Testing a new STARprobe^{TM} Measurement Based Ratio Control Algorithm Using a Dynamic Cell Simulator

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In addition to the two main tasks an aluminium reduction cell controller has to perform, namely to keep both the dissolved alumina concentration in the bath and the anode cathode distance (ACD) under tight control [1], modern cell controllers are also in charge of keeping the bath ratio (or excess AlF_3) concentration under control.

This task has proven to be quite challenging despite the fact that, at first glance at least, it looks quite straightforward. Fluoride evolves out of the cell; a big fraction of that fluoride is captured by the fresh alumina in the scrubber and returns to the cell as part of the secondary alumina feed to it. The part that is not returning to the cell must be compensated by direct AlF_3 feeding in order to keep constant the bath ratio in the cell. The cell controller performs that task using feedback control algorithms based on regular measurements performed by cell operators.

Recently Alcoa has develop a revolutionary new technology to measured bath ratio in potroom almost as quickly as you can measure bath temperature [2,3]. Furthermore, in addition of the excess AlF_3 concentration, the new STARprobe^{TM} can also measures the bath temperature, the dissolved alumina concentration and the cell superheat. That last information can be use as part of the cell control logic as previously presented in [4] per example.

GeniSim's Dyna/Marc dynamic aluminium reduction cell simulator cell simulator has been used to compare the efficiency of the traditional combined bath sample/XRD analysis and bath temperature measurement bath ratio control logic and a new control algorithm based on STARprobes^{TM} excess AlF_3 concentration and superheat measurements.

Performing the AlF_3 mass balance

Using a 300 kA cell as example, the fluoride mass balance can be performed as follows. Fluoride evolved out of the cell at a rate dictated by many factors like the bath ratio and temperature and the state of the anode cover [5]. In the current example, the fluoride evolution rate is calculated to be 33.6 kg F / T Al with the cell conditions selected, namely 10% excess AlF_3, 970 °C and a good anode cover. For a 300 kA cell producing 94.7 kg Al / hr, this represents the equivalent of 4.7 kg of AlF_3 that evolves out of the cell and hence must be replaced each hour.

Assuming that after taking into consideration the neutralization of some of the fluoride absorbed by the fresh alumina in the scrubber by the sodium already present into it, the equivalent of 3.6 kg /hr of AlF_3 is fed back to the cell by the secondary alumina (on average or at the nominal 100% alumina feeding rate). This leaves 1.1 kg /hr of AlF_3 that must be directly fed using a point breaker feeder (PBF) under the supervision of the cell controller.

Considering that the cell contains close to 8 tons of bath and hence about 800 kg of excess AlF_3, this means that if the direct AlF_3 is completely stopped for some reason, it would take about 72 hours for the mass of excess AlF_3 to be reduced by 80 kg and hence the bath excess AlF_3 concentration to drop by 1% to 9%. Considering that relatively slow response time of the cell, it should be rather easy to keep the excess AlF_3 concentration under tight control, but since it is clearly not the case in the great majority of smelters, some other factors must be complicating things.

Daily operations influence on bath ratio: In the above mass balance calculation, about 75% of the AlF_3 is fed back to the cell as part of the alumina feeding, but in modern continuous tracking control logic, the alumina is never fed at the nominal 100% rate to the cell. As a result, the excess AlF_3 concentration is evolving up and down according to the feeding cycle. The direct additions are also performed in discrete events, per example 2 kg every 110 minutes, in order to average 1.1 kg / hr per example. Those discrete additions also influence the short term variation of the excess AlF_3 concentration.

In addition of the irregular AlF_3 addition, the excess AlF_3 concentration variation is influenced by thermal events affecting the AlF_3 evolution like the bath temperature but more importantly by the ledge thickness variation: as ledge is mostly pure cryolite, ledge formation increases the concentration of the excess AlF_3. Ledge formation occurs after anode change events per example. Figure 1 shows the daily variation of the concentration of AlF_3 in the bath in absence of control and any AlF_3 mass imbalance. The standard deviation on the average value is about 0.1%.

Sampling frequency and delayed XRD results: The next factor complicating things is the fact that assessing the bath chemistry required manual interventions. The traditional way of proceeding requires manual bath sampling, manual processing of the bath samples, at best semi-automatic analysis of the bath samples by a XRD instrument and manual input of the results in a database accessible to cell controllers. Considering the cost of a XRD analysis, it is typical to take bath sample every second day and to get results at 8 to 24 hours after the actual bath sampling.

Figure 2 shows the variation of the AlF_3 for a period of 20 days again without control and any mass imbalance. Figure 3 shows the results of the bath sampling performed once a day always at the same time. The delay between the actual sampling and the time the results of the analysis becomes available is clearly not an issue when the concentration is drifting very slowly. Yet any delay in the feedback response can cause instability depending on the controller setup.

So far, despite the daily events "process noise", the sparse sampling frequency and the delay in getting the sampling analysis results, considering the very slow cell response time, there is no serious problem that would explain why it is so difficult to control the bath ratio.

Bath sampling noise problem: But, a new problem affecting bath ratio control has recently been identified: it is the bath sampling noise due to the fact that the bath is far from being homogeneous [6]. The standard deviation of that bath sampling noise has been evaluated to be around 0.5 % which is 5 times greater than the process noise generated by daily events. That bath sampling noise, contrary to the daily events noise is completely unpredictable. Figure 4 shows the results of bath sampling performed on the 20 days period presented in Figure 2 when a 0.5% white noise is added to the noise free results presented in Figure 3.

Simulated process response using standard control without any process perturbation:

Now, we want to test a typical control logic where both the delayed XRD analysis from bath samples and measured bath temperature are used to correct the direct AlF_3 feeding rate as it is commonly done in the industry these days. The proportional band was set to 0.5 kg/hr% for the 24 hours delayed bath XRD analysis results and -0.1 kg/hr°C for the bath temperature measurement. The bath sampling and the temperature measurement are done simultaneously every 24 hours.

A bath sampling noise having a standard deviation of 0.5% have been added to the XRD analysis results following observation recently reported [6]. For the temperature measurement, a bath sampling noise having a standard deviation of 2.5 °C have been added as reported in [6].

Figure 5 present the obtained results in the dynamic cell simulator for a period of 100 days. The top graph presents the results obtained without any control in the absence of process perturbation. The initial bump is an indication that the steady state conditions used as initial transient conditions are not 100% representative of the long term pseudo steady state conditions.

The bottom graph presents the results obtained with feedback control active. Unfortunately, it is not as good as the results without control indicating that the bath sampling noise combined with the 24 delay in the bath sampling analysis result is affecting the stability of this feedback control loop.

Simulated process response using standard control with a significant process perturbation:

In order to more seriously test the stability of the feedback control loop, a major perturbation is added to the simulation. On day 14, about half of the anodes cover material is removed in doing so increasing the anode panel heat loss by about 30 kW from 230 kW to 260 kW. As we can see in figure 6, as a natural response, the cell must reduce its cathode heat loss of the same amount by reducing its superheat by about 1 °C and increasing its ledge thickness by about 5 cm. As a result, of this extra ledge formation, the excess AlF_3 increase by about 2% and remains close to 12% if the direct AlF_3 additions remain unchanged.

This is clearly a case where some feedback control is required. Figure 7 presents the results obtained using the standard control described above. After the change of superheat, the 970 °C temperature target is no longer compatible with the 10% excess AlF_3 target, this combined with the 1 day offset between the AlF_3 feedback and the temperature feedback generates a cyclic response characteristic of somewhat unstable feedback control. That type of oscillations with a wave length of about 20 days and an amplitude of about 2.5% are very common place in smelters. Those undesired oscillations occur despite the fact that the values of the proportional constants were careful selected in order to avoid feedback loop instabilities.

The new STARprobe^{TM}

The STARprobe^{TM} is a portable device that takes real−time measurements of bath properties, such as Superheat, Temperature, Alumina concentration and bath Ratio or acidity (STAR), in electrolysis cells. This synchronicity of measurements is a most important step forward in improving the control and efficiency of electrolysis cells. It unites the conventional processes of temperature measurement and bath sampling-analysis into one online measurement, simplifies and greatly shortens the process and time space from measurement/sampling to pot control decision. The pot control decision can therefore be based on the real time cell conditions rather than those from few hours ago or from as long as 24 hours ago.

This integrated real-time measurement system consists of four major components:

- Reusable probe tip
- Portable stand to fit various pot configurations
- Electronics for data acquisition and analysis, and wireless communications for data transfer
- Tablet PC with programs to perform all necessary tasks during measurements.

Considering the great advantages of the STARprobe^{TM}, Alcoa has decided to share the technology with the rest of the aluminium industry starting from 2012. In this regard, Alcoa has just appointed STAS, a well recognized leader in the aluminium industry (www.stas.com), to commercialize the new STARprobe^{TM} analyzing system.

Simulated process response using STARprobe^{TM} measurements based control with a significant process perturbation: The exact same major perturbation is use to test the efficiency of a STARprobe^{TM} measurements based feedback control loop. The same 1 day measurement frequency is used and the same 0.5 kg/hr% proportional constant for the AlF_3 feedback loop. Obviously in this case however, the measurement results are available without delay. In addition, the measured superheat is also used in a separate feedback loop where the target cell resistance is adjusted based on the offset between the target superheat and the measured superheat.

The measured superheat is also affected by a very significant bath sampling noise. That bath sampling noise was estimated to have a standard deviation of about 2°C in [6] so a 2°C standard deviation white sampling noise was added to the simulation.

The obtained results are presented in the figure 8. We can see that the response to the perturbation is slower than in the previous case because there is no longer a correction based on the temperature offset and a ±1 °C deadband on the superheat target was used in order not to wrongly respond to the noise in the superheat measurements. Yet after a 25 days transient response to the perturbation, the excess AlF_3 concentration goes back to its target value and remains on target without oscillations after that.

Figure 9 shows the evolution of the target cell resistance, a result, a 0.01 micro-ohm correction on the target cell resistance was apply each for 15 days for a total 0.15 micro-ohm correction after a delay of 6 days. This 0.15 micro-ohm "permanent" correction ensure that the superheat remains within the 3.5 °C to 5.5 °C range despite the fact that the anode panel now dissipates an extra 30 kW of heat loss.

Conclusions

This study demonstrates study the value of using a dynamic cell simulator to optimize existing cell controller algorithms or to test new ones without putting real cells at risk. The Dyna/Marc cell simulator used in this study is available to the whole aluminium industry through GeniSim Inc. Version 14 supports adding the observed bath sampling noise to the AlF_3 measurements and using STARprobe^{TM} measurements instead of bath samples/XRD analysis to perform bath ratio control.

A new control logic scheme based on independent control of the excess AlF_3 and the cell superheat made possible with the revolutionary new STARprobe^{TM} measurement tool was demonstrated to be superior to the standard single feedback control loop using two target variables namely the excess AlF_3 and the operating temperature to control a single control action namely the direct AlF_3 additions.

The STARprobe^{TM} developed by Alcoa [2,3] is now available to the hole aluminium industry through STAS (http://www.stas.com/en/starprobetm.html).

References

[1] M. Dupuis, Testing cell controller algorithms using a dynamic cell simulator, ALUMINIUM • 1-2/2012, (2012), 50-55.

[2] Wang, X., Hosler, B. and Tarcy, G. Alcoa STARprobe^{TM}, Light Metals, (2011), pp 483-489

[3] Wang, X., Tarcy, G., Batista, E. and Wood, G. Active pot control using Alcoa STARprobe^{TM}, Light Metals, (2011), pp 491-496

[4] T. Rieck, M. Iffert, P.White, R. Rodrigo and R. Kelchtermans, Increased Current Efficiency and Reduced Energy Consumption at the TRIMET Smelter Essen using 9 Box Matrix Control, Light Metals, (2003), pp 449-456.

[5] W. Haupin, H. Kvande, Mathematical Model of Fluoride Evolution from Hall-Héroult Cells, Proceedings from the International Jomar Thonstad Symposium, ed. by A. Solheim and G. M. Haarberg, Trondheim, Norway, October 16 – 18, (2002), 53 – 65.

[6] M. Dupuis, P. Bouchard and J. P. Gagné, Measuring bath properties using the STARprobe^{TM} , 19th International ICSOBA *Symposium* (2012), to be published.

Author

Dr. Marc Dupuis is a consultant specialized in the applications of mathematical modeling for the aluminium industry since 1994, the year when he founded his own consulting company GeniSim Inc (www.genisim.com). Before that, he graduated with a Ph.D. in chemical engineering from Laval University in Quebec City in 1984, and then worked ten years as a research engineer for Alcan International. His main research interests are the development of mathematical models of the Hall-Héroult cell dealing with the thermo-electric, thermo-mechanic, electro-magnetic and hydrodynamic aspects of the problem. He was also involved in the design of experimental high amperage cells and the retrofit of many existing cell technologies.

Jean-Pierre Gagné is the Director of the ALCOA – STAS R&D Team. Master degree in Active Control of Vibrations, I obtained in 1993. Since 1997, I am working for STAS mainly in R&D projects. STAS is a company specialised in the design, fabrication and manufacturing of equipment for the aluminum industry as well as in commercialisation of new technologically advanced equipment. STAS is located in the heart of Quebec, Canada, where more than 10% of the world's primary aluminum is produced in the most technologically advanced plants.

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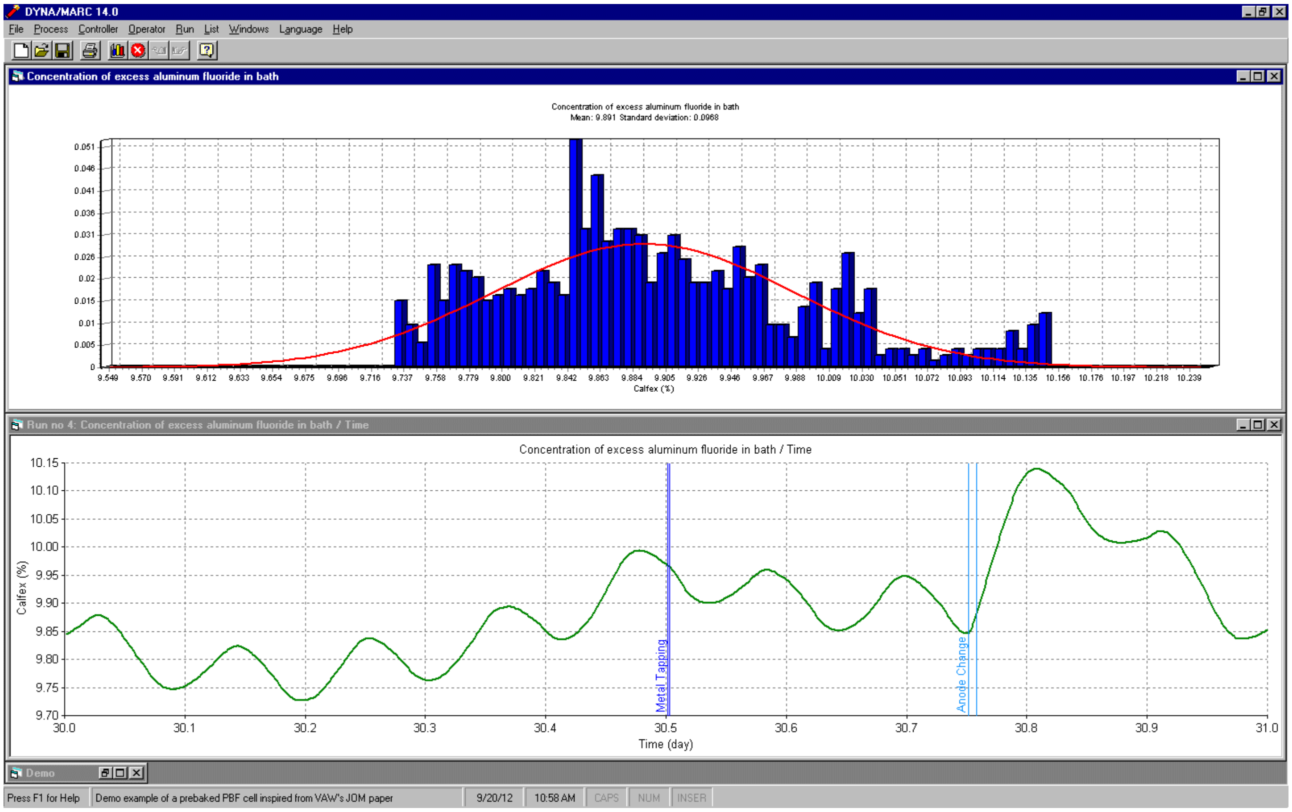
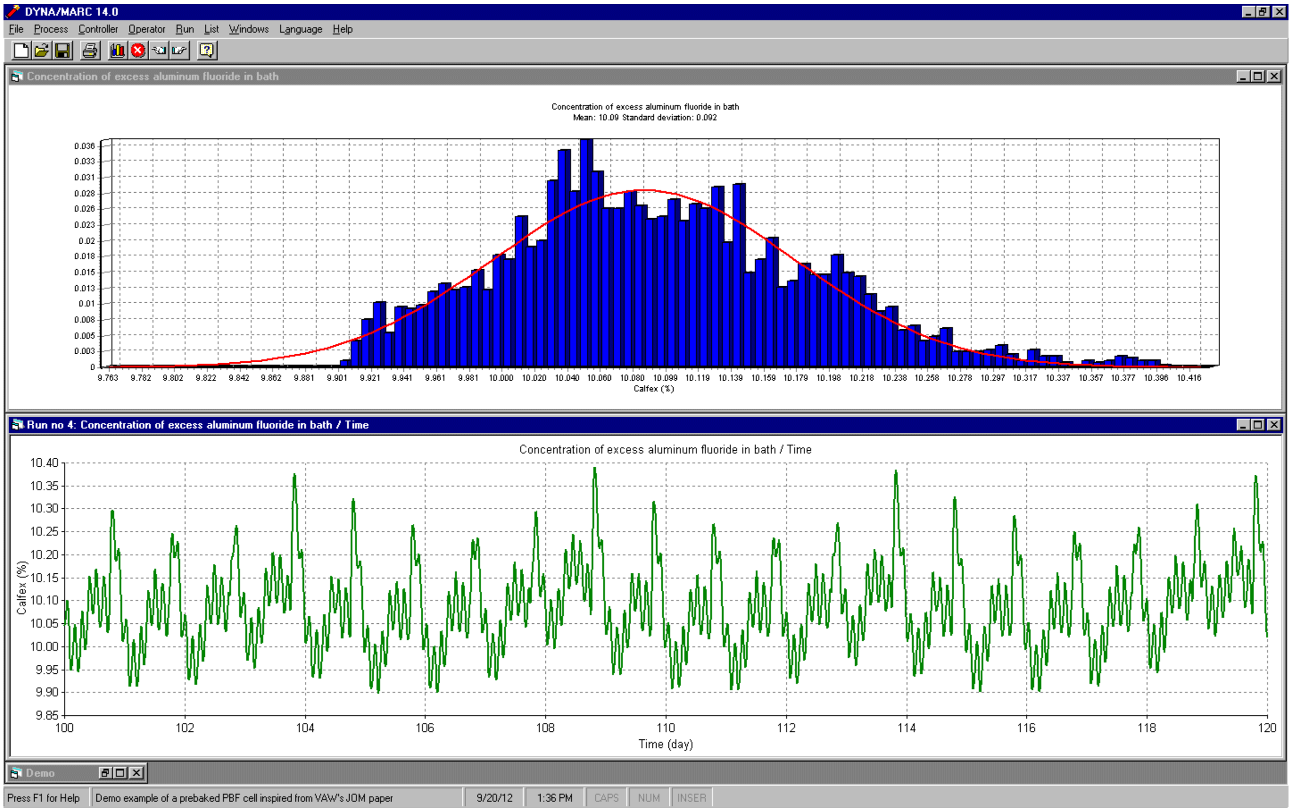


Figure 1: Daily excess AlF_3 concentration variation without control and any mass imbalance as generated by Dyna/Marc cell simulator



Demo example of a prebaked PBF cell inspired from VAW's JOM paper

Figure 2: 20 days excess AlF_3 concentration variation without control and any mass imbalance

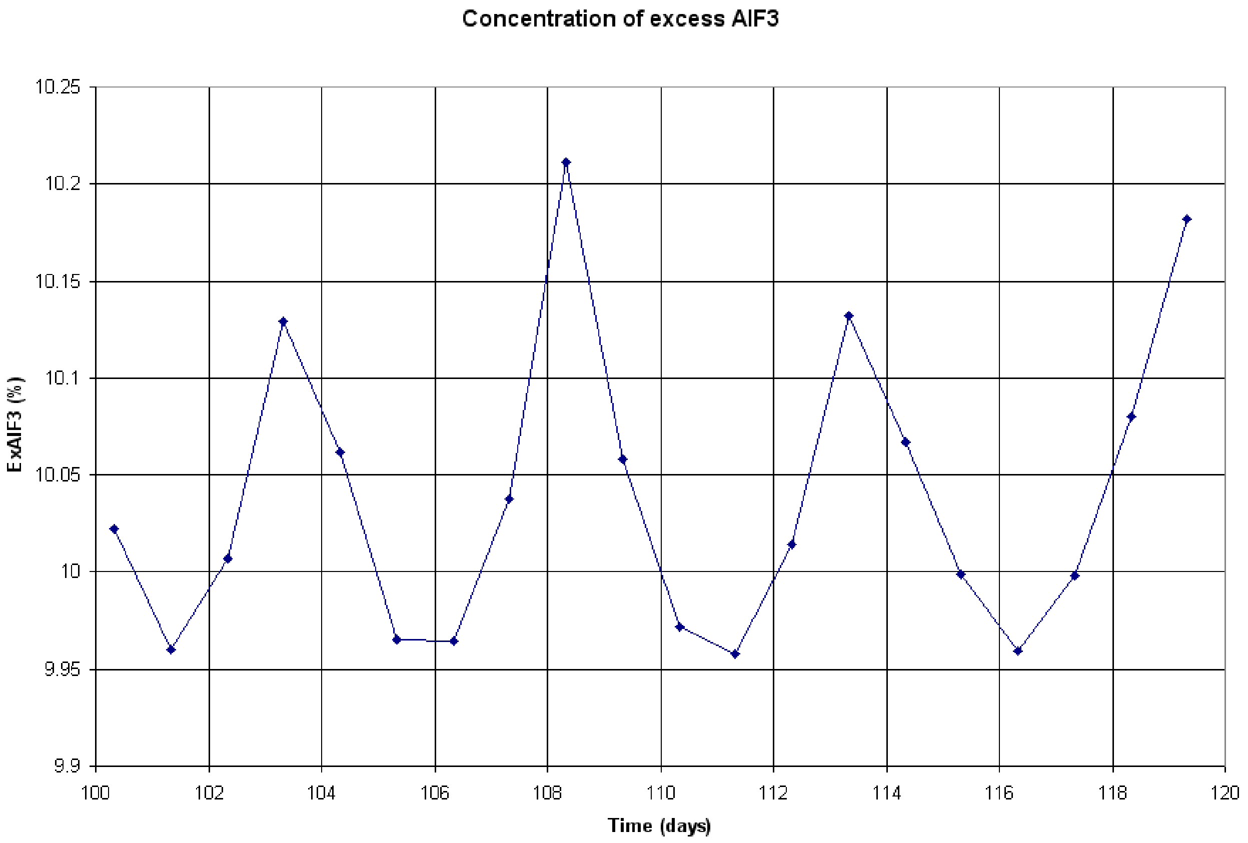


Figure 3: Corresponding 20 days of excess AlF_3 concentration sampling results assuming no bath sampling noise

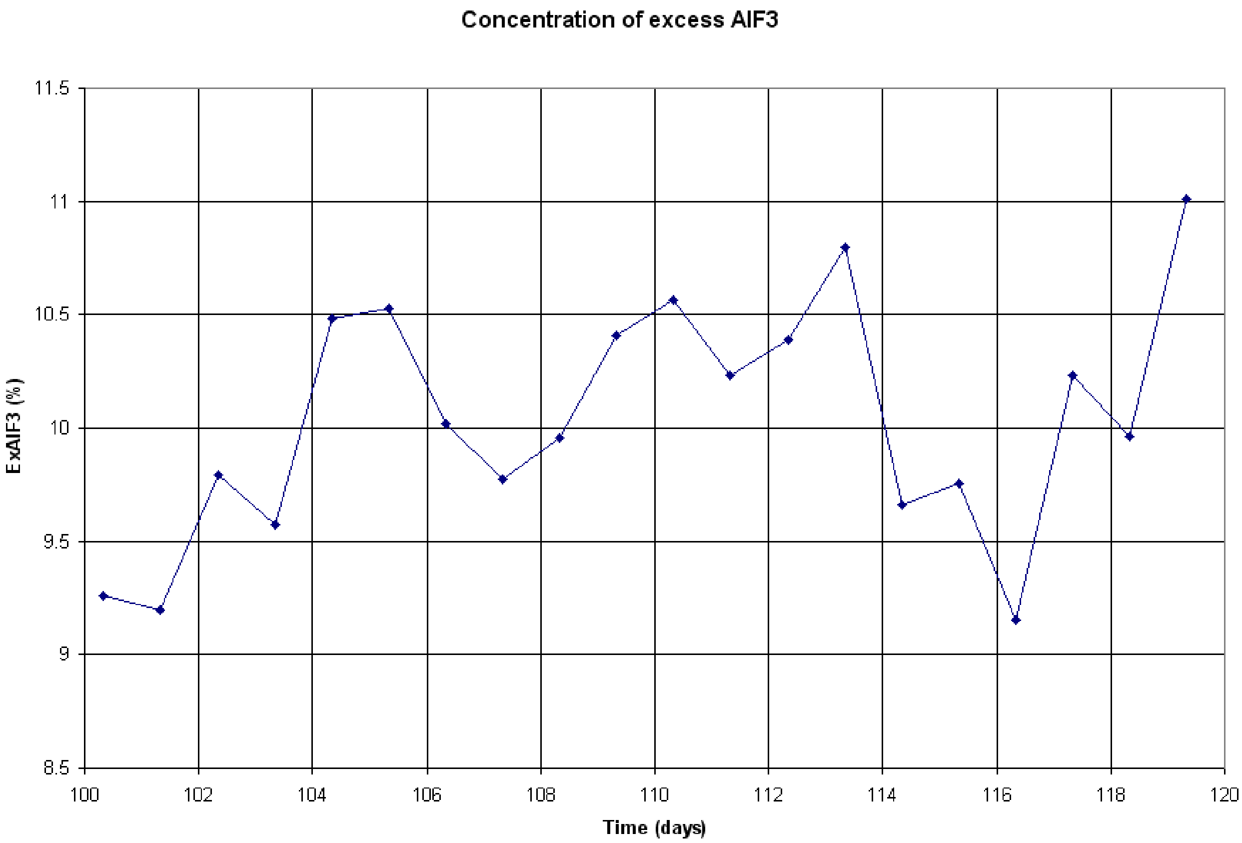


Figure 4: Corresponding 20 days of excess AlF_3 concentration sampling results assuming 0.5 % standard deviation white sampling noise

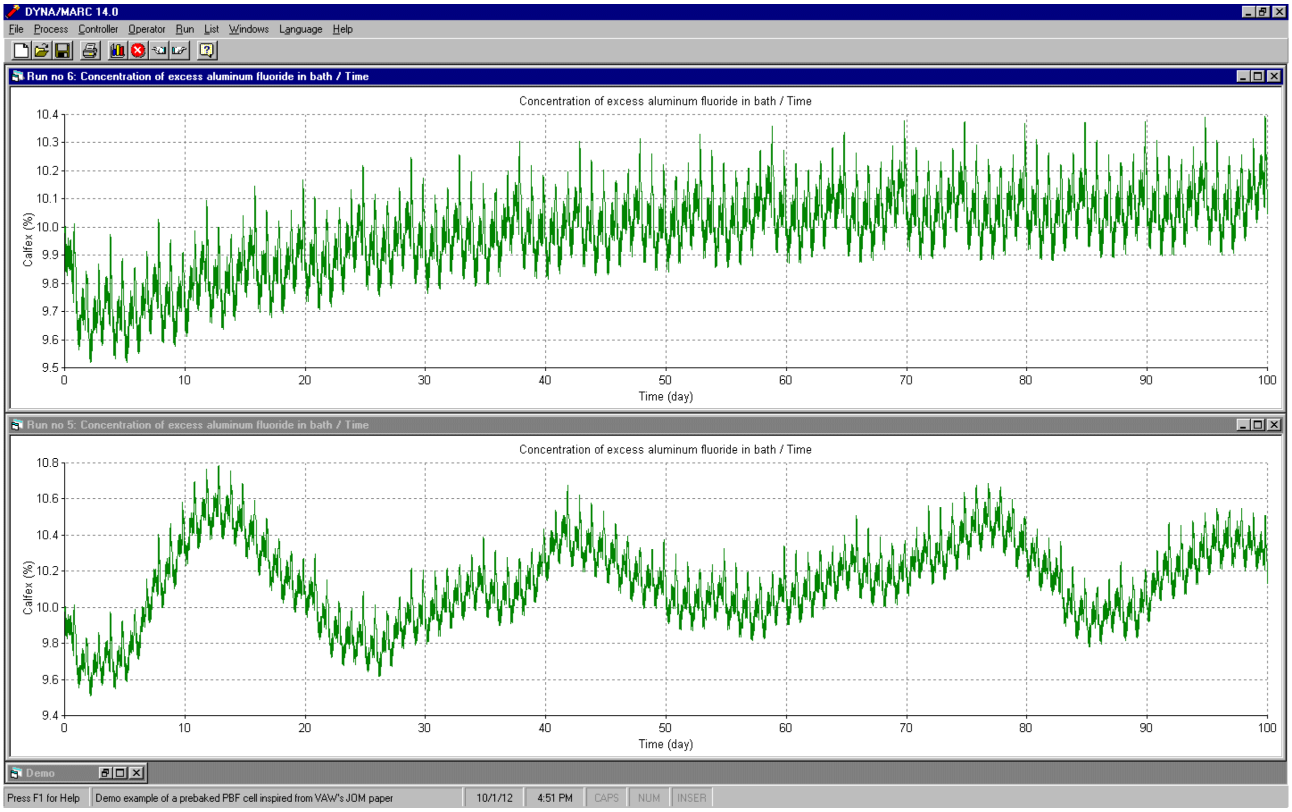


Figure 5: Simulation of the process without perturbation; top without control, bottom with feedback control, 10% target concentration (XRD results, once per day, 1 day delay, 0.5 kg/hr% proportional band and -0.1 kg/hr°C proportional band)

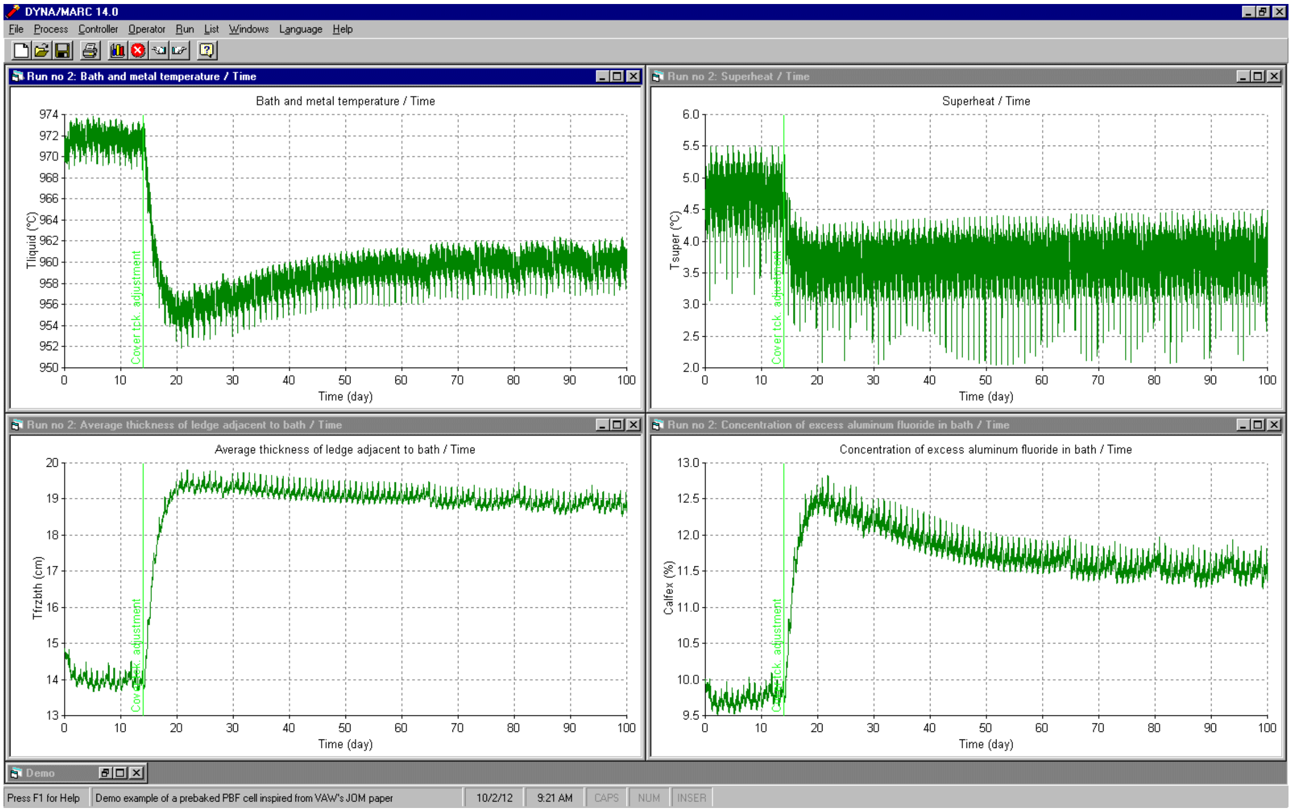
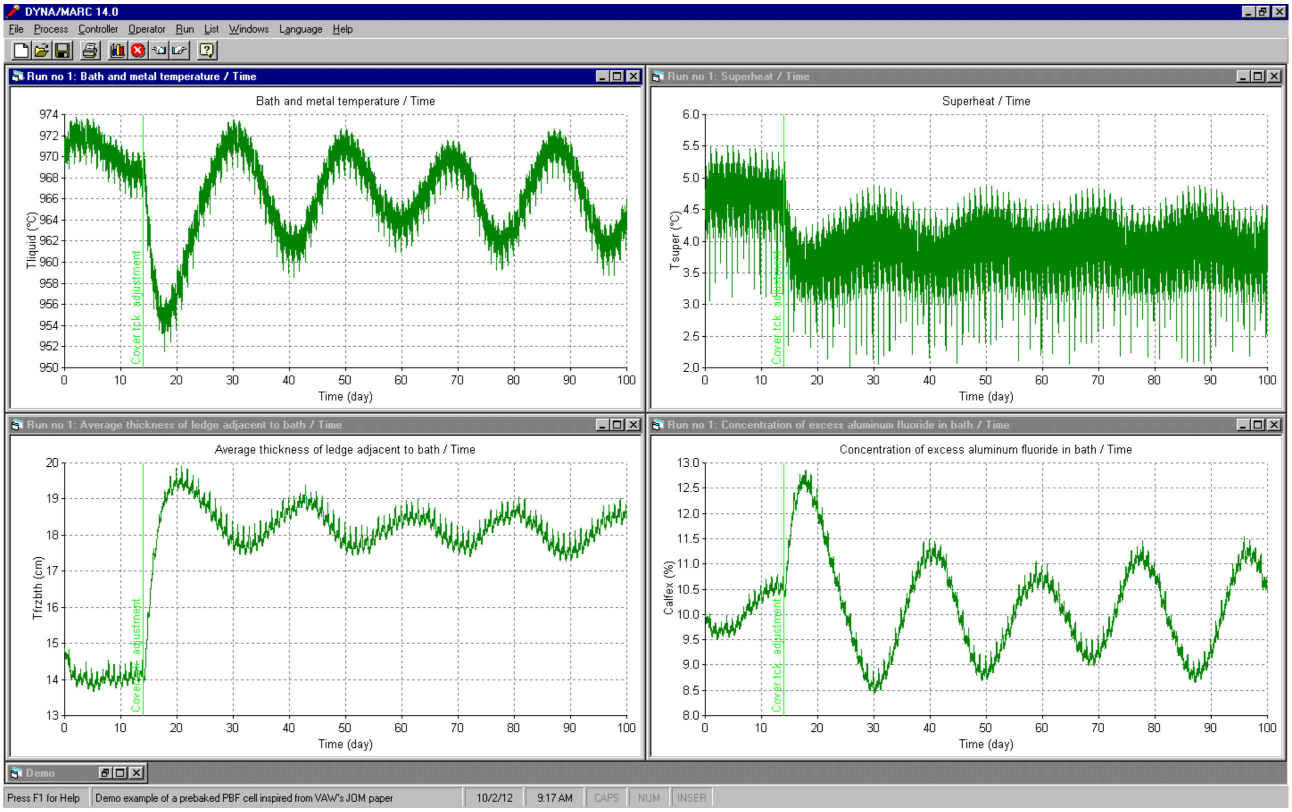


Figure 6: 100 days natural response (no control) to a significant reduction of the anode cover material thickness resulting in an increase the anode panel heat loss by 30 kW



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Demo example of a prebaked PBF cell inspired from VAW's JOM paper

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Figure 7: Simulation of the process with a significant perturbation; feedback control, 10% target concentration (XRD results, once per day, 1 day delay, 0.5 kg/hr% proportional band and -0.1 kg/hr°C proportional band)

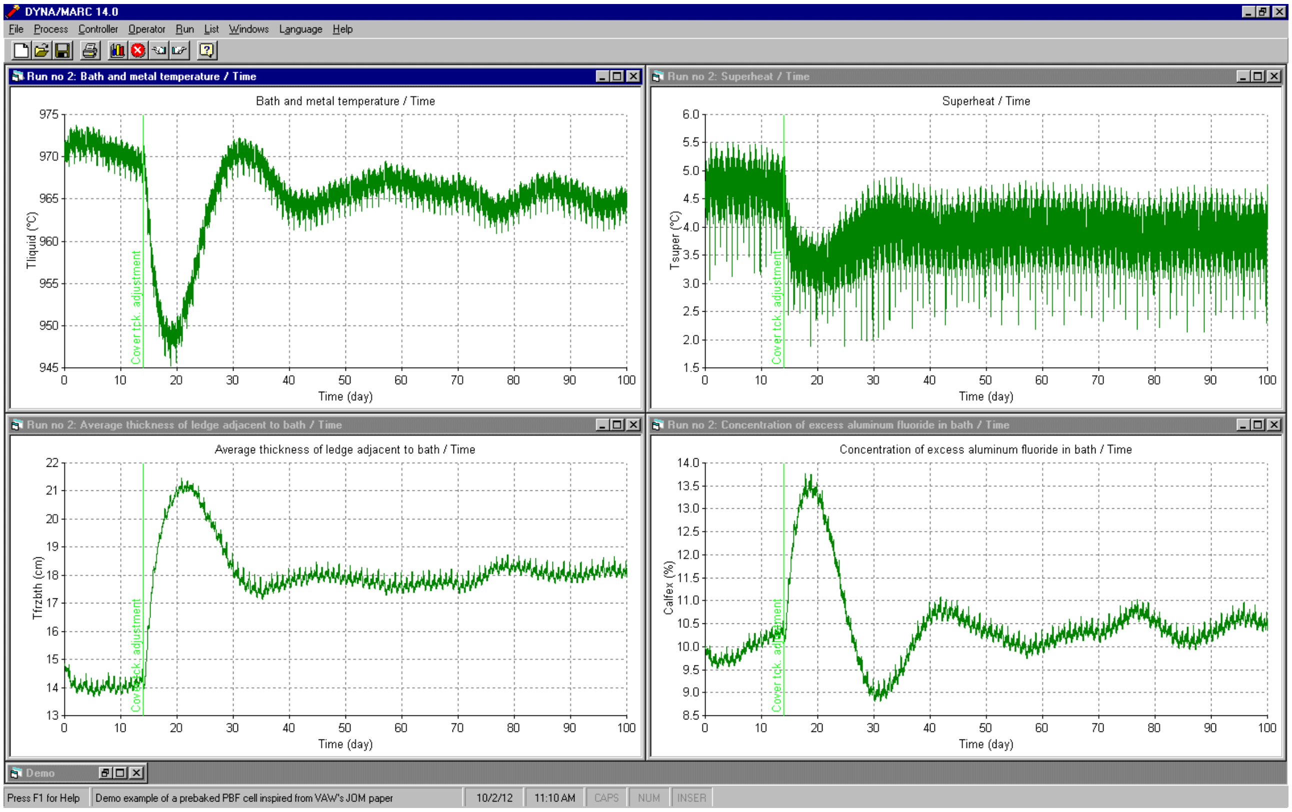
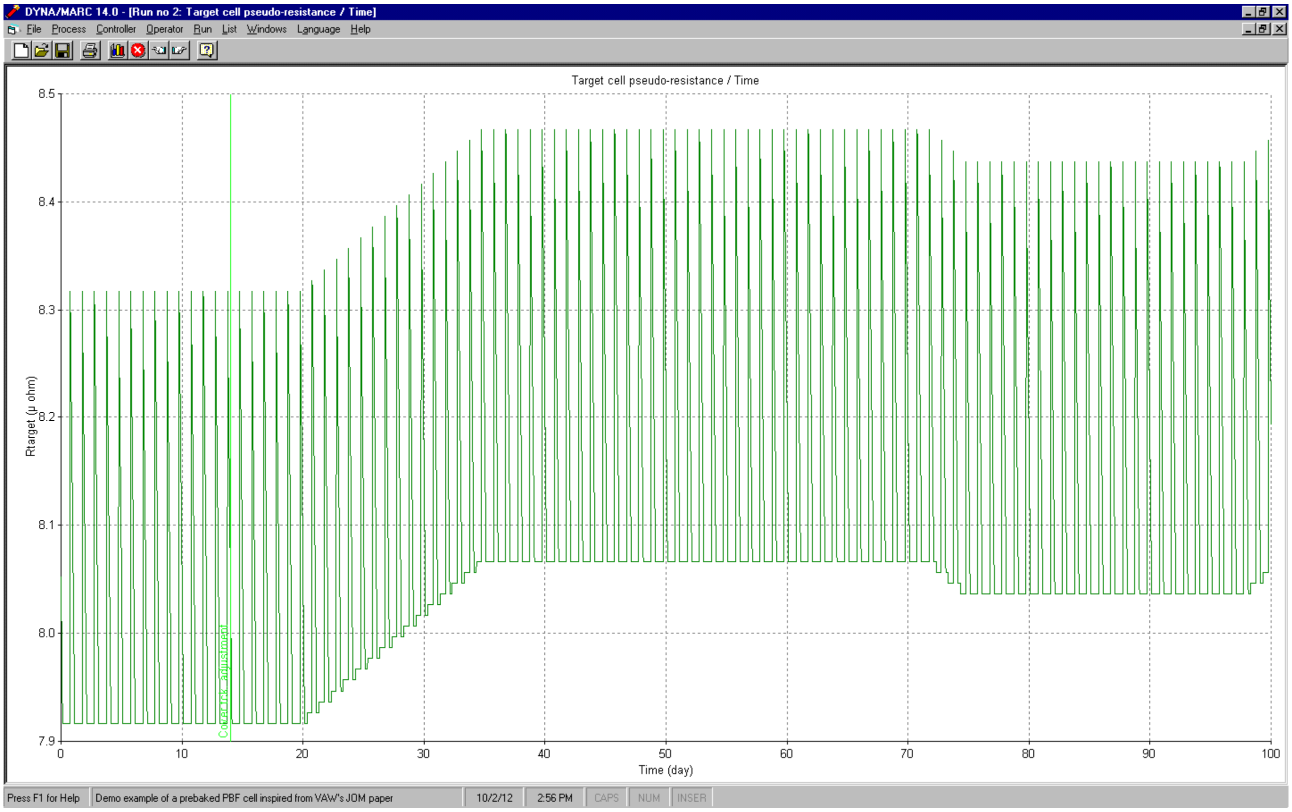


Figure 8: Simulation of the process with a significant perturbation; feedback control, 10% target concentration (STARprobe^{TM} measurements once per day, 0.5 kg/hr% proportional band and daily 0.1 micro-ohm target resistance correction due to superheat offset from target)



Demo example of a prebaked PBF cell inspired from VAW's JOM paper

Figure 9: Evolution of the cell target resistance (there is a 0.4 micro-ohm change of target resistance each day during the anode change event)