Final Technical Report

Project Title:	Reduction of Carbon Footprint and Energy Efficiency Improvement in Aluminum Production by Use of Novel Wireless Instrumentation Integrated with Mathematical Modeling
Award Number:	DE-EE0003500
Project Period:	08/16/2010 to 10/15/2011
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Date of report:	03/30/2012

Acknowledgments: This report is based upon work supported by the U. S. Department of Energy under Award No. DE-EE0003500. An in-kind cost-share from Alcoa is also gratefully acknowledged.

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Acronyms and glossary

ACD	Anode-cathode distance
AE	Anode effect
AWS	Amazon Web Services
BTU	British Thermal Unit
CE	Current efficiency
DS	Downstream (direction of current flow in potline)
GHG	Greenhouse gas
IAI	International Aluminium Institute
kA	kiloamp
kWh	kilowatt.hour
PFC	polyfluorinated hydrocarbon
US	upstream (direction opposite to current flow in potroom)
WIT	Wireless Industrial Technologies, Inc.

Alumina	aluminum oxide feed to a cell
Anode	carbon electrode in the cell
Anode effect	upset condition characterized by excess voltage and PFC emissions
Anode rod	metal rod from which the anode is suspended
Bath	molten salt electrolyte within the cell
Bus, busbar	large electrical conductor bringing current to/from cell and electrodes
Pot	electrolytic cell
Potline	line of a few hundred pots connected in series
Potroom	building housing potline

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Executive Summary

Scope and objective. The work, now completed, addressed the greenhouse gas emission and electrical energy consumption of the aluminum industry, within the US and worldwide. The objective of the project was to provide a means for reducing both through the application of wireless instrumentation, coupled to mathematical modeling. Worldwide the aluminum industry consumes more electrical energy than all activities in many major countries (e.g. the UK) and emits more greenhouse gasses (e.g. than France). Most of these excesses are in the "primary production" of aluminum; that is the conversion of aluminum oxide to metal in large electrolytic cells operating at hundreds of thousands of amps. These cells operate at an energy efficiency of only 45-50%, providing scope for efficiency improvements which themselves would bring reductions in GHG emission due to reduction in emissions from fuel burning power plants that are part of the mix of power suppliers to the industry. However, a more industry specific GHG emission has been the focus of the present work. The electrolytic cells periodically, but at irregular intervals, experience an upset condition known as an "anode effect". During such anode effects the cells emit fluorinated hydrocarbons (PFCs) at a rate far greater than in normal operation. These PFC have high "global warming potential"; a ton of emitted CF_4 has 6,000 times the greenhouse effect of a ton of CO_2. Thus curbing anode effects will reduce GHG emissions. Anode effects are marked by a sudden increase in the voltage across the cell and this is the present signal for a control computer to take corrective action to quench the anode effect.

Results. Prior work by the recipient company (Wireless Industrial Technologies – WIT) had indicated that the distribution of electrical current within the cell experiences significant shifts in the minutes before an anode effect. The thrust of the present work was to develop technology that could detect and report this early warning of an anode effect so that the control computer could avoid the anode effect altogether or at least reduce its duration. A system was developed to achieve this goal and, in collaboration with Alcoa, was tested on two cells at an Alcoa plant in Malaga, Washington over a period of many months. Ample evidence was gathered that the current redistribution, seen in a few instances in earlier work, occurred with all anode effects of the investigated cells. In most instances the early warning of the anode effect was sufficient (~20 seconds to a few minutes) that the control computer would have been able to exploit the warning to avoid or reduce anode effects. Alcoa's analysis of the data from the WIT project showed the same early warnings.

The project has also pointed to the possibility of additional improvements that could result from measurement of the current distribution. Notable among these is an improvement in efficiency (current efficiency) that could result in an increase in cell output at little extra operating cost.

Prospects for commercialization have emerged in the form of purchase orders for further installations. The commercialization plan is to continue growth of WIT though application of the technology, brought to commercial viability by this project, at aluminum smelters worldwide.

Conclusions and recommendations. The work has demonstrated that a system for monitoring the current of individual anodes in an aluminum cell is practical. Furthermore the system has been installed twice on a smelter in the US without exposing workers to hazard usually associated with running signal wires in aluminum plants; this avoidance of hazard results from using wireless transmission of data from the cells to a computer. The results display the "early warning" of an anode effect that potentially can be used to minimize such anode effects with their excessive GHG emissions. They also point to a possible, but substantial, economic benefit that could result in improved current efficiency by anode adjustment based on individual anode current measurements.

It is recommended that the aluminum industry continue testing of this technology; no direct government involvement is necessary unless unforeseen difficulties arise. It is recommended that DOE consider supporting the application of wireless measurement systems to other heavy industry that can benefit from such measurements, notably the chlor-alkali, copper and zinc industries where production relies on electrolytic technology akin to that of the aluminum industry.

1. Introduction

The objective of the project was a substantial reduction in the greenhouse gas emissions of the aluminum industry (estimated to be 17-25 million metric tons per year in the US alone) through

- Minimization of emissions of PFCs occurring in the large electrolytic cells, used for primary aluminum production, during an upset condition, known as an "anode effect".
- Reduction in the electrical energy consumed in primary aluminum production.

[Primary production of aluminum is the electrolytic reduction of aluminum oxide in the large electrolytic cells – "pots" in the terminology of the industry – of a smelter.]

Both reductions were sought by wireless instrumentation for measuring cell parameters that are not presently measured on a commercial scale. Concept definition wherein novel wireless sensors, for measuring electrical current distribution within cells, are built and tested (ultimately in an aluminum plant) with guidance from mathematical modeling, was the focus of the work.

A typical aluminum cell has 18-30 carbon anodes dipping into the electrolyte of the cell; current flows down through "anode rods", from which the anodes are suspended, and into the electrolyte. A typical plant would have a few hundred cells. The methodology employed in the project was the measurement of current distribution among the anodes of the cells. Such measurements, which have only been done intermittently hitherto, permit a significant improvement in cell performance: the early warning of an imminent anode effect so that the control computer can act to avoid or minimize that effect and its associated emissions. The methodology was embodied in a "master and slave" system whereby "slaves", containing sensors for measuring (indirectly) the current passing through each anode of a cell were connected to a "master" that provided power and onward (wireless) transmission of measurements to a computer connected to the internet where data were processed and archived. The master and slave system was developed by the recipient organization, Wireless Industrial Technologies (WIT).

The project was a collaborative one with Alcoa providing a cost-share in-kind. Alcoa provided two cells at one of its smelters, together with manpower to assist in the test work at the smelter. WIT and Alcoa independently analyzed the data to determine whether early warnings of anode effect were indeed realized.

A second benefit of anode current measurements is that it provides another indicator of cell performance, and one that might have a direct economic benefit. The performance of a cell is frequently judged by its "current efficiency" which is a measure of productivity and is indirectly linked to the energy efficiency of the cell. Work at Alcoa has indicated that current efficiency is lowered if the distribution of current among the anodes is skewed. Consequently the results of the work might provide an opportunity for improved current efficiency and plant economics.

2. Background

As is evident from Fig. 1, a large fraction of the greenhouse gas emissions of the World are emissions resulting from manufacturing. Of those manufacturing emission, the making of metals, including aluminum, are a significant part.

According to the January, 2012 statistics of the International Aluminium Institute[i], the world produced 43.4 million metric tons of primary aluminum in 2011, the largest production ever, of which 5.0 million metric tons were produced in North America. Of those, 2.0 million tons were produced in US primary smelters[ii]. Pots emit fluorinated hydrocarbons (PFCs) in quantities large enough to contribute significantly to climate change. In particular CF_4 and C_2F_6 are emitted; the former has a Global Warming Potential of 6,500 (i.e 1 ton of CF_4 has the global warming effect of 6,500 tons of CO_2) while the GWP of the latter is 9,200[iii]. These PFC emissions occur mostly during a pot upset condition, known as an “anode effect” that is described in detail below. By minimizing the occurrence and duration of anode effects the industry has been able to reduce PFC emissions but, according to the IAI there were still 0.7 tons CO_2 equivalents per ton of aluminum produced in 2007 due to anode effects [i].

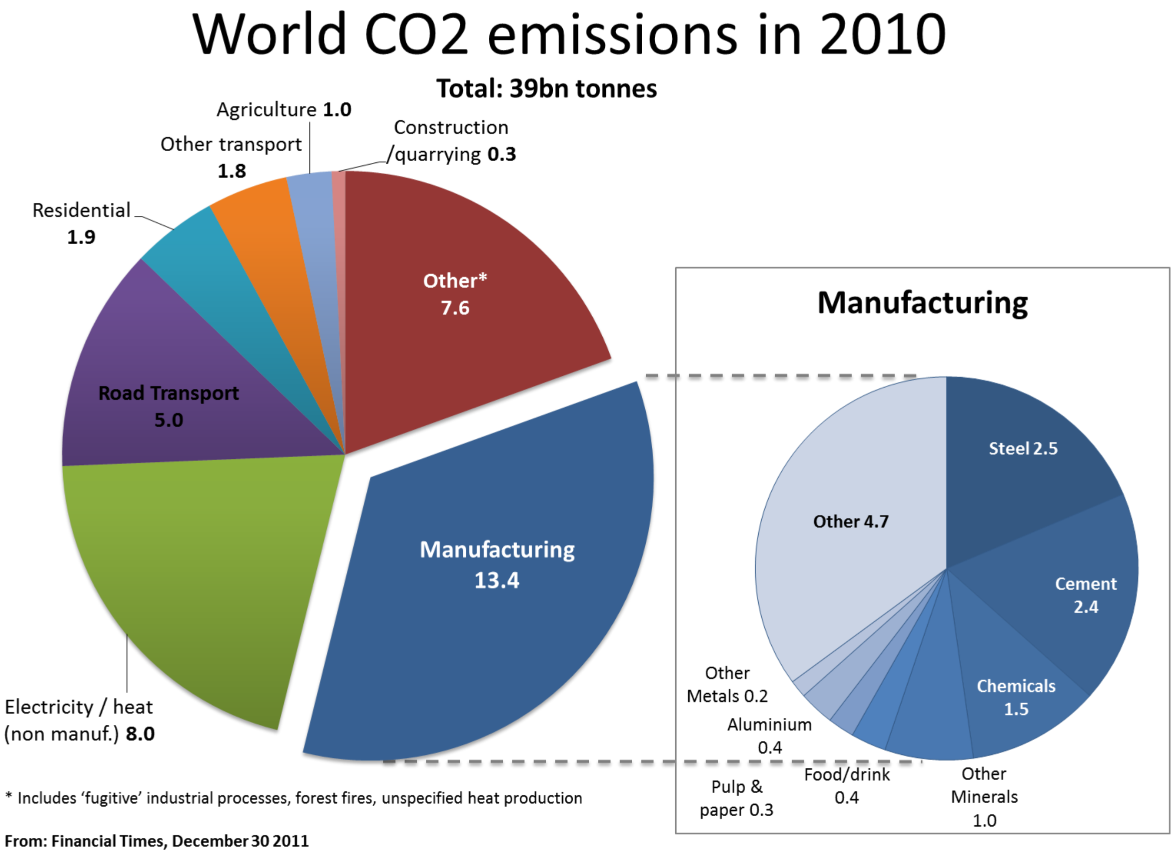


Fig. 1. Emissions of GHGs (CO_2 equivalents), from data of the Financial Times.

The contributions from CO_2 generated by the electrolytic reaction within the pot itself (1.22tons CO_2/ton Al), from adventitious "air burning" of the carbon anodes (0.3 tons CO_2/ton Al) and from burning of fuel in the furnaces making anodes (0.12 tons CO_2/ton Al)[iv] add to the numbers above. Myklebust and Runde [v] have estimated the CO_2 emissions at the power plants producing electricity for the aluminum industry as ranging from 0.41 to 0.67 tons CO_2/kWh. Applying these values to the energy consumption detailed below and totaling the CO_2 emissions, yields 378 to 552 million metric tons of CO_2 (or equiv.) emissions per year due to primary aluminum production of which 17 to 25 million metric tons are estimated to be produced in the US. For comparison, the GHG emissions of the whole of France, for all activities, are 374 million metric tons (CO_2 equivs.) per year[vi].

422,000 gigawatt.hours of electricity were used globally for primary aluminum production in 2010. This gigantic consumption of electricity in the production of aluminum exceeds the electrical energy consumed by the whole of the UK (344,700 gigawatt.hours in 2008)[vii]. And yet the efficiency with which this energy is consumed is only 40 to 45%. That is, 40-45% of the electrical energy entering a pot is required to bring reactants to reaction temperature and break chemical bonds; the remaining 55-60% becomes waste heat and there are no methods commercially practiced for recovery of that waste heat. [The thermodynamic requirement for electrical energy is 6.34kWh/kg aluminum (see "Aluminium Smelter Technology" by Grotheim and Welch, P83[viii]) while IAI statistics show actual energy consumption ranging from 14.6kWh/kg to 15.7kWh/kg of aluminum.] There are therefore major opportunities for saving energy, and thereby greenhouse gas emissions associated with burning fossil fuels, if the energy efficiency of primary aluminum production can be raised.

Fig. 2 is a drawing of a pot in cross-section. The pot would typically be approximately 10 ft in horizontal dimension, 10 ft tall and 40ft or more in the direction perpendicular to the plane of the figure. Current flows from top to bottom in the cell starting at the anode busbars running along the top of the cell, down the anode rods from which carbon anodes are suspended and into those anodes. The anodes, there are usually between 20 and 40 per pot – 14 per side in the pots of Figure 1 - , are partially immersed in a molten salt electrolyte (mostly sodium and aluminum fluorides) at 950-9600C. At the anode-electrolyte interface a reaction occurs, consuming the carbon anode and producing CO2; the oxygen of the CO2 is from aluminum oxide fed to the cell periodically. Current flows down through the electrolyte to the surface of a pool of molten aluminum metal below the molten salt. This distance through the electrolyte (the anode-cathode distance or ACD) is approximately 40mm and is crucial to the energy performance of the pot as it is here that approximately 40% of the electrical energy is dissipated in mere resistive heating of the electrolyte ("bath" in industry terminology). At the bath-metal interface a second reaction creates aluminum from the aluminum oxide fed to the pot. The current continues on its way down through the metal pool, into the carbon lining of the pot and thence exits the pot along steel "collector bars" set into the carbon lining. The collector bars are connected to a cathode busbar running around the outside of the pot. From the cathode bus the current flows upwards and over to the anode bus of the next pot in line along a "riser" (not shown in Fig. 2).

Fig. 3 is an overhead view of a typical smelter with a scale attached showing the size of the potrooms. This and Fig. 4 illustrate the need for efficient transmission of data over large distances if effective monitoring and control of an aluminum smelter is to be achieved. Wireless sensor networks are a cost effective and efficient means to this end

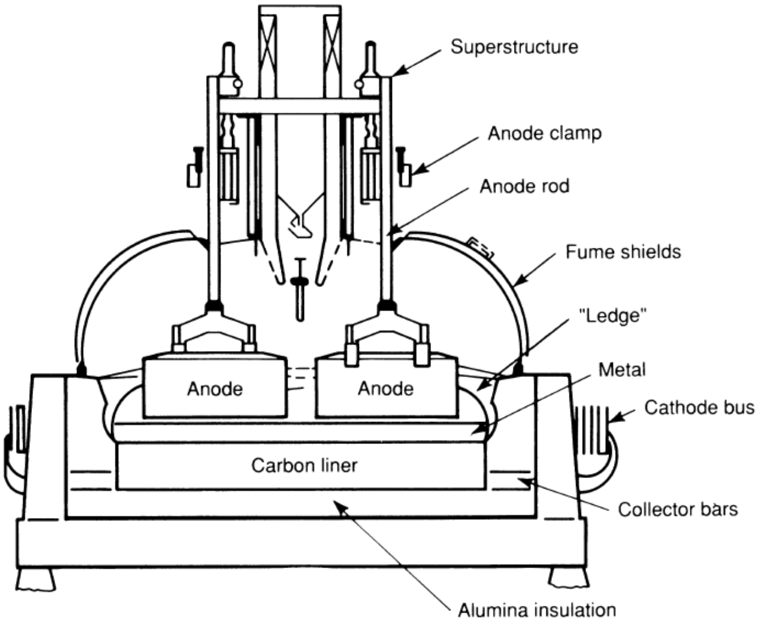


Fig. 2. Cross section of an electrolytic cell ("pot") used in the production of aluminum.

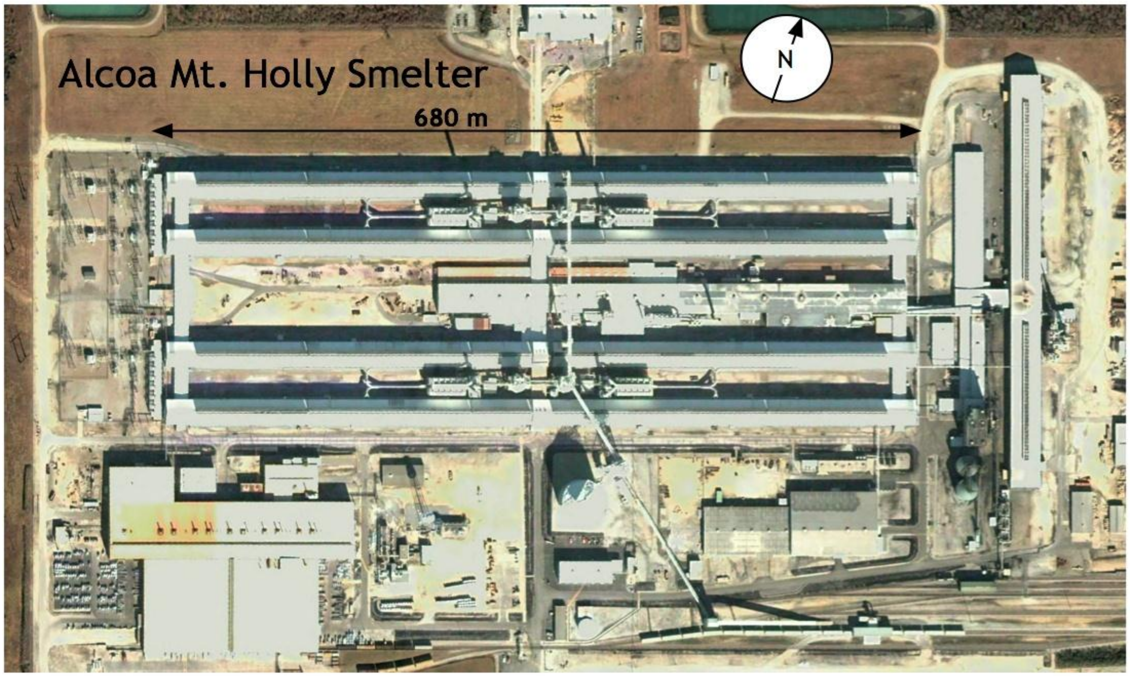


Fig. 3. A typical primary aluminum plant ("smelter"). Note lengths of the buildings ("potrooms"), each containing a potline of a few hundred cells ("pots")

3. Results and discussion

3.1 Hypothesis and experimental approach

The hypothesis behind the work was that the very large environmental impact and energy consumption of the World's aluminum industry could be mitigated by the improved instrumentation that wireless technology permits. Because it is primary aluminum production that is responsible for GHG emissions and large consumption of (electrical) energy within that industry, it is this part of the aluminum industry that has been the focus of the present project.

Primary production of the aluminum is the electrochemical reduction of aluminum oxide (alumina) to aluminum in large electrolytic cells ("pots"). While many cell variables are amenable to measurement, but not presently measured, the distribution of DC currents among the anodes of the cell was thought to be the most likely to yield benefits in GHG reduction and energy conservation. As discussed above, GHG emissions peak during a cell upset condition known as an "anode effect" (AE) and prior work at WIT[ix] and elsewhere[x] had demonstrated that, a minute or so before a typical cell experienced an AE, the currents started to redistribute themselves among the anodes, providing an early warning that the plant computer could exploit to prevent/minimize the AE. Prior work had also indicated that the electrochemical efficiency of the cell ("current efficiency" – CE) is impacted if the current is not uniformly distributed among the anodes, which happens as a consequence of the consumption of the carbon anodes and their periodic replacement by operators. Thus measurement of current distribution among the anodes also provides an opportunity for improvement of CE by equalizing anode currents.

The experimental approach was to employ anode current measurement that was "wireless". Fig. 4 is a photograph taken within a primary aluminum plant. About fifty cells can be seen in a line of, perhaps, a couple of hundred. Inspection of the photo shows "anode rods" – in this case 14 per side – protruding upward from each cell. These are the rods, from which the anodes are suspended, that carry current down to the anode from the "bus" to which the rods are attached. It is standard practice to measure the cell voltages continuously in such plants. No other continuous measurements are made on the cells because of the difficulty, cost and hazard of running signal wires. The voltage across a cell is normally 4-4.5V DC so that, connected in series, the cells have lethal voltages compared to ground. Long metal objects such as signal wires are therefore anathema in the plant; most plants have strict safety codes preventing use of metal ladders, tape measures, power tools etc. Relaying data from cells is therefore best practiced wirelessly or using optical fibers, although there is tolerance of signal wires around each cell as long as there is no link to ground or the other cells. The approach adopted was a "master and slave arrangement" whereby each cell had a "daisy chain" of slaves on each side of a cell. The slaves were placed alongside each anode rod and detected the current in that anode rod (thereby anode) and relayed it to a master (one of two) at the end of the cell.

Fig. 5 is a photograph of a slave, mounted in an "enclosure" that was under test at WIT prior to shipment to the smelter for the field trial. The printed circuit board seen in Fig. 5 is only 18mm high and has five Hall effect sensors that respond to the magnetic field generated by the current in the adjacent anode rod.

Fig. 4 . A line of cells within an aluminum plant. Approximately 50 cells ("pots") can be seen but there could be 200 or more cells, connected in series, in this "potline". Two workers can be seen at the upper right.

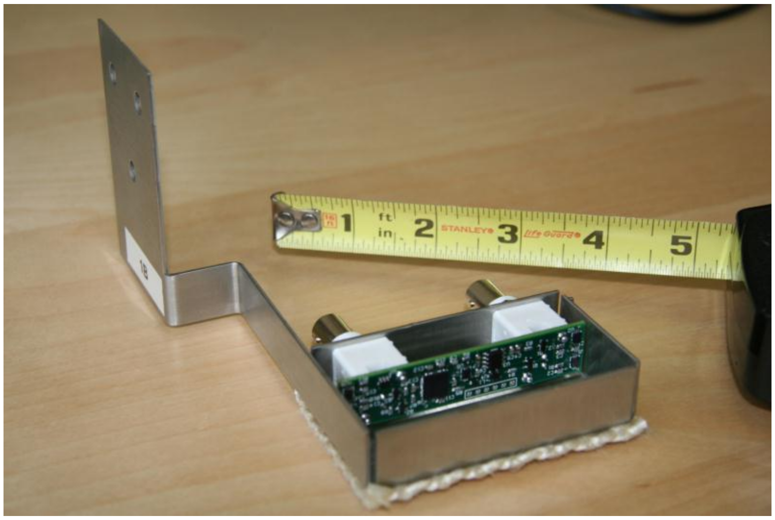


Fig.5 . A "slave" mounted in a stainless steel "enclosure". Scale is in inches.

[The sensors were; a pair of high sensitivity, a pair of intermediate sensitivity and a low sensitivity sensor. In this way the likely range of magnetic field was covered and the requirement for a minimum of two sensors per slave, discussed below, satisfied.] The field values are relayed along co-axial cable connected to the BNC connectors seen at the back of the circuit board. In this way only one cable runs down each side of the cell and this cable supplies power to the slaves and is a conduit for the data generated by the slaves. This non-contacting approach to anode current measurement is regarded as superior to contacting methods (pairs of contacts measure the millivolt drop along a known length of anode rod) because anodes are replaced every 20-30 days so contacting methods would add removal/reattachment of contacts to the burden of an anode change.

Fig. 6 shows a master, prior to shipment for field tests. The cable connecting to slaves (off the photograph) is seen on the left. At the upper right is a connection to the cell voltage (when the master is in the field). The cell voltage, 4-4.5V DC is a convenient one for powering the electronics and was so used. In this way powering the devices from a wall socket (precluded anyway by plant safety rules) became unnecessary. Also unnecessary was powering from batteries (although the masters had back-up batteries); this last is important as the cost and labor entailed in battery checking/replacement – significant in larger scale deployments – was avoided. Early in the project it was expected that masters would be powered by thermoelectric generators (TEGs). Preliminary tests showed TEGs unsatisfactory in that it was hard to find surfaces on which they could be mounted in a “Goldilocks range” between insufficiently hot to give the necessary output and too hot for the TEG to survive. Furthermore the TEGs were expensive (~$100 each) while power from the cell entailed little cost; finally the TEGs tended to have their cooling fins clog from the alumina which finds its way into most places near a potline.

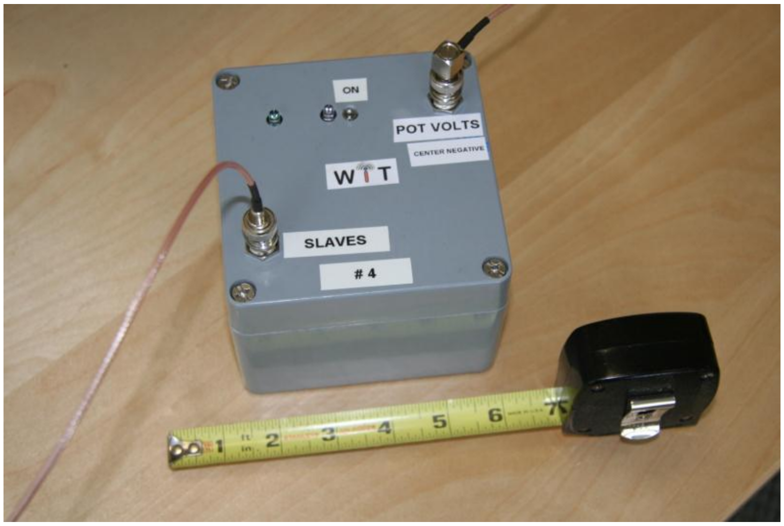


Fig. 6. A “master” under test at WIT. The scale is in inches.

The master-slave arrangement was tested at WIT prior to shipment to Alcoa's Wenatchee smelter as follows.

- Each of the five magnetic field sensors of every slave was calibrated using a DC electromagnet driven from a DC power supply. The field put out by the electromagnet was itself calibrated against the voltage applied across it (more precisely read than the current through it) using a commercial gaussmeter.
- Assembled daisy chains of slaves and a master were checked (e.g. for slaves correctly reporting their positions along the chain) using a hand-held permanent magnet.

Fig. 7 shows a batch of slaves prior to shipment to the aluminum plant for the field test on a (P100 design) cell at Alcoa's aluminum smelter in Malaga, Washington (commonly known as the "Wenatchee" plant), while Fig. 8 shows a few of the slaves mounted underneath the anode bus and behind anode rods at Wenatchee. The anode rods are the brown vertical rods in this photo. The cable (now sheathed in thermal insulation) running from one slave to the next is visible on the lower left.

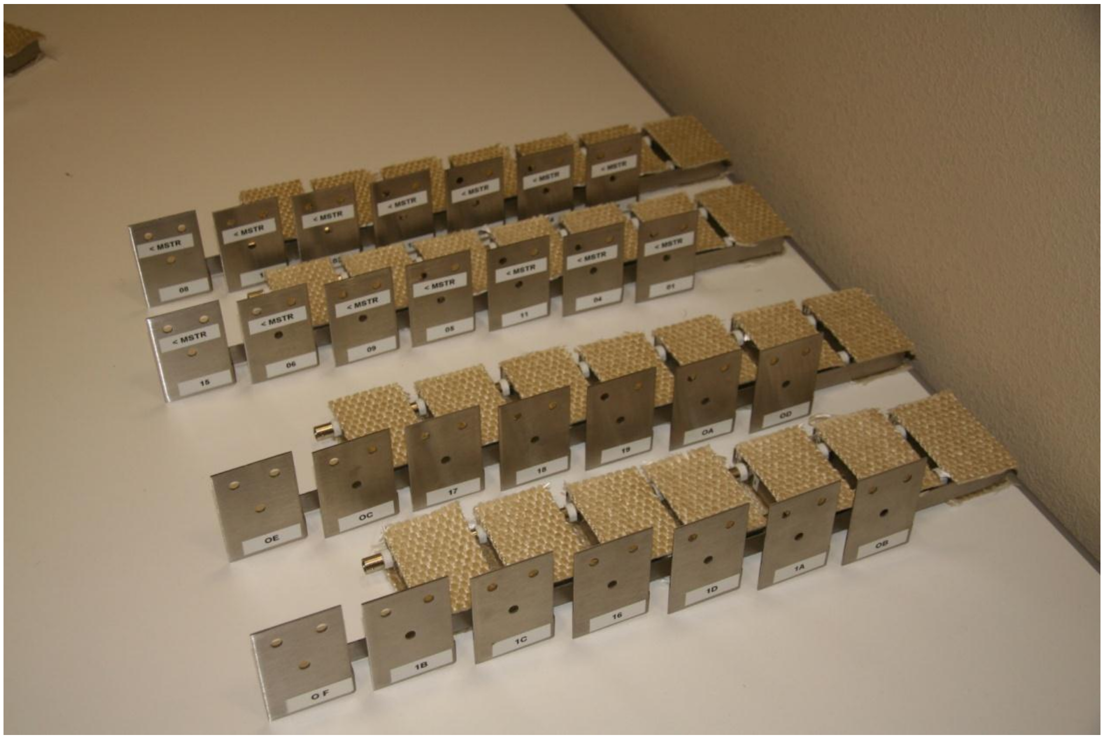


Fig.7. A batch of slaves ready for shipment to the field test. Upper insulation now in place.

Fig. 8. Slaves mounted on cell at Wenatchee plant of Alcoa.

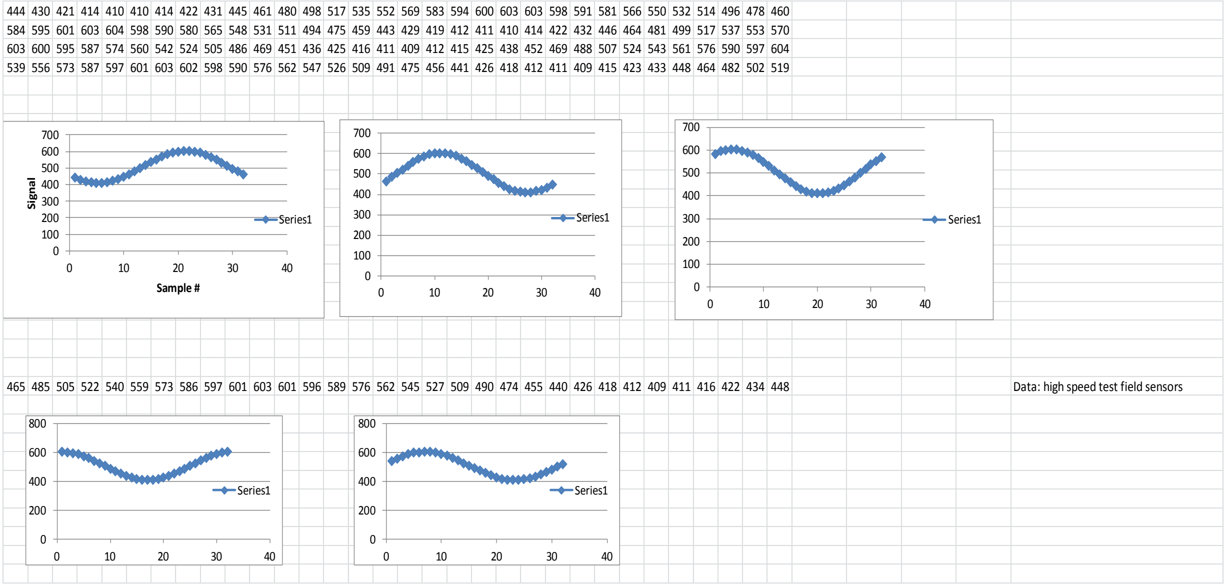
Fig. 9 is a photograph of a master (yet to be connected to pot volts) mounted on the end of the Wenatchee cell. The master contained a commercial wireless transceiver that transmitted magnetic field measurements, gathered from the slaves, to a wireless transceiver located in an instrument shed near the potline. The second wireless transceiver was connected to a notebook computer (later an industrial computer) that served to receive data, process them and forward them via the internet to a commercial data archive (Amazon Web Services). Each second 110 measurements (three fields and one temperature per slave, pot voltage and master temperatures, plus some system data) were transmitted from the cell to AWS. At WIT the data were archived and plotted in various ways.

The experimental results were measurements of the magnetic fields generated by the currents in the anode rods, rather than the currents *per se.* In many cases (some shown below), the magnetic fields themselves, or their trends with time, were sufficient information. In other cases it was necessary to “deconvolute” the field measurements to yield the anode currents. This deconvolution addressed the problem that a slave would pick up the field from the adjacent anode rod, but also from other anode rods. The deconvolution was carried out using a mathematical model, developed by sub-contractor Nobuo Urata, which took into account the geometry of the Wenatchee cell and the current carrying conductors (anode rods and others) of the cell. That model worked best when employed on *differences* between sensor readings of a slave because the difference was less susceptible to "cross-talk" from anodes other than the one adjacent to the slave. Hence the advantage of multiple sensors on a slave.

Fig. 9. Master mounted on the end of a pot at Alcoa's Wenatchee plant.

There were two test campaigns at Wenatchee. The first began with an installation of the system on a cell December 14-17, 2010. That installation lasted until the pot "tapped out" in late April, 2011. ["Tapped out" is industry terminology for the failure of the cell lining, typically occurring after 3-5 years of service, which requires rebuilding of the cell. It was unconnected with the project but did end the first campaign.] The second campaign began with installation of the system on a second cell May 2-5, 2011. The second system entailed minor improvements on the first system such as the ability to control the system (e.g. which of the five magnetic field sensors to use) from WIT offices in California.

Also incorporated was the ability to do brief periods of high speed data acquisition – 32 times in 16.7 milliseconds versus the usual once per second. Table I shows four sample data sets and their corresponding plots for a test at WIT of the high speed data acquisition feature. A slave was positioned over the electromagnet, this time driven by AC, and the magnetic field data gathered on a computer via a master connected to the slave and a receiving transceiver. The expected sinusoidal variation in the magnetic field is clearly visible in all four data sets.



444	430	421	414	410	410	414	422	431	445	461	480	498	517	535	552	569	583	594	600	603	603	598	591	581	566	550	532	514	496	478	460
584	595	601	603	604	598	590	580	565	548	531	511	494	475	459	443	429	419	412	411	410	414	422	432	446	464	481	499	517	537	553	570
603	600	595	587	574	560	542	524	505	486	469	451	436	425	416	411	409	412	415	425	438	452	469	488	507	524	543	561	576	590	597	604
539	556	573	587	597	601	603	602	598	590	576	562	547	526	509	491	475	456	441	426	418	412	411	409	415	423	433	448	464	482	502	519
465	485	505	522	540	559	573	586	597	601	603	601	596	589	576	562	545	527	509	490	474	455	440	426	418	412	409	411	416	422	434	448

Data: high speed test field sensors

Table I. Test of the high speed data acquisition feature of the slaves of the second campaign. The slave clearly detects the sinusoidal field variation of an electromagnet driven at 60Hz.

The second campaign lasted from May, 2011, until the end of experimental work in September, 2011, for most of which time the system gathered data.

3.2 Results and discussion – early detection of anode effects.

With the wireless anode current measurement system producing readings corresponding to 24 anode currents every second for most of a period of nine months, it becomes necessary to present only representative data in this report, rather than the whole data set. Indeed, for the primary purpose of this project (avoidance of anode effects) the data is rather uneventful as a representative pot will experience an anode effect less frequently than once per week. However these AEs were identified in the data without difficulty. Fig. 10 is a representative plot from early in the first campaign (February 7th, 2011) showing the plot of the cell voltage over a period of 50 minutes (red line). The voltage is stable at its usual ~4V until ~1214 minutes when it shoots up to over 30V. This is an AE and it is during this period that the cell would be generating fluorinated hydrocarbons (PFCs), with their high global warming potential, at a high rate. It is at this point that the plant computer recognizes an AE and starts to take action. The black line in the figure is calculated from the wireless anode current measurements; this index is the rate of change of the most rapidly changing current. In this case, after ~ 1212 minutes, one of the anodes is shedding current rapidly as the resistance to passage of current through this anode increases, hence the time derivative of its current is negative. The gap of approximately two minutes between the onset of current shedding and the detection of AE by the plant computer is the early warning sought in this project.

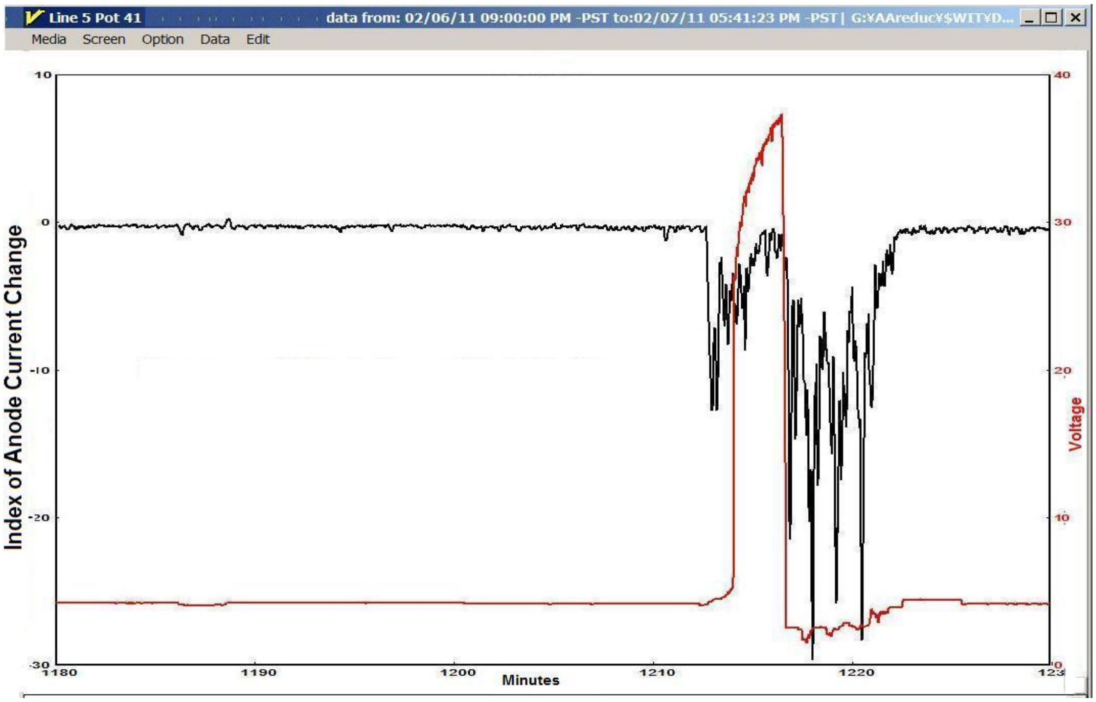


Fig. 10. Early warning (~ 2 min.) of anode effect obtained from wireless current measurements

There were 19 anode effects experienced by the cell under study for the quarter January-March, 2011. This count was confirmed by Alcoa (from cell voltage data). An early warning from the anode current measurements was detectable in 16 of the 19 cases although one warning was probably too late (20 seconds before voltage rise) to have been made use of by the control system. The other warnings ranged from 30 seconds to a few minutes – sufficient time for the control system to have avoided an anode effect or to have shortened its duration.

The ability to provide an early detection of AEs continued in the second campaign with Figs. 11 and 12 being representative of that period.

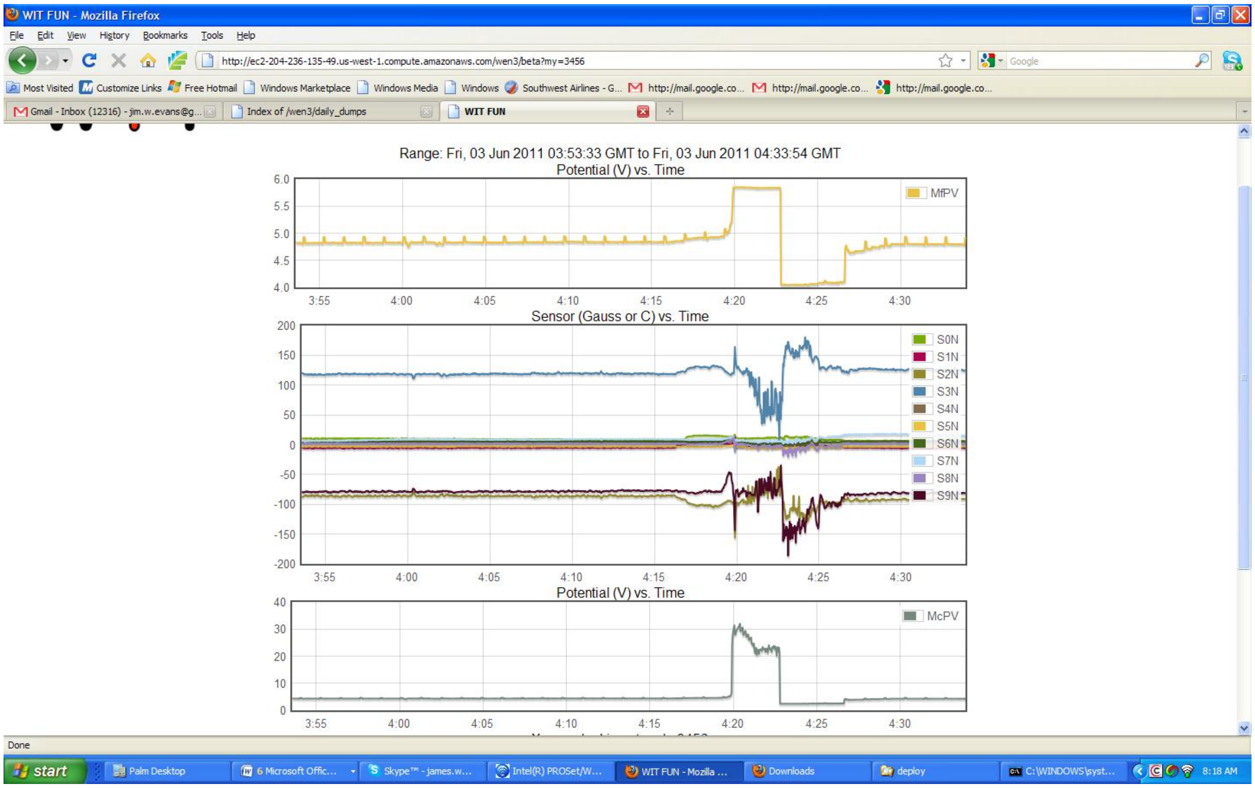


Fig. 11. Early warning of AE. Screen shot of representative data from second campaign (June 3rd, 2011). In this case the fields (center graph - proportional to currents) rather than currents are plotted and they start to shift approximately 3 minutes before the voltage change due to the AE (lowest plot)

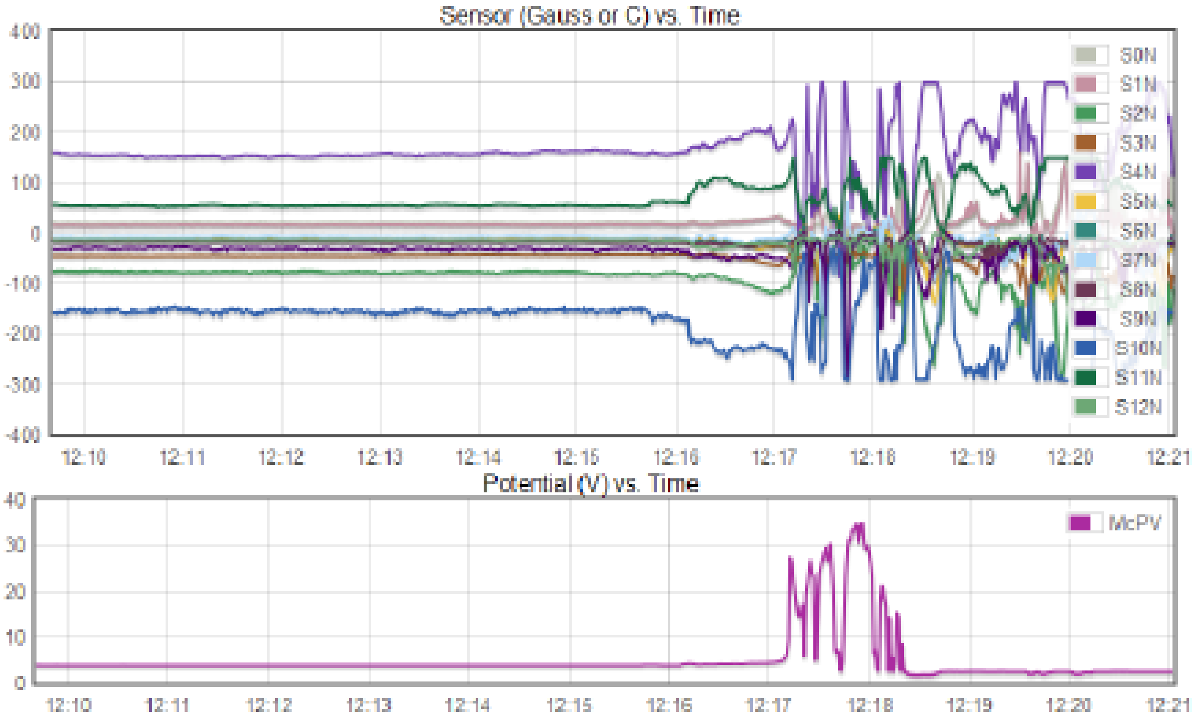


Fig. 12. Second example from second campaign (Sept 4th, 2011). In this case the currents (represented by fields in the upper plot) start to shift about 80 seconds before the voltage escalation (lower plot)

As part of its contribution-in-kind to the project, Alcoa has subjected the data obtained on the project to its own analysis. Fig. 13 is one result. It is evident that by casual inspection (Figs. 11 and 12), mathematical deconvolution of current (Fig. 10), or by Alcoa's algorithm (Fig. 13) the measurement of current distribution gives an early warning of AE. The story will be complete when the control loop is closed and measurements such as these are fed to the control computer. That activity would not fall within what is possible for WIT. However Alcoa has started to feed current distribution data[1] into the control computer at one plant and reports to us:

" Massena West is testing an anode effect predictor in 33 pots since Nov. 2011. This predictor uses the anode mV readings to prevent the anode effect occurrences. We have been able to reduce anode effect frequency and time by 20-30% without any negative effects. The code still has bugs which will be removed and the predictor parameters were set on the low risk side. As the bugs from the code are removed we will proceed with the fine tune to maximize the results."

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[1] These data were obtained by an alternative technique (measurement of millivolt drops across "flexes" connected to the anodes) to the one described in this report but uses the same kind of data (current distribution). That alternative technique is inapplicable at most other aluminum plants.

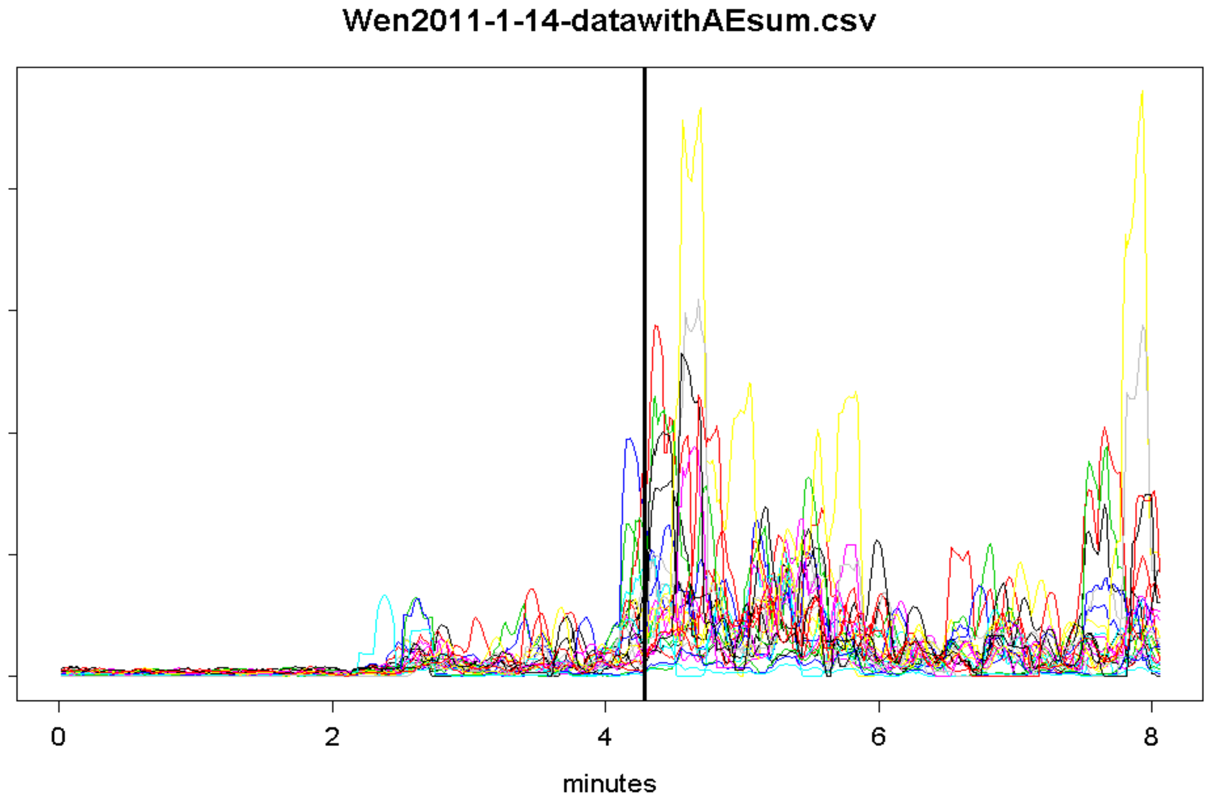

Fig. 13. Data from the project at Wenatchee subject to a proprietary analysis by Alcoa. The colored curves are functions of the anode current measurements from the project and show clear disturbance approximately two minutes ahead of the vertical black line which is the time at which the anode effect was determined by the plant computer from cell voltage.

3.3 Results and discussion – current efficiency improvements

While the results on potentially reducing anode effects have been encouraging, there are few places where such reduction brings economic benefit to the smelter. One such place is Australia where the government has recently imposed a tax on carbon emissions that is likely to significantly affect the Australian aluminum industry.

Fortunately the measurement of individual anode currents might also provide an opportunity for an improvement in current efficiency (CE) which *does* have an immediate economic benefit. CE is an important metric of pot performance. CE is a measure of how effectively the current passing through the pot is generating aluminum; this is of the order of 90-95% for a typical pot. CE is to be carefully distinguished from energy efficiency (45-50%)

although it does indirectly affect the energy efficiency. Each 1% improvement in CE means a 1% improvement in productivity (tons of aluminum per day). As many costs are independent of productivity, or weakly dependent thereon, improvements in CE reward the plant handsomely. Even a 1% improvement in CE is regarded by the industry as worth striving for.

There is anecdotal evidence in the industry that the CE of a cell is impacted if the current is not uniformly distributed among the anodes. During the course of the work, WIT was granted access to Alcoa data substantiating that belief. Fig. 14 shows Alcoa data obtained by an experimental technique known as the silver dilution method. Graphed is the dependence of CE on the largest anode current. Thus when all anodes are carrying 3kA the CE is ~95%, which would be typical of a well-run cell. However, if the currents are so skewed that one anode is carrying 9kA then the CE drops to ~84%, which would be regarded as the CE of a poorly performing cell. Individual anode currents have not been routinely measured in the past but now that facility is provided by the WIT wireless instrumentation and loss of CE due to imbalanced currents among the anodes can be determined. Fig. 15 plots the calculated CE for the Wenatchee cell under test during February/March 2011. Clearly, if these data are correct, there is a significant loss of CE on this cell due to imbalanced anode currents. There is no reason to suppose that this imbalance is atypical so the results of Figs. 13 and 14 lead to the conclusion that there could be substantial economic advantage to the current measurements, provided there is the ability to adjust anodes to bring them into balance.

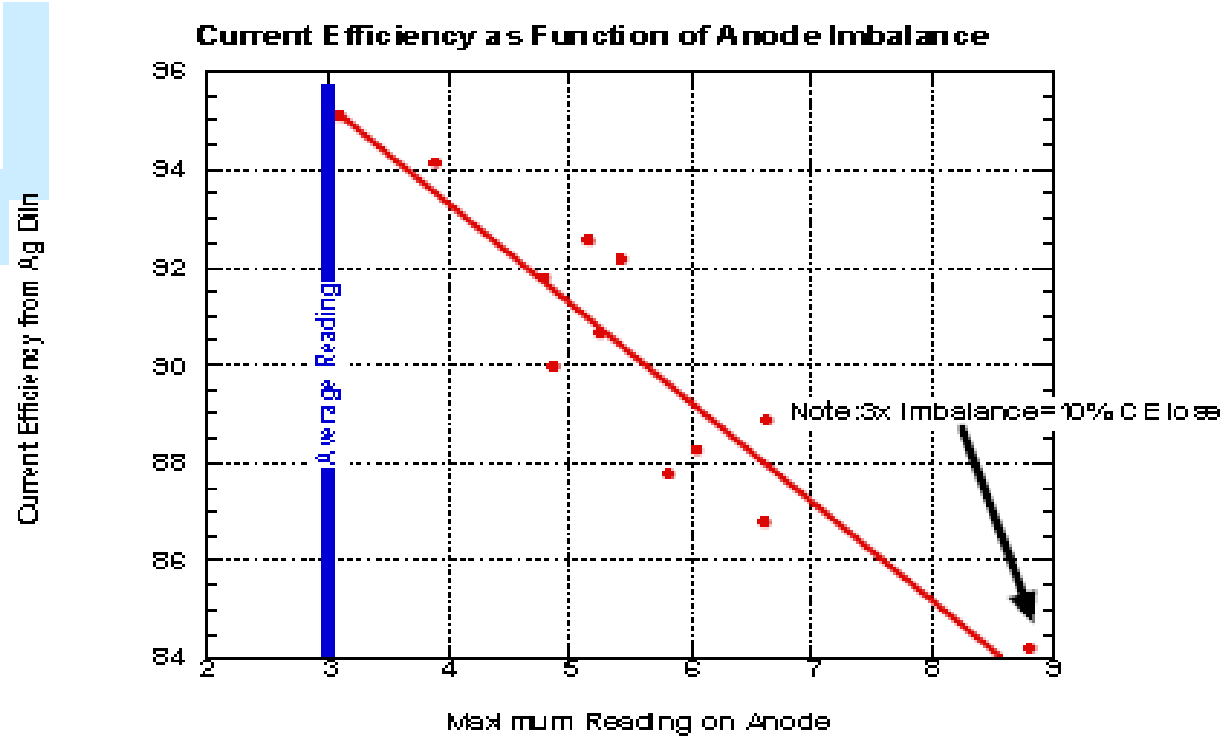

Fig. 14. Alcoa data showing how current efficiency is impacted if the anode currents are uneven.

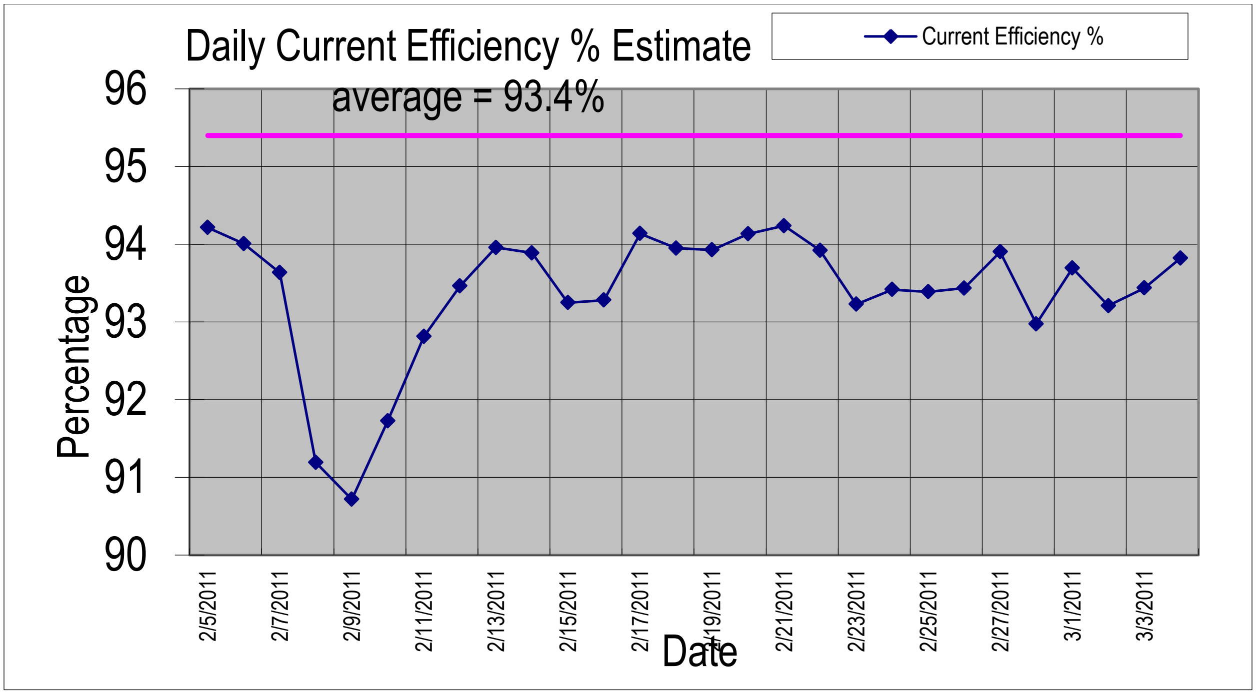

Fig. 15. Current efficiencies computed for the cell under test from the individual anode current measurements and the slope of the line in Fig. 14. [Magenta line is the CE expected in the absence of current imbalance among the anodes.]

3.4 Results and discussion – other potential improvements

The ability to measure individual anode currents confers other possible improvements in primary aluminum production. Fig. 16 shows plots of all the anode currents for a ten hour period in February, 2011, for the cell under test. The horizontal axes are in minutes. “US” means upstream anodes (those on the riser side of the cell) while “DS” means downstream. Attention is drawn to the currents for DS anodes 9 and 10 (last row, third and fourth column) and the different vertical scales for these anodes, compared to the others. The sudden drop in currents at ~250 minutes for DS#9 and 10 correspond to the start of an anode change during which two anodes were replaced (leaving others in place). What is notable is that the two new anodes do not immediately carry full current. This is well-known in the industry and is due to (partial) freezing of the molten electrolyte around a cold anode. It is usual, during this period of anode warm-up, to increase the cell voltage and thereby the energy consumption rate, to compensate for the anode(s) being cold. However, without individual anode current measurement the correct period of enhanced energy consumption can only be estimated. With individual anode current monitoring this period can be terminated in a controlled way, potentially saving energy. For example, anode DS#10 reaches normal current after about 200 minutes while DS#9 takes approximately 100 minutes longer.

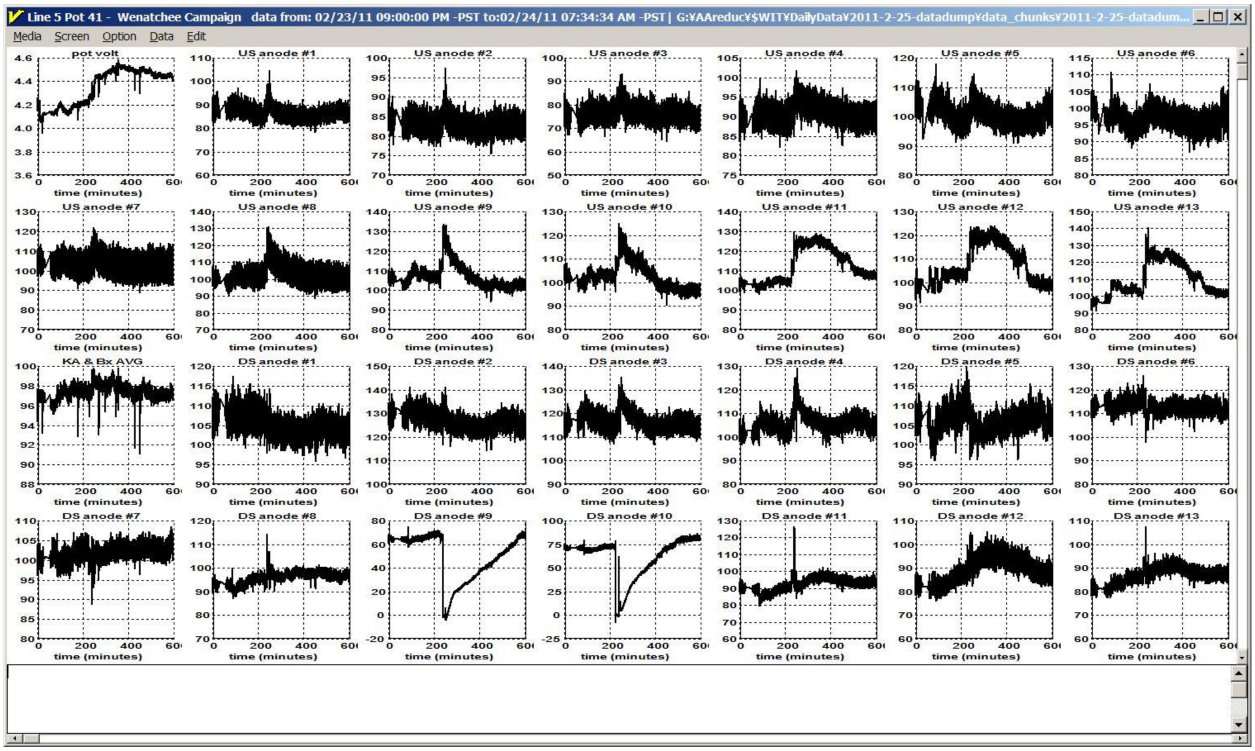

Fig. 16. Plots of anode currents (and other variables) for ten hours in February, 2001, during which two anodes were changed.

Another potential benefit to individual anode current measurement is the ability to anticipate an anode “burn-off”. This is when part or all of the anode carbon falls off its anode rod imposing a great burden on operations as the carbon fragments must be fished from the 950-960^{0}C interior of the cell. Burn-offs are frequently due to an anode carrying excess current, coupled to poor anode quality. Consequently, individual anode current measurement provides an opportunity to get a warning of an imminent burn-off.

3.5 Results by task

Task 1: Multiplexed Wireless Measurement of Current Distribution in Aluminum Pots.

This task was successfully executed (with the exception of task 1.2 – see under task 2). A “master and slave” system for measurement of individual anode currents was developed (e.g. Figs. 5-7), tested at WIT and deployed at the Wenatchee smelter of Alcoa. The system was capable of acquisition at the normal rate of one set of data (all anode currents) per second, as well as at a higher rate (32 sets of data every 16.7 milliseconds) the latter having been demonstrated at WIT (Table I). The system used wireless transmission of data, via an industrial computer, to a commercial data archive.

Task 2: Mathematical Modeling of Aluminum Pots

A mathematical model was adapted to deconvolute the anode currents from the magnetic field measurements obtained from the slaves. Examples of the result of application of the model are seen in Figs. 10, 15 and 16.

Task 3: Field testing of hardware and software at an aluminum smelter

This task was successful in all but one respect. The systems installed at Alcoa, Wenatchee functioned correctly in providing early warnings of anode effect (Figs. 10-13) as well as other indicators of cell performance (Figs. 15 & 16). Survival of the system in the harsh industrial environment clearly extends beyond months. However, in one respect the system did not meet expectations. The high speed data acquisition capability was intended to allow exploration of the concept of powering the slaves by induction from the AC “ripple” common to the “dirty” DC typical of aluminum plants. That ripple, predominantly at 360Hz, had been seen in data previously obtained from Alcoa (for another, unknown plant). Fig. 17 shows the magnetic field sensed by a slave operating in the high speed acquisition mode at Wenatchee and should be contrasted with the sinusoidal fluctuations seen in Table I. Clearly there is noise (almost certainly of electrochemical origin) in the data of Fig. 17, but no regular variation, and this was true of other data sets gathered at Wenatchee. There was therefore no prospect of powering slaves by induction from the non-existent ripple at Wenatchhee and this approach was abandoned. The impact of this result on the commercial viability of the technology is small as powering the master-slave system from the ~4.5V of the pot proved inexpensive and reliable.

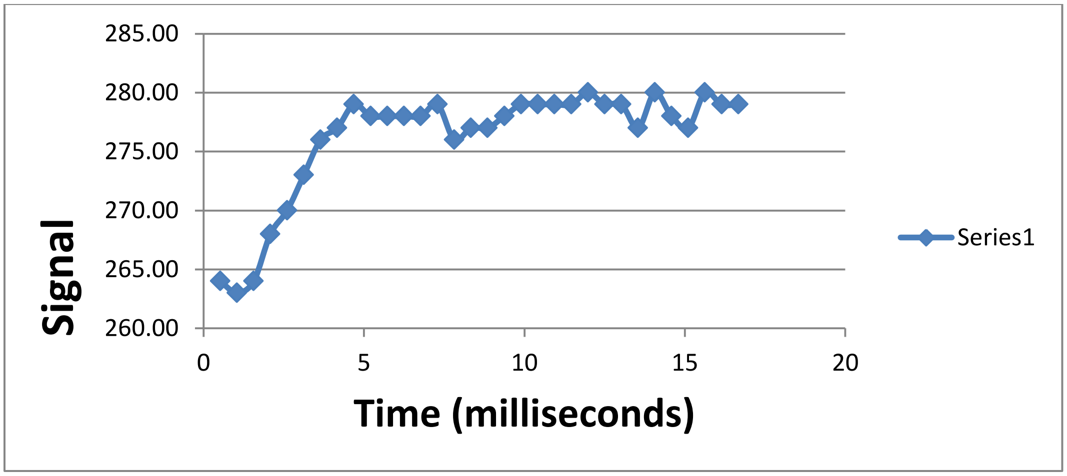

Fig. 17. High speed data from a slave at Wenatchee.

Task 4: Potential Benefits Assessment

Completed; see below.

Task 5: Project Management and Reporting

With this report, all technical reporting requirements will have been completed

4. Benefits assessment

Linearly extrapolating primary aluminum production from 1999 through 2010, the world production of primary aluminum should be 56.5 million tons per year in 2020. A conservative estimate of the reduction in energy intensity resulting from the technology under study is 2%. It is estimated that the technology will start to be adopted by aluminum companies in 2013. In the results that follow a penetration of the technology into 25% of the world's aluminum production is assumed for 2020. On that basis the energy saving is calculated to be 12.7 TBTU/yr in 2020 with an economic saving of $112million/year. Corresponding figures for the US are estimated to be 0.59 TBTU per year and $5.2million per year. The estimated reduction in GHG emissions for the assumed 25% penetration is 29,588 Mlbs/yr CO_2equivs/yr [1,360 Mlbs/yr CO_2equivs/yr in the US] from curtailment of anode effects alone. Further reduction results from reduction in electricity consumption (dependent on mix of fuel sources, hydro versus coal etc., for electric power production). Aluminum production capacity in the US is 3.4million tonnes. Assuming a use of 80% of this capacity in 2020 and a market penetration of 40% by WIT technology, then a 2% energy saving yields a benefit of $8.6 million/yr calculated at a very conservative energy cost of 3cents/kWh.

These are macroeconomic estimates and it is appropriate to estimates the benefits to a smelter that could result from measurement of individual anode current. Of course those benefits depend on such factors as plant size, current cost of electricity, present value of the produced aluminum and the cost (if any) of carbon emissions. A spreadsheet was developed to facilitate estimation of benefits for a plant and Table II below depicts results for a representative (albeit fictional) plant. This spreadsheet makes assumptions about what results can be achieved with individual anode current measurement, such as a 1% or 2% increase in CE. It is appropriate to point out that these assumptions are reasonable. For example, Fig 15 points to the improvement in CE that might be achieved if the anode currents can be balanced in a cell. This would entail adjusting the positions of some, perhaps all, of the anodes in a cell which would bring costs in plant labor. To explore the costs/benefits of such adjustments the break-even curves of Fig. 18 were calculated. Considering first the blue curves of Fig. 18; these tell of whether it is advantageous to adjust an anode to correct its current imbalance and thereby improve the CE, or to let it alone. This is a function of the degree of imbalance (vertical axis), the days remaining before the anode would naturally be replaced (horizontal axis) and the cost of the adjustment (constant noted on the curves). This last parameter has been a matter of discussion with people in the industry with estimate of the cost of an anode adjustment ranging from a few dollars (not shown) to $200 (uppermost curve).[2] Clearly there are many circumstances where individual anode adjustment should be worthwhile; for example, if an anode is carrying 60% more than the normal current ("Imbalance" = 0.6), would normally stay a further 10 days in the cell and costs $100 to adjust, then there is economic benefit in adjusting, according to these break-even curves.

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[2] The economic benefits are also a function of the value of the produced aluminum and the cost of the alumina feed to the cell; in these calculations the difference between the two has been set at $1300/ton Al.

The red curves have been calculated to allow for “self-correction” of the anodes. An anode carrying high current will be consumed more rapidly than its fellows and thereby reduce its current towards the norm. This is a process occurring over a few days (as we see in the WIT data) so an approximate allowance for this self-correction has been made in the break-even curves by assuming that there is a self-correction after three days. Even with this allowance there are still many circumstances where adjustment of anodes, driven by individual anode current measurements, is called for. With the example given in the previous paragraph, anode adjustment would still be appropriate at the $100 adjustment level (even at $150 per adjustment).

Quantitative analysis of benefits to an aluminum smelter of improvements in process performance

Constants:									
F	96485								
lbs/kg	2.205								
Al at. wt.	26.98								
CO2/Al	2.95	ton CO2/ton Al							
Plant:									
volts/pot	4.2	volts							
pots	300								
current	300	kAmps							
current efficiency	95	%							
energy efficiency	45	%							
prodn.	0.027	kg/pot/second							
prodn.	2.30	mtons/pot/day							
prodn.	7.97	kg/second							
prodn.	688,558	kg/day							
prodn.	251,323,796	kg/year							
prodn.	251,324	mton/year							
power	1260	kW/pot							
energy	30,240	kWh/pot/day							
energy	11,037,600	kWh/pot/year							
energy	3,311,280,000	kWh/year							
energy	13.18	kWh/kg Al							
energy	5.98	kWh/lb Al							
"wasted" energy	1,821,204,000	kWh/year							
Economics:									
price on LME	2200	$/metric ton							
Al price	0.64	$/lb							
Al price	2.2000	$/kg							
electricity	3	c/kWh							
carbon trade	14	Euros/mton	**Benefit from reduction of volts from**			**4.2**	**to:**		
currency	0.76	Euros/$	**4.15**					**4.1**	
carbon trade	18.42	$/mton							
electricity bill	907.2	$/pot/day							
electricity bill	331,128	$/pot/year	3,942	$/pot/year				7,884	$/pot/year
electricity bill	99,338,400	$/year	1,182,600	$/year				2,365,200	$/year
value of wasted energy	54,636,120	$/year							
electricity bill	395.26	$/ton	**Benefit from increasing current efficiency (%) from**				**95**	**to:**	
			96					**97**	
production value	5,049.43	$/pot/day							
production value	1,843,041	$/pot/year	19,400	$/pot/year				38,801	$/pot/year
production value	$552,912,352	$/year	5,820,130	$/year				11,640,260	$/year
electricity bill/value	17.97	%	Does not include alumina cost.						
			Benefit of reducing CO2 emissions from			**2.95**	**ton CO2/ton Al**	**to:**	
			2.6					**2**	
CO2 equivalents	6.77	CO2 mtons/pot/day							
CO2 equivalents	124.73	$/pot/day							
CO2 equivalents	45,525	$/pot/year	5,401	$/pot/year				14,661	$/pot/year
CO2 equivalents	741,405	CO2 mtons/year							
CO2 equivalents	13,657,464	$/year	1,620,377	$/year				4,398,166	$/year
% of production value	2.47	%							
Projected world Al prod 2020	56500000	mtons/y							
Electrical energy/mton	13180	kWh/mton							
Projected energy	7.4467E+11	kWh/y							
Projected energy	2.5423E+15	BTU/y							
Projected energy	2542.30338	TBTU/y							
Assume 25% market penetration	12.7115169	TBTU/y							
and 2% energy saving									
Current LME price	2400	$/mtom							
Energy cost/ton	395.26	$/mton							
2% saving assumed	7.905212438	$/mton							
25% penetration	111,661,125.69	$/y							
	111.66	$millions/y							
Assume reduction in CO2 is 0.95ton/ton	53,675,000.00	mtons/y							
Conversion to pounds	2205	lbs/ton							
CO2 reduction	1.18353E+11	lbs/y							
25% penetration	29588343750	lbs/y							
CO2 reduction	29,588.34	Mlbs/y							
US aluminum capacity	3,396,000.00	mtons/yr							
assume 80% operating	2,716,800.00	mtons/yr							
assume 40% penetration	1,086,720.00	mtons/yr							
assume 2% energy saving	8,590,752.46	$/yr							

Table II. Benefits analysis for a smelter installing individual anode current measurement.

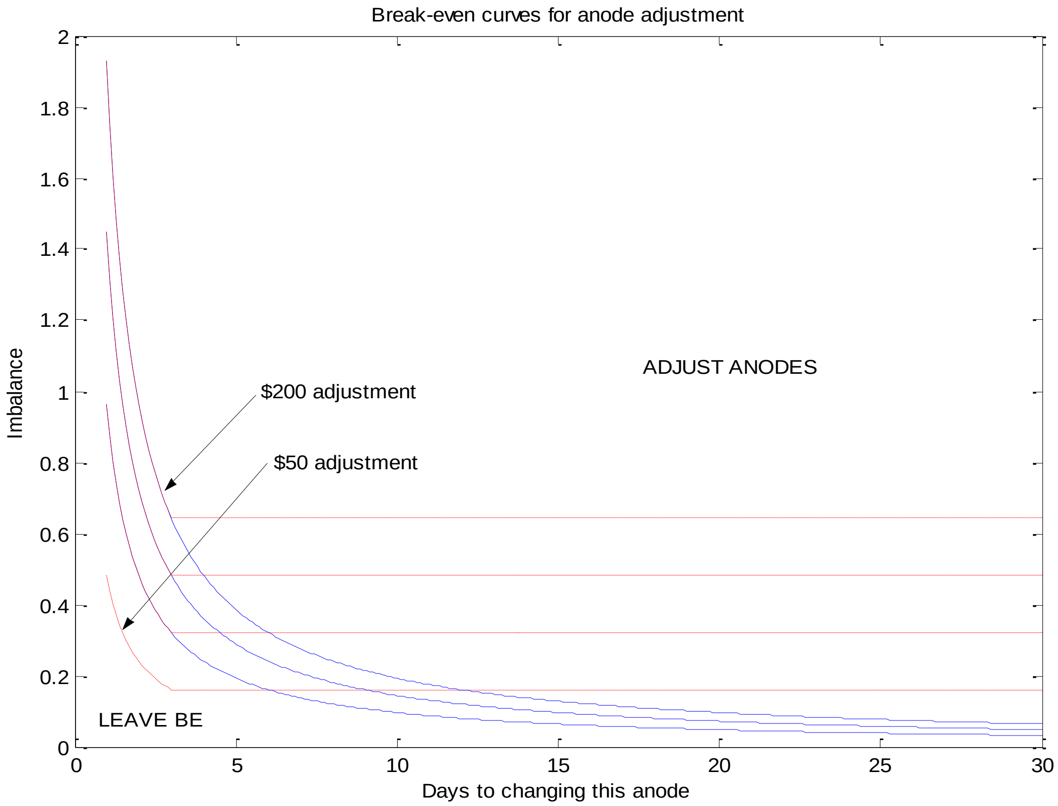

Fig. 18. Break-even curves for anode adjustment. Red lines for “self-adjustment” after three days.

5. Commercialization

Commercialization of the technology will proceed in collaboration with the aluminum industry. That industry is best equipped to assess the benefits to the industry and the costs associated with its deployment. By the end of the project, Alcoa had become sufficiently persuaded of the potential benefits of the technology that it had awarded WIT a purchase order for installation of anode current monitoring on two cells at another smelter. The equipment for that installation has been shipped at the time of writing. As yet further indication of interest, WIT has been informed that a second purchase order for an installation on up to 25 cells is being prepared. This last installation is to be completed this year. If successful, it can reasonably be expected that installation on a full potline (200-400 cells) will follow in 2013.

While Alcoa has seized the initiative in moving to commercialize the WIT technology, other companies are expressing interest, in part stimulated by a description of the work presented at the Launceston conference (see below).

6. Accomplishments

1. Successful development of a practical system for measuring individual anode currents of the electrolytic cells that produce both the World's aluminum and a significant fraction of its greenhouse gasses.
2. Field testing of the system on two cells over a period of many months at the Wenatchee smelter of Alcoa.
3. Demonstration that the measurements give an early warning of an upset condition (anode effect) responsible for GHG emissions from the cells.
4. Presentation of the results of the work at the 10th Australasian Aluminium Smelting Conference, October 10-14, 2011, Launceston, Tasmania: "Technical and Operational Benefits of Individual Anode Current Monitoring" and publication in the conference proceedings, thereby, stimulating industry interest in the technology.
5. Acceptance of the claims of a patent application, related to the technology, by the US Patent Office. [Although this application was submitted prior to the project period, its claims were modified based on experience during the project.]
6. Receipt of a purchase order from Alcoa for further testing of the technology.

7. Conclusions

The work has demonstrated that a system for monitoring the current of individual anodes in an aluminum cell is practical. Furthermore the system has been installed twice on a smelter in the US without exposing workers to hazard usually associated with running signal wires in aluminum plants; this avoidance of hazard results from using wireless transmission of data from the cells to a computer. The results display the “early warning” of an anode effect that potentially can be used to minimize such anode effects with their excessive GHG emissions. They also point to a possible, but substantial, economic benefit that could result in improved current efficiency by anode adjustment based on individual anode current measurements.

8. Recommendations

It is recommended that the aluminum industry continue testing of this technology; no direct government involvement is necessary unless unforeseen difficulties arise. It is recommended that DOE consider supporting the application of wireless measurement systems to other heavy industry that can benefit from such measurements, notably the chlor-alkali, copper and zinc industries where production relies on electrolytic technology akin to that of the aluminum industry.

9. References

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