efficient with respect to its electrical resistance / voltage drop, since the conducting stubs can effectively span the anode top surface area and at the same time reach close to (and eventually below) the electrolyte surface to provide a very low current path length. In contrast, a CPA anode will have its electrical contact at the perimeter of the anode, with a current path length determined by the anode area and the minimum acceptable distance between the electrical contact and the electrolyte surface without incurring damage to the contact system.

It is apparent from the above that there is likely to be a higher anode voltage drop of the order of 0.3-0.5 volt for a CPA cell, and potentially a higher heat loss from the cell associated with the tall anode stack, when compared with conventional technology. This higher energy demand will be partly offset by the elimination of hot butt replacements during conventional anode change, and the capability to cover and insulate the CPA stack.

As a competitor to the inert anode in the quest for a zero direct CO_2 emission technology (incorporating carbon capture from the CPA off-gas stream), it should be considered that the inert anode cell will itself incur an additional voltage penalty of approximately 1 volt due to the higher reversible potential for an oxygen-emitting anode. In a retrofit cell application where the heat losses from an inert anode cell will be similar to the conventional prebaked anode cell, it has been estimated that the overall energy requirement of the inert anode cell will be around 3 MWh/t Al higher than for conventional technology [4].

Increasing power prices have in the past led cell technology development in the somewhat competing directions of higher capacity / current creep, and lower specific energy consumption as the drivers of technology value. Let us put specific energy consumption into an economic context against the new paradigm of carbon emission cost, assuming the smelter is supplied from a renewable (zero carbon) power source. If the inert anode cell requires an additional 3 MWh/t Al, at an industry typical power price of \$50/MWh, we have an additional power cost of \$150/t Al. The inert anode will also avoid approximately 1.5 tonnes direct CO_2 emission per tonne Al, with the current carbon permit market in Europe for example at around \$110 per tonne CO_2. Put simply, the additional power cost is more than offset by the saving in CO_2 cost in this example. For the CPA cell, any potential increase incurred in specific energy consumption should therefore be reconciled against concurrent savings in CO_2 emission. A reduction in CO_2 emission has significant economic value, which can be expected to increase relatively faster than the cost of renewable energy into the future.

4. The Advantages of Continuous Prebaked Anode Technology

The advantages of CPA technology are many.

4.1 Cost Savings Through Elimination of the Anode Butt Recycle

From a lean manufacturing perspective, the complex operations to recover and recycle anode butt material should be considered as waste, since they add no value to (and in fact detract from) the cost and quality of the product aluminium. The process and material waste incurred by anode butt recycle are indicated in Figure 2.

Specifically, elimination of anode butts brings the following substantial benefits:

- Elimination of complex rodding room and ancillary operations that typically represent 10% of the smelter capital cost. For a modern smelter at say 750 000 tonnes per year capacity this represents savings of around \$450 million in capital cost.
- Reduction in operating costs primarily associated with elimination of butt processing, reduced processing rate (and fuel consumption) through the anode baking furnaces by 20-25 %, and elimination of rodding operations. Put simply, the gross carbon requirement becomes the net consumption ratio. Collective operating cost savings of around 5 % are estimated, equivalent to around \$80 million per year for the same 750 000 t/y capacity smelter.
- Refractory condition in the anode baking furnaces is significantly improved by the elimination of fluoride-contaminated butts, and there is the opportunity to avoid

scrubbing of the baking furnace exhaust for fluoride removal where such requirements currently exist.

- The CPA technology brings new capital and operating costs in the form of additional cell superstructure complexity, machining of anode surfaces to accommodate top surface gluing and electrical contact to the side faces, and glue application. Estimates of these costs at approximately $200 million CAPEX and $30 million per year OPEX have been allowed for within the savings estimates provided above.

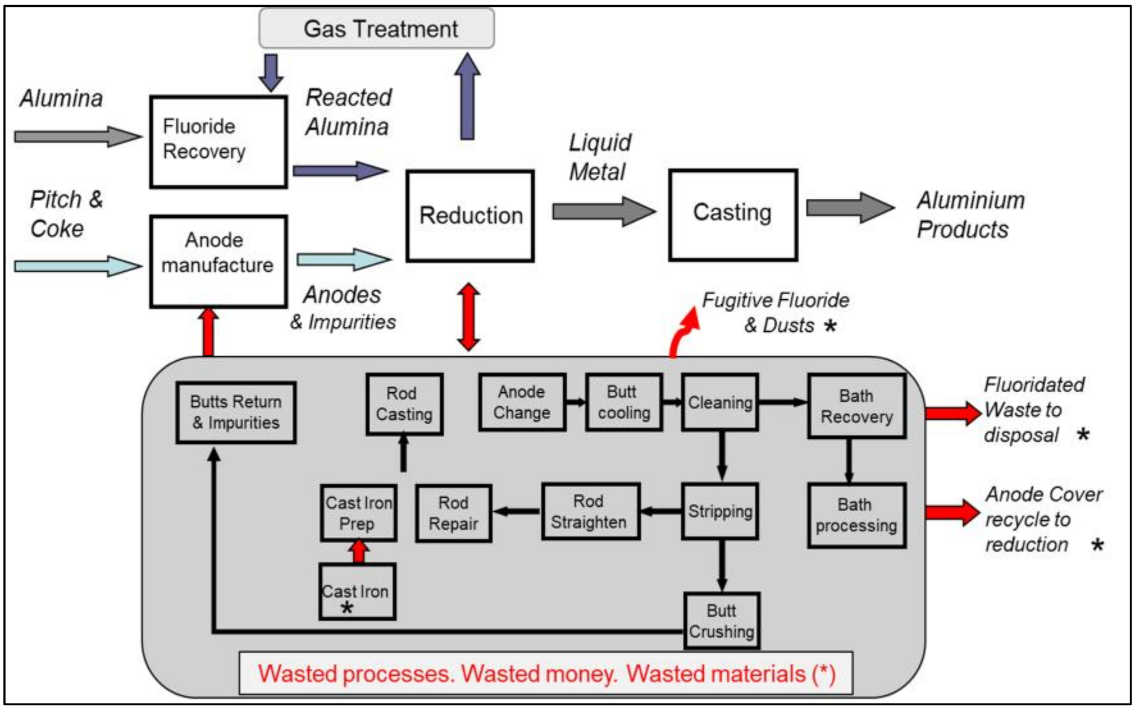


Figure 2. Anode butt recycle from a lean manufacturing perspective.

4.2 Operational Improvements through a Simplified Anode Change

The anode replenishment process is achieved without interruption to electrolysis or the need to open the cell to atmosphere. This brings many benefits and indirect cost savings that are difficult to quantify but are nevertheless significant:

- The cell operation becomes more continuous in nature by eliminating its biggest process discontinuity - anode butt removal and setting of the new, cold anode. This has direct benefit for thermal stability, bath chemistry stability, alumina solubility, avoidance of anode effects, and avoidance of anode problems generated by thermal variation such as cracking and spiking. These benefits are ultimately reflected in higher current efficiency, lower specific energy consumption and lower anode consumption.
- The anode replenishment process is much faster to perform. There is no requirement for use of anode covering material, eliminating a significant cause of cell variation and of fugitive dust emission. The avoidance of cross-contamination between cells using recycled cover material also opens the pathway for different cells targeting different chemistry settings or product purity targets.

4.3 Occupational Health & Safety Improvement

The anode replenishment is achieved without exposure of the operator to an open cell and associated contact with radiant heat, dusts and fume. The conventional anode change process and associated transport and handling of butts are major causes of OH&S exposure by operators. Their elimination may provide a pathway for reduced personal protective equipment requirement by operators under normal working conditions.

4.4 Anode Quality Improvement through Elimination of the Butt Recycle

- Sodium impurity in the anode introduced by butt contamination is a major cause of anode reactivity in the cell. Air oxidation and carboxy reactivity are both adversely affected by the sodium contamination and have a direct impact on the net carbon consumption and hence also the CO_2 emission. Indirectly, the reduction in anode area caused by these reactions adversely affects most other performance KPIs and operating cost.
- The elimination of the butt recycle also opens the opportunity for smelters to buy anodes externally from specialist producers of potentially higher quality.

4.5 Improvement in Aluminium Purity

Iron contamination by electrolyte corrosion of the anode stubs is the main source of contamination of the aluminium product. An effective CPA design will significantly reduce the opportunity for iron contamination.

4.6 Reduction in Fugitive (Roof) Emission of Dusts and Fluoride

The conventional anode change process is the major source of fugitive dusts and gaseous fluoride emissions which are subject to license regulation. These emissions predominantly occur during the anode change and covering process, through butt transport, butt cooling and cleaning, and anode cover recycling operations. All these operations are eliminated by the CPA technology.

4.7 The Opportunity for Improved Cell Sealing

The conventional cell design requires removable hoods to isolate the process from atmosphere, as individual hoods require removal to enable the anode change operations. An anode replacement is shown in Figure 3. In order to minimise fugitive emissions during anode replacement, each cell is operated under negative pressure (approximately -500 Pa) with draught rates typically of the order of 150 Nm^3/min for a modern 350 kA cell. The gases released from the anode (predominantly CO/CO_2 in approximately 5:95 weight ratio) are diluted around 100-fold and cooled to around 140°C by the very large quantity of air drawn into the system. This large air dilution factor makes carbon capture or heat recovery from the cell exhaust stream unviable.

Figure 3. Anode change in a conventional cell.

In contrast, the CPA technology does not require open access to the cell for anode replenishment. This enables sealing of the cell more effectively below the level of the anode top surface, with a major reduction in the air dilution requirement and therefore opportunities for:

- A CO_2 capture system from the concentrated gas stream
- Heat recovery for utility heating or generating usable steam for power generation
- Major reduction in the size of the fluoride scrubbing system, possibly installing an individual scrubber at each cell based on counter current contact with the incoming alumina supply.

These possibilities represent a future pathway for cell development, with CPA as the enabling technology. The viable extent of dilution of the exhaust gas stream by air will depend on factors such as CO concentration avoiding explosion limits, temperature limits for the CPA frame infrastructure, and target temperatures for the scrubbing operations.

5. Prior Development of Continuous Prebaked Anodes

The continuous prebaked anode concept is not new. VAW operated the small Elbewerk smelter using CPA technology until its closure in 2006. A detailed description of the technology and its performance is provided by Scholemann & Wilkening [5]. Developed in the 1950s as a retrofit of a horizontal stud Soderberg cell, and known as the Erftwerk cell, the technology was applied at various VAW smelters in Germany including the larger Rheinwerk plant from 1962-1984, when it was replaced by conventional prebaked anode technology in a modernisation program.

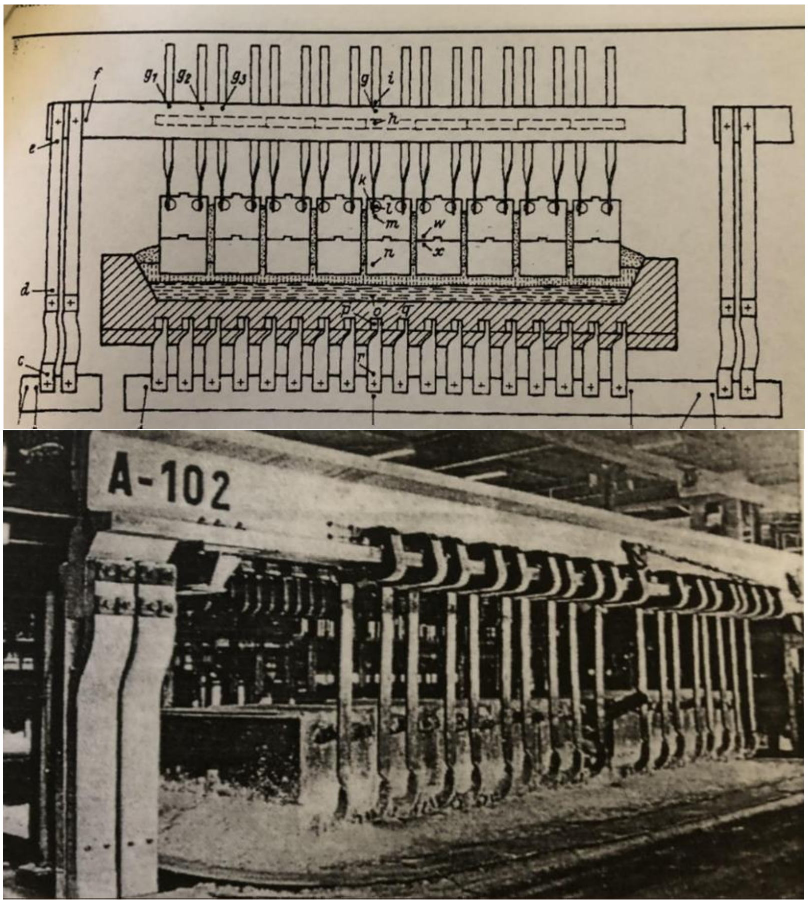


Figure 4. VAW Erftwerk cell.

Over more than 50 years of operating experience VAW developed operating systems and a robust anode gluing system (based on petroleum coke and pitch) to support the CPA technology. The principal weaknesses that prevented further application were its labour-intensive side break feeding and stud removal operations. The anodes were almost one metre tall, so that when studs were raised to the upper anode position a significant voltage increment was incurred, which was incorporated into the control system voltage regulation.

The VAW experience clearly pointed to the need for a more efficient electrical contact system if CPA technology was to progress and compete with conventional prebaked anode technology. One such system was developed and patented by Dr Siegfried Wilkening of VAW [6] during the later years of operation at Elbewerk, but was not implemented as the plant was already slated for closure. The design used a packed bed of granular graphite contained within a high temperature steel cassette surrounding each anode, which provided both mechanical support and electrical contact to the anode, as shown in Figure 5. The cassette was raised periodically (after release of pressure on the graphite bed) by an independent jacking frame also supporting the anode stack.

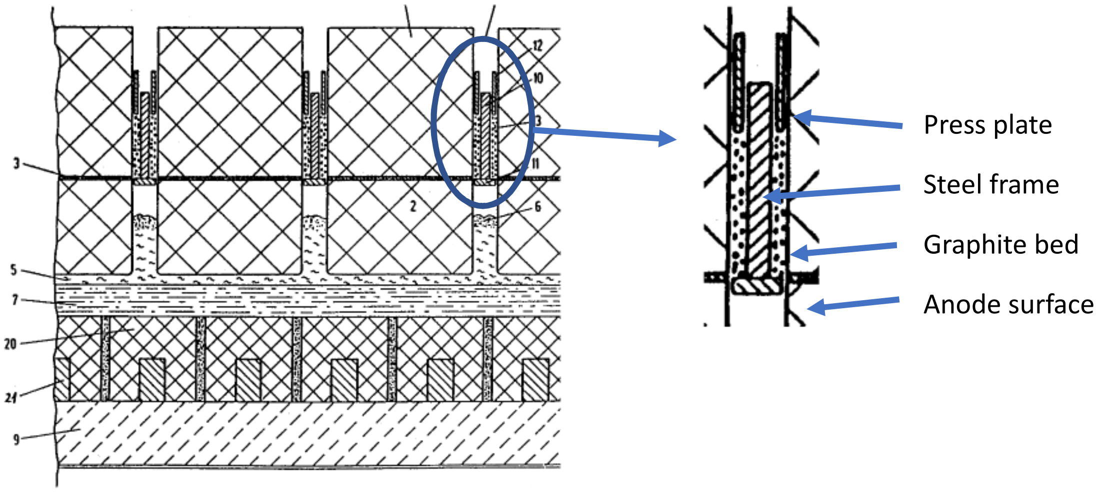


Figure 5. Wilkening patent [6] using pressed granular graphite electrical contact.

While the graphite bed contact system offered a good electrical contact, issues were subsequently identified with respect to:

- High vertical force requirement to transmit sufficient horizontal force to the graphite bed for anode support. This translated to a need for strong / expensive frames to contain the stresses experienced at high operating temperature.
- High force requirement to raise the frame, as the graphite bed does not readily decompact on release of pressure.
- Potential for airburn of the graphite and subsequent loss of anode support.

Other potential CPA designs are described by patents assigned to Norsk Hydro [7] and Comalco [8] using direct clamping force and wedging plates respectively to provide both the electrical contact and the anode support. Both patents include the provision for heat exchange to lower the working temperature of the support structures. The Comalco patent includes the use of sacrificial aluminium as a contact medium between the anode surface and the contact plate to provide enhanced contact resistance.

6. Work by Aluminium Smelter Developments Pty Ltd (ASD)

In 2006 the authors formed a collaboration with Worley Parsons Pty Ltd to undertake design and bench-scale proving work for an improved electrical contact and anode support system for a CPA technology. This collaboration was in the form of a joint development company Aluminium Smelter Developments Pty Ltd (ASD). The ASD objectives in time sequence were to:

i. Obtain bench scale data at the expected service temperature to define the contact pressure required to achieve a satisfactory electrical resistance from steel to anode carbon.
ii. Explore innovative and mechanically efficient means to achieve that pressure.
iii. Develop concept designs for a technically and economically viable CPA contact system and support structure.
iv. Protect the IP generated via patents.
v. Identify and collaborate with an aluminium company to prototype and develop the proposed design within a smelter. Detailed engineering drawings to be developed at that stage.

This paper describes the work completed in i) to iv) above spanning a six-year period. A number of major aluminium companies were approached to extend the project to industrial prototyping but none were inclined to enter into a joint development. The work was subsequently put on hold.

6.1 Bench Scale Trials

The conventional anode stub is a highly efficient electrical contact as it generates compressive forces of around 5 MPa at operating temperature by virtue of the differential expansion of steel / cast iron versus carbon. A practical solution was required for a surface contact system that did not require large forces, cause material creep or uneven current distribution at the contact faces.

The initial work focussed on measurement of contact resistance between high temperature (stainless) steel and a carbon anode at different pressures. Different surface treatments were evaluated including the use of aluminium as an interfacial contact. A rig was fabricated (Figure 6) to undertake these measurements at temperatures up to 600 °C using anode sizes and current densities replicating the industrial scale. From these results it was concluded that a direct steel-carbon contact could provide an acceptable voltage drop (Figure 7).

Figure 6. The ASD test rig.

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6.2 A Mechanically Efficient Design

The focus then turned to the mechanical engineering challenge of how best to achieve the required contact pressure through a cost-effective design that would be robust to the challenging conditions of the cell environment. This ultimately led to the concept of counter-acting wedges placed under tension and forced onto shape-matched anode surfaces, where the contact pressure is delivered by independently controlled tensioning devices. The tensioned wedges provide both mechanical support and electrical contact to the anode. Anodes are arranged in cassettes of up to four pieces and the entire cell assembly is further contained within a tensioned frame that enables cell resistance regulation by vertical movement of the entire anode assembly. The design is described in patents assigned to ASD [9, 10, 11], from which the basic anode support principle is shown in Figure 8. Other views of a concept cell design are shown in Figures 9-11.

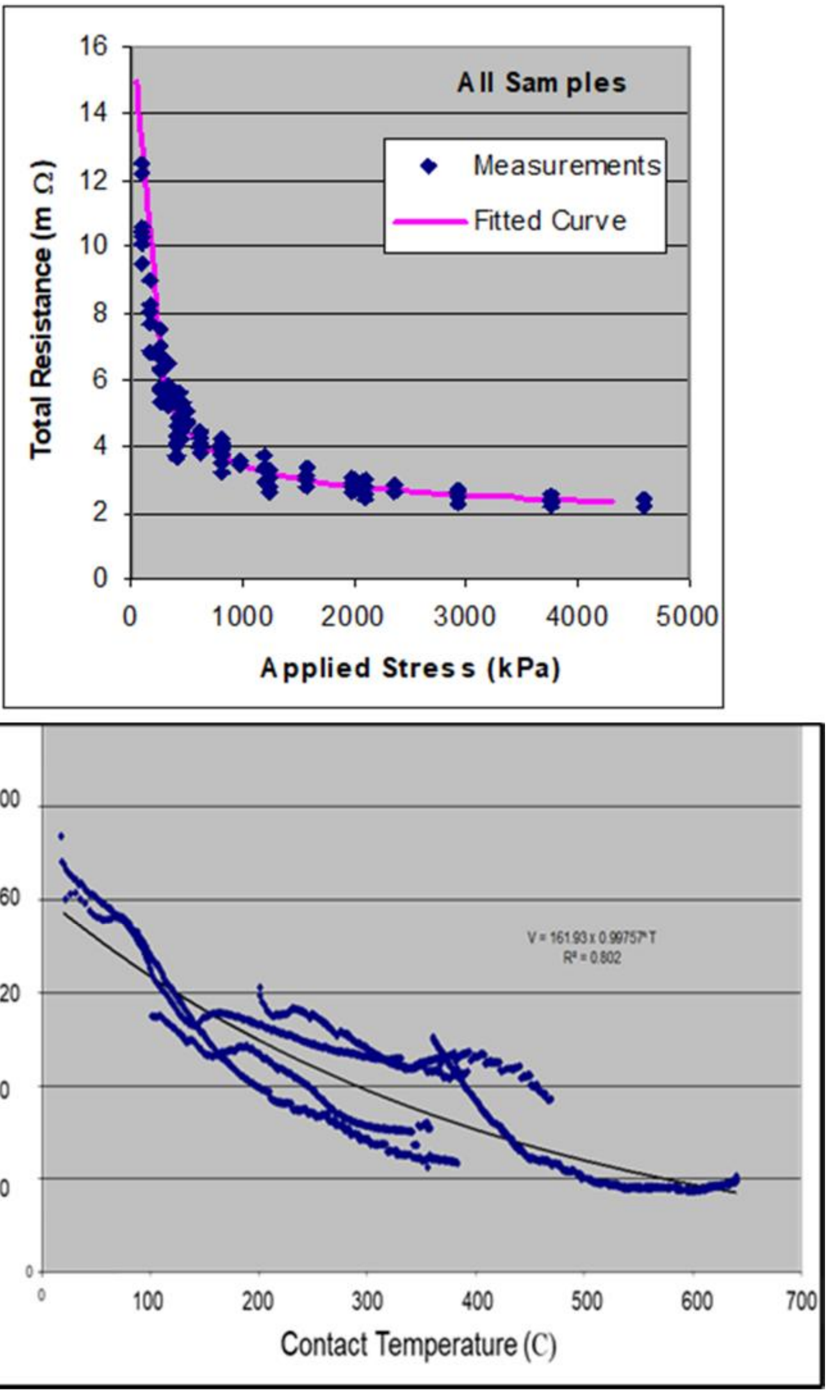
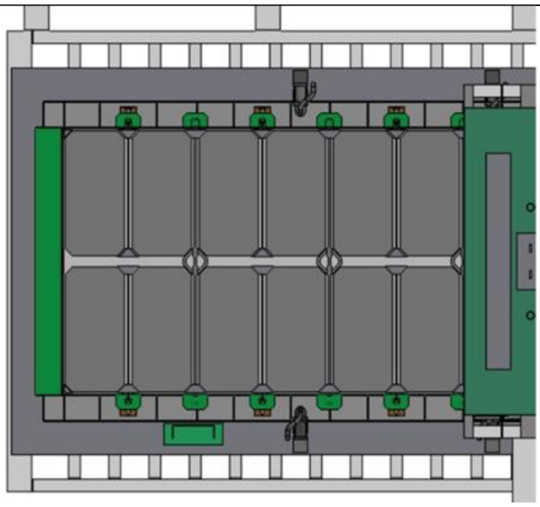
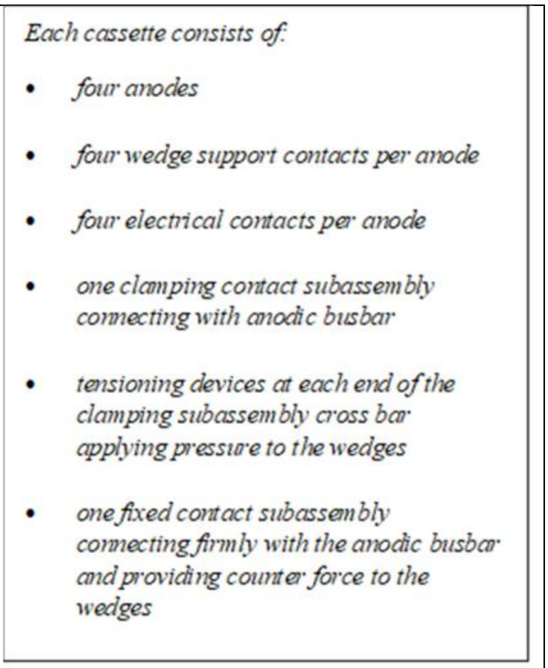


Figure 7 Test rig measurements.





Each cassette consists of:

- *four anodes*
- *four wedge support contacts per anode*
- *four electrical contacts per anode*
- *one clamping contact subassembly connecting with anodic busbar*
- *tensioning devices at each end of the clamping subassembly cross bar applying pressure to the wedges*
- *one fixed contact subassembly connecting firmly with the anodic busbar and providing counter force to the wedges*

Figure 8. Contact system schematic (part cell view from top).

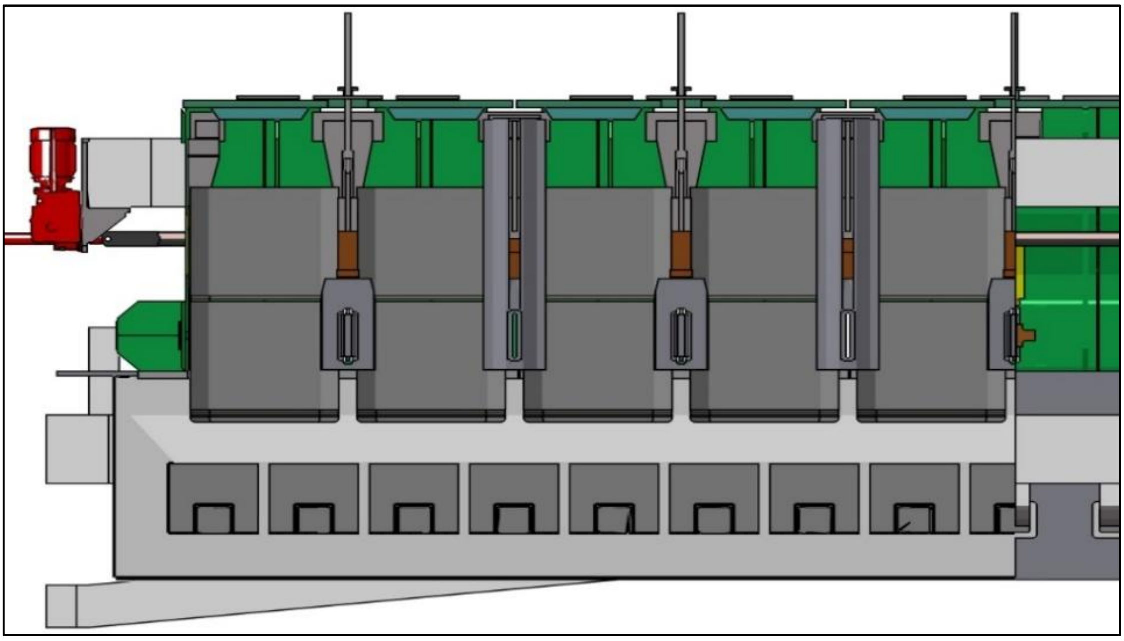


Figure 9. Concept cell side view.

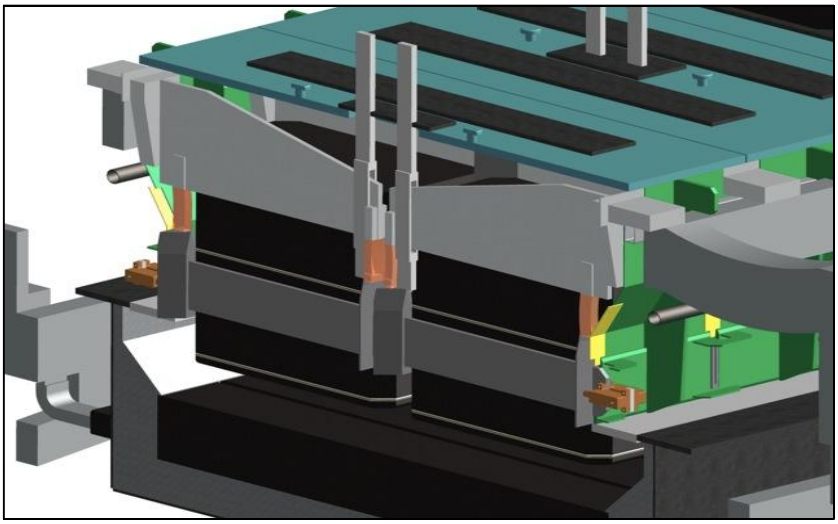


Figure 10. Concept cell section view showing clamping subassembly.

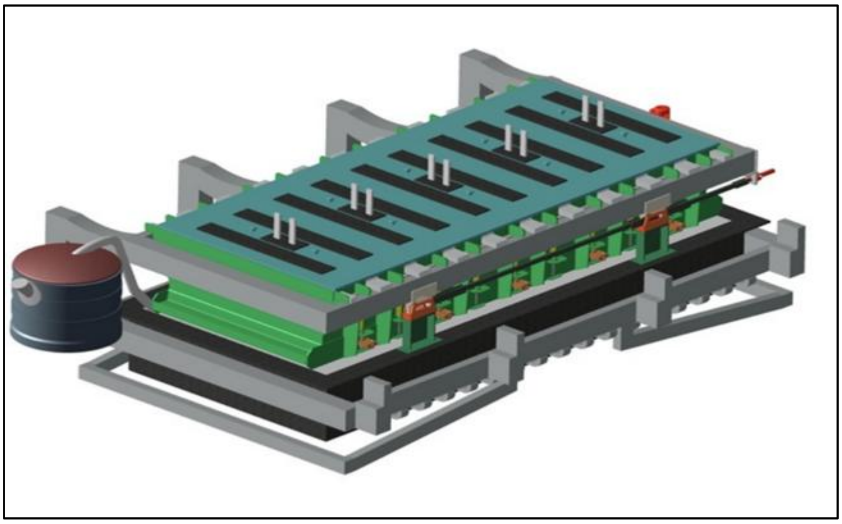


Figure 11. Concept cell showing assembly support frame.

6.3 Operating Considerations & Design Challenges

Many operability considerations were involved in developing the concept design. Some of the more critical ones are described below.

- From an efficiency perspective, the anode area should be maximised within the available cell area. This favours large anodes spanning the full width of the cell. This approach carries some important disadvantages however, such as reduced perimeter for anode gas release, difficulties in producing the large anode size in a retrofit smelter, and the need to maintain electrical integrity of the cell should an anode fail and require replacement. Anodes of the typical conventional prebaked cell area were selected, with two anodes spanning the cell width. Alumina feeding may be achieved by increasing the spacing between selected cassettes, or preferably at the side channels.
- There is a requirement to provide a reasonably short current path length through the anode while at the same time keeping the contact system and anode support structure at an acceptable temperature. The preferred design provides for symmetrical electrical contact from the four corners of each anode enabling uniform distribution of current. A hollowed structure with internal air cooling may be required to maintain the integrity of the tensioning bars operating close to the electrolyte. Ultimately, the mechanical structures

may be protected from radiant heat by a permanent crust on the cell surface between anodes, noting that there is no requirement for regular breaking of the crust for anode change.

- Vertical movement of the anode stack is required for the routine operation of the cell to support resistance regulation, instability control, anode effect suppression and metal tapping. This is achieved by a jacking system which is mounted external to and on each side of the anode stack as shown in Figure 11. With normal pot control jacking, all anodes and their wedge assemblies move up and down with the anode beam as one fixed system.
- There is also the need to raise the contact system periodically relative to the anodes, to account for anode consumption. This will be achieved by a 'push down frame' placed on top of the cell to hold the anodes fixed while the supporting frames are raised. Tensioning is maintained on the wedges during this operation. This routine operation is analogous to the routine beam raising operation conducted on conventional cells. However, since raising the contact system will incur a step increase in the current path length and the anode voltage drop, it is desirable to do this operation more frequently. Frequent operation of the push down frame also allows the contact system to operate at a more stable temperature and distance from the electrolyte surface. A push down frame may be a fixture on each cell superstructure, or shared between a number of cells.
- Glue protection. The glue will pass through a soft / weak phase before it reaches its curing temperature on the anode stack. During the anode push down operation, it must therefore be protected from squeeze stress. It must also be protected from mechanical rupture in the cured state. This is achieved by anode surface machining and by maintaining a relatively small anode adhesion area.
- Control of anode airburn. This is a critical requirement for a technology that depends on anode surface integrity for its mechanical support. Design and management of an effective cell sealing and draught extraction system will be critical. The cooling system proposed for the tensioning bars, and the insulation covers on top of the anode stack, will also be critical components in the control of anode stack temperature and avoidance of airburn.

7. Conclusions

The potential advantages of a continuous prebaked anode technology are compelling across multiple considerations:

- Elimination of the anode butt recycle which brings operating complexity and cost to the smelter while adding no value to the product aluminium. This is a waste process in terms of lean manufacturing principles.
- Significant reductions in smelter capital and operating cost, and operating labour requirement.
- Elimination of the most hazardous smelter operator-process interfaces in terms of exposure to heat, dust and fume.
- Major improvement in fugitive fluoride emission by maintaining a sealed cell through the anode replenishment process.
- Elimination of the major process discontinuity and the many cell disturbances and process problems caused by anode change.
- Improvement in anode quality by elimination of the contaminated butt component.
- Improvement in metal quality by elimination of iron stub wash.
- The potential for viable carbon capture and heat recovery from the cell off-gas, by collecting the gas in a far more concentrated form.

There are challenges to solve to bring this technology to a practical and commercial reality. These challenges are not at the forefront of science however, requiring development of new materials or processes. They are challenges for our inventive capability to improve an existing process through the application of sound mechanical engineering, followed by the inevitable development pathway of prototypes to ultimately deliver a viable technology.

VAW demonstrated the CPA concept through nearly 50 years of commercial operation, albeit with significant need for further development of that technology. It is time for another look at this ‘diamond in the rough’ by those up for the challenge.

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