Testing Cell Controller Algorithms Using a Dynamic Cell Simulator

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The two main tasks of an aluminium reduction cell controller are to collect and process the raw cell amperage and voltage and then use that information to send instructions to the point breaker feeder and the anode beam in order to keep both the dissolved alumina concentration in the bath and the anode cathode distance (ACD) under tight control.

There is an obvious advantage to test a modification to the cell controller algorithms using a simulated cell instead of conducting those tests on real cells. This is true as long as the behavior of the simulated cell is reliable enough to provide useful feedback. In order to achieve that goal, the Dyna/Marc cell simulator has been continuously improved since 1994. It already demonstrated its ability to reproduce measured cell dynamic evolution in previous publications [1, 2].

Testing cell voltage noise filtration algorithms: Since version 1.0 issued in 1998, Dyna/Marc has been offering the option to add amperage and voltage noise to the simulation. For the cell voltage that is an output to the simulation, the noise generated by the bath-metal interface motion and the bubble release is added to the calculated noise free voltage at the end of each time step. The level of the added noise is function of the ACD, the thickness of the metal pad, the amount of sludge and the fraction of the anode surface covered by frozen bath. This noise level, that can be made to affect current efficiency, can be reduced by automated voltage treatment since version 1.4 issued in 1999.

The cell controller cannot directly use the noisy cell voltage to calculate the slope of the cell resistance as it would lead to useless results. Since version 13.0 issued in 2011, Dyna/Marc is offering linear and quadratic root mean square (RMS) noise filtration algorithms [3]. Figure 1 is showing the comparison between the noise-free and the noisy evolution of the cell pseudo-resistance. The aim of the cell controller noise filtration algorithm is to use the noisy data to estimate the evolution of the slope of the noise-free curve. Figure 2 is showing the comparison between the noise-free slope evolution and the slope evolution estimated using three different modes of filtration.

The first one on the left was obtained using linear RMS fitting using 60 datapoints that are themselves 5 seconds averaged value of the raw cell voltage measured at a 10 Hz frequency. As it can be seen, the resulting estimation is still a bit noisy. The second one in the middle was obtained using 120 datapoints instead of 60 datapoints. The result is almost noise-free but now the estimation is dragging 5 minutes behind the noise-free slope that is being estimated. This is to be expected as it is the best linear fit of cell voltage evolution using the last 10 minutes of datapoints collected so it best represents the state of the slope 5 minutes ago. In the example presented in Figure 2, the slope is doubling in 5 minutes during a no-feed observation, so the estimated value is noise-free but about half of the real value. The third mode of filtration on the right of Figure 2 was obtained using quadratic RMS fitting also using 120 datapoints. Using quadratic RMS fitting of the cell voltage evolution eliminates the drag in the slope estimation which is important, but for the same number of datapoints used, generates a more noisy estimation.

Testing feed control algorithms: These days, the majority of aluminium reduction cell alumina feed control algorithms are based on continuous tracking or underfeeding and overfeeding cycles where the shift from underfeeding to overfeeding is dictated by a trigger value or either the slope of the cell pseudo-resistance or the slope of the cell normalized voltage. One of the earliest versions of that algorithm can be found in Figure 3 of Aluminium Pechiney 1988 TMS paper [4]. That algorithm is available in Dyna/Marc simulator under the name Pechiney Tracking Feed Control [5].

The basic concept that lead to the development of that algorithm was the observation that the cell current efficiency is maximized by operating very lean in alumina, so very close to the anode effect conditions and taking advantage of the fact that during underfeeding, the slope of the cell pseudo-resistance starts to rise significantly before the anode affect. Figure 3 presents the results by running that feed control algorithm in Dyna/Marc. The top graphic is showing the 24 hours evolution of the cell pseudo-resistance. Metal is tapped out at noon and anodes are changed at 18 hours. It can be noticed that the cell is more noisy after the anode change. The middle graph is showing the noise-free evolution of the slope of the cell pseudo-resistance in blue. It also presents the estimated slope evolution that results from using linear RMS fitting with 60 datapoints, each datapoint being the results of 5 seconds cell pseudo-resistance evolution averages. At that time scale, the 2.5 minutes delay between the noise free pseudo-resistance evolution of the estimated pseudo-resistance evolution is not noticeable but do affect the timing of the feeding regime shift. The third lower graphic is showing the feeding rate evolution resulting from the algorithm decision. The underfeeding rate is 70% of the nominal feeding rate while the overfeeding rate is 140% of the nominal feeding rate. The overfeeding rate duration was set to 1 hour. As a result, the resulting evolution of the dissolved alumina concentration in the bath in the same graph is varying from around 2% to around 2.5%, 2% being the alumina concentration that would trigger an anode effect.

It is important to notice that the alumina concentration continue to decrease by about 0.1% before starting to increase when the feeding rate is changed from underfeeding to overfeeding. That delayed response will trigger an anode effect if the shift of feeding regime is done too late; hence the importance of eliminating as much as possible the delay in the pseudo-resistance slope estimation. Figure 4 presents the resulting 24 hours averaged specific power consumption and current efficiency: 12.96 kWh/kg and 94.71 % respectively.

It is now well recognized that the usage of this type of continuous tracking feed control algorithm led to a significant current efficiency increased over the usage of feed control algorithms that were using nominal feeding rate most of the time. It is also well known that the shorter feeding cycle also lead to current efficiency increase; this can be tested using the cell simulator. Figure 5 presents results obtained using a shorter 40 minutes overfeeding rate duration. As a result, the dissolved alumina concentration only varies from around 2% to around 2.3%. In Figure 6, this leads to a predicted improvement of the current efficiency to 94.78% and a slight increase of the specific power consumption to 13.01 kWh/kg if the ACD is kept constant.

The demand feed control algorithm developed by Kaiser and implemented in Celtrol cell controller [6] is also available in Dyna/Marc. The same reduction of the feeding cycle study presented above can be repeated using this time the demand feed control algorithm. Figures 7 and 8 present the base case results: 12.91 kWh/kg and 94.67 % current efficiency, while Figures 9 and 10 present results for the case with shorter feed cycles: 13.09 kWh/kg and 94.65 % current efficiency. Despite a very similar increase of the feed cycles and reduction of the range variation of the dissolved alumina concentration, results on the global process efficiency predictions are different this time: the current efficiency is not affected and the specific power consumption is increasing. The difference is explained by the fact that this time, it was not possible to keep the same average ACD and operating temperature, they both increased for the shorter cycles case.

Developing and testing feed control algorithms: A dynamic cell simulator can be even more useful to develop, without putting real cells at risk, a completely new feed control algorithm. One such innovative new feed control algorithm that was recently tested using Dyna/Marc cell simulator, it is the *In Situ* feed control algorithm [3, 7, 8, 9].

The main innovation at the core of the new *In Situ* feed control algorithm is realization that it is possible to indirectly measure the concentration of dissolved alumina in the bath during a no feed track by numerically establishing the relationship that exists between the slope of the normalized cell voltage and the alumina concentration. In fact, that correlation is implicitly used in all continuous tracking algorithms that monitor the slope of the pseudo-resistance (or the slope of the normalized cell voltage) to decide when it is time to shift from underfeeding to overfeeding.

Verifying that there is a unique correlation between the concentration of dissolved alumina in the bath and the slope of the normalized cell voltage and numerically establishing that unique correlation if it exits is something that can be quite easily done using a cell simulator. Figure 11 presents the results by running the *In Situ* feed control algorithm in Dyna/Marc for 24 hours. A no feed-track is called every 3 hours in order to evaluate the dissolved alumina concentration. Figure 12 presents the correlation between the slope of the normalized cell voltage and the dissolved alumina concentration. The black line is the fit of the average path during the tracking, all 8 tracks are following the same trajectory. This is why the In Situ feed algorithm can use the shown equation to establish the alumina concentration at the end of each track. So, there is a unique correlation, because each track start from identical conditions, the conditions the *In Situ* feed algorithm is trying to maintain.

The second innovation at the core of the *In Situ* feed control algorithm is the usage of the primary calibration surface [3], at the end of each track, to establish the ACD once the dissolved alumina concentration has been established. Then, based on an estimated evolution rate of the ACD, that same primary calibration surface is used as well as an assumed ACD value to estimate every 5 minutes the dissolved alumina concentration from the cell normalized voltage. Finally, a simple PID controller is used to maintain the estimated dissolved alumina concentration on its target value. In the example shown in Figure 11, that target concentration was set to 2.25%.

Figure 13 presents the results of a second run, calling for a track every 12 hours only, this time with the normal anode change event that was removed in the previous run in order to keep things more simple. Figure 14 presents the corresponding 24 hours averaged specific power consumption and current efficiency: 13.02 kWh/kg and 94.77 % respectively. Those results are quite similar to those obtained using continuous tracking feed control algorithm with shorter cycles, but with far less risk of having anode effects.

Conclusions

The author hopes that this demonstration study highlights the value of using a dynamic cell simulator to optimized existing cell controller algorithms or to test new ones without putting real cells at risk. Dyna/Marc cell simulator used in this study is available to the whole aluminium industry through GeniSim Inc. Version 13 included the linear and quadratic RMS noise filtration algorithms and the *In Situ* feed controller algorithm. Dyna/Marc cell simulator can also be used as a cell design tool as demonstrated in [10].

References

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Author

Dr. Marc Dupuis is a consultant specialised in the applications of mathematical modelling 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.

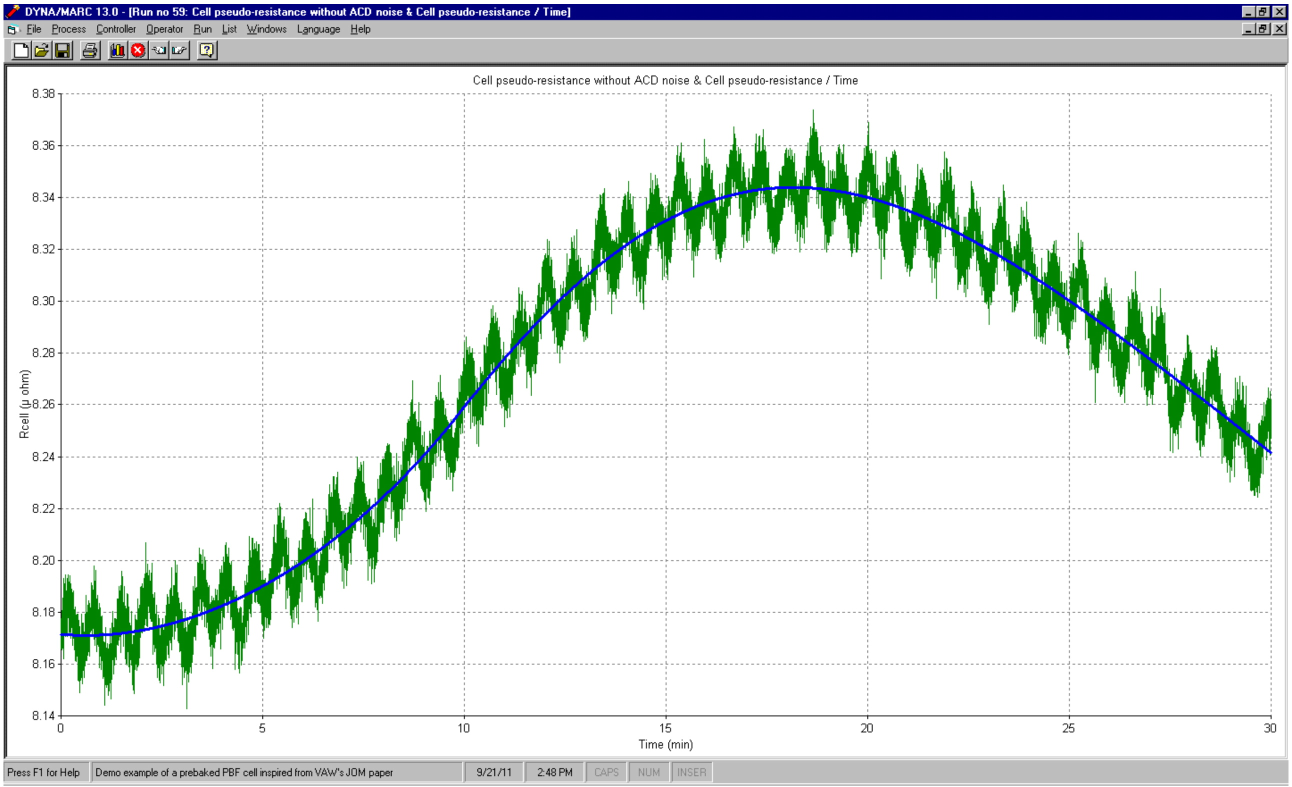

Figure 1: Noise-free (in blue) and noisy (in green) cell pseudo-resistance evolution as generated by Dyna/Marc cell simulator

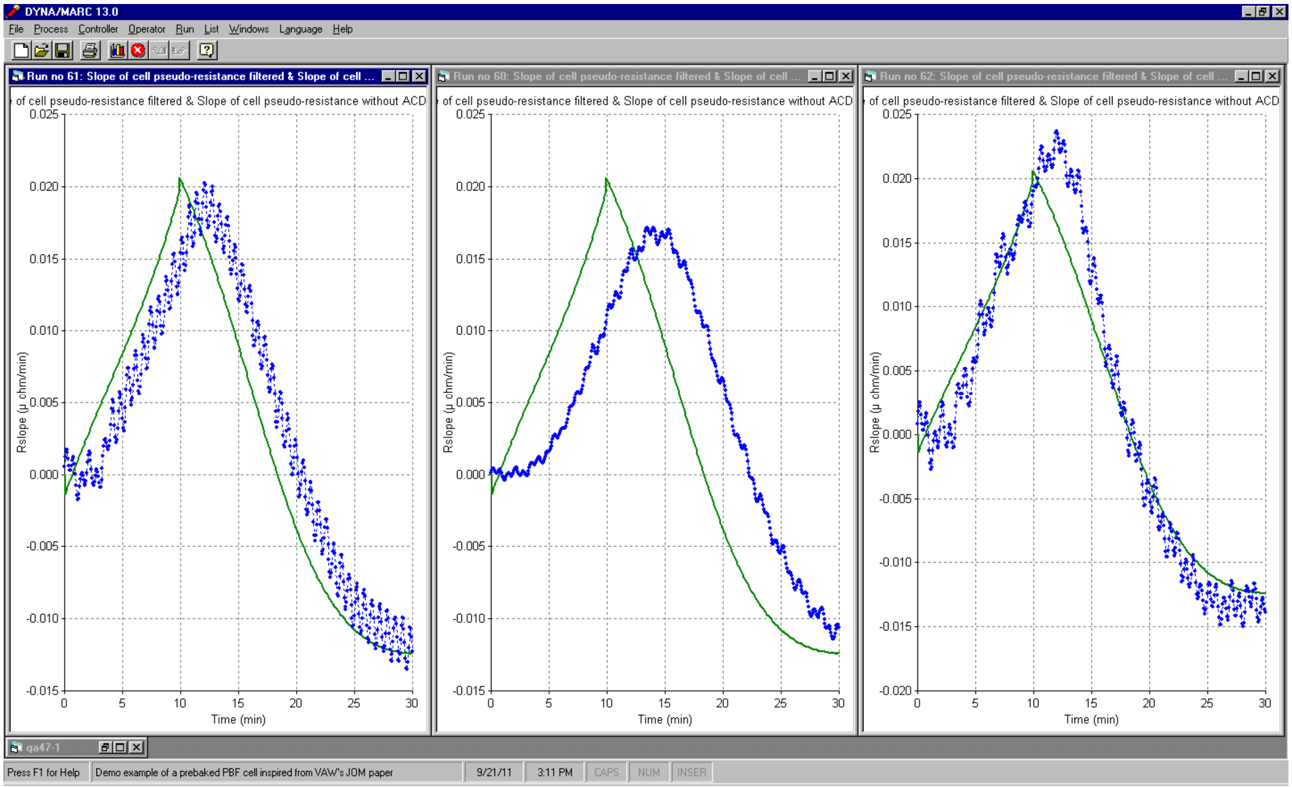

Figure 2: Noise-free (in green) and filtrated (in blue) slope of the cell pseudo-resistance using 60 datapoints linear RMS fit on the left, 120 datapoints linear RMS fit in the middle and 120 datapoints quatratic RMS fit on the right.

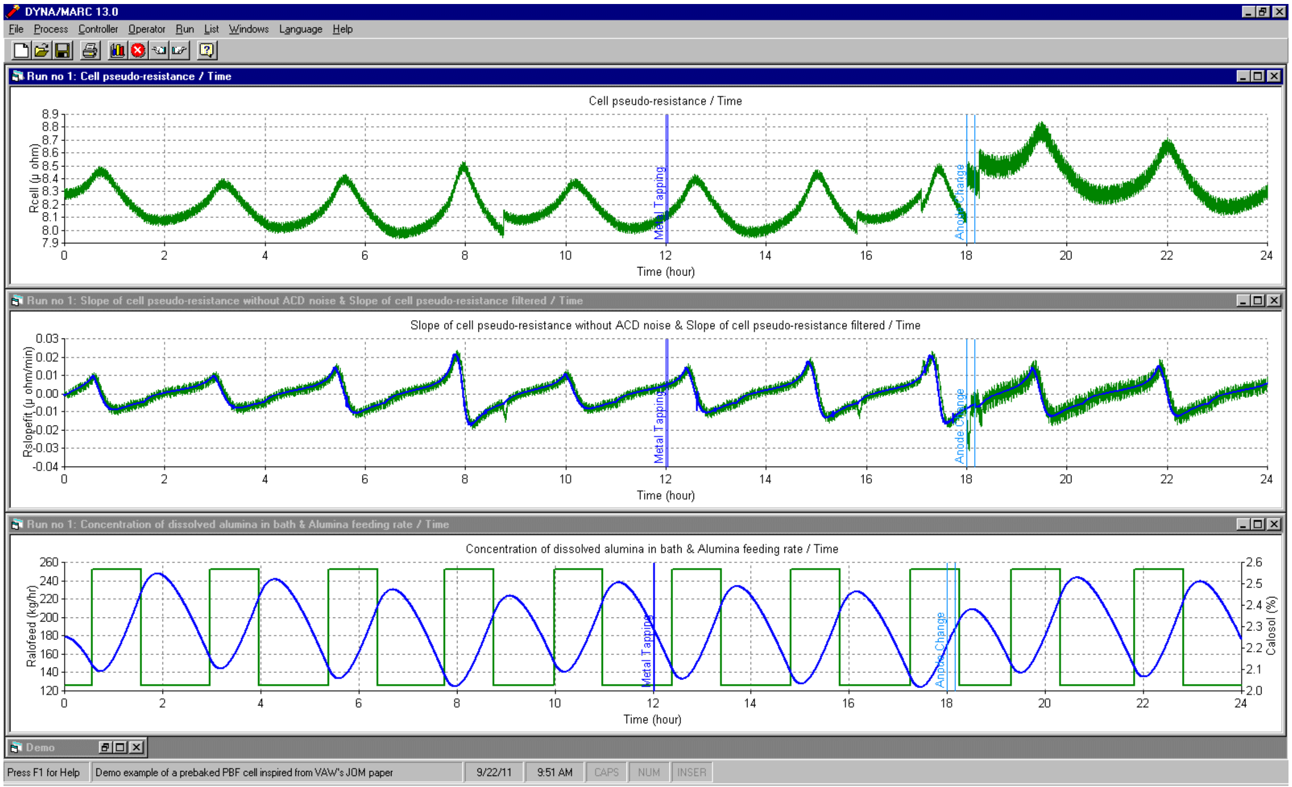

Figure 3: 24 hours Dyna/Marc simulation using the Pechiney Tracking Feed Control

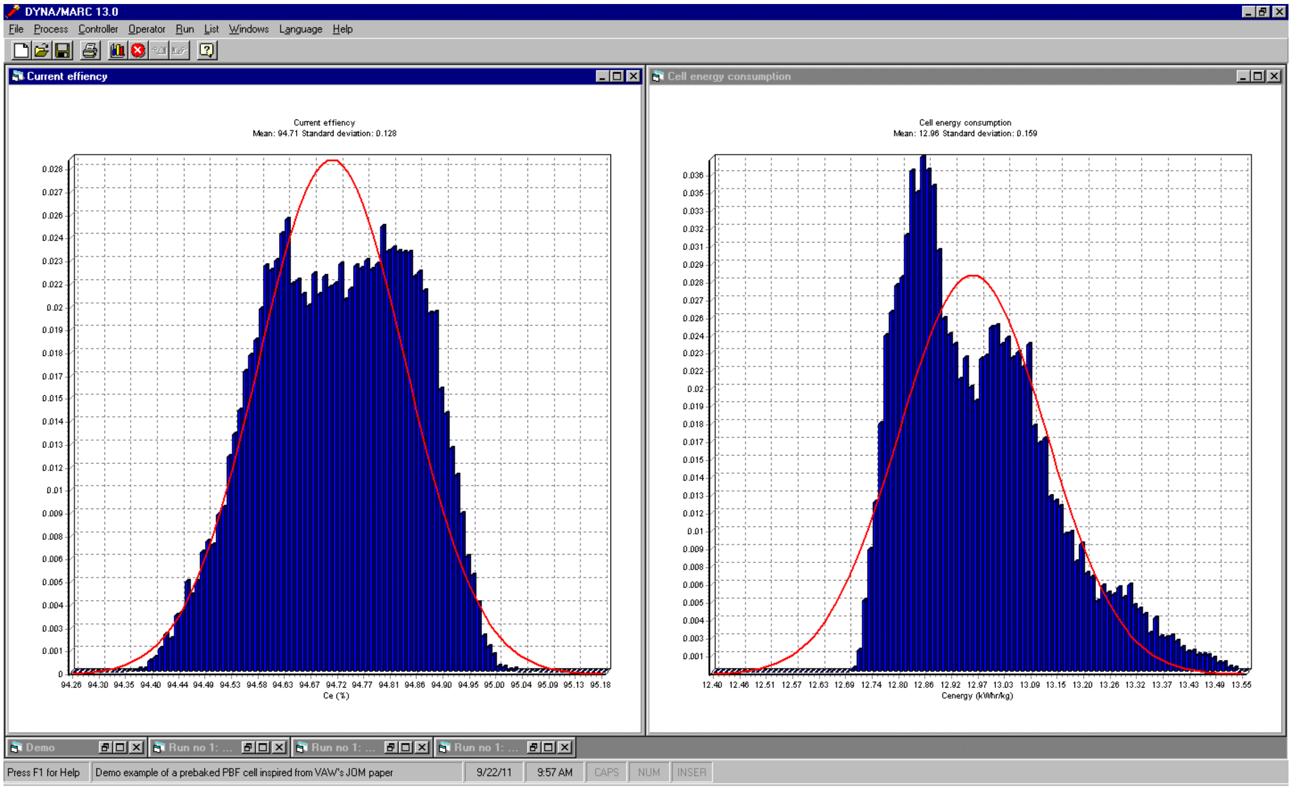

Figure 4: Predicted 24 hours averaged cell power and current efficiency, using the Pechiney Tracking Feed Control

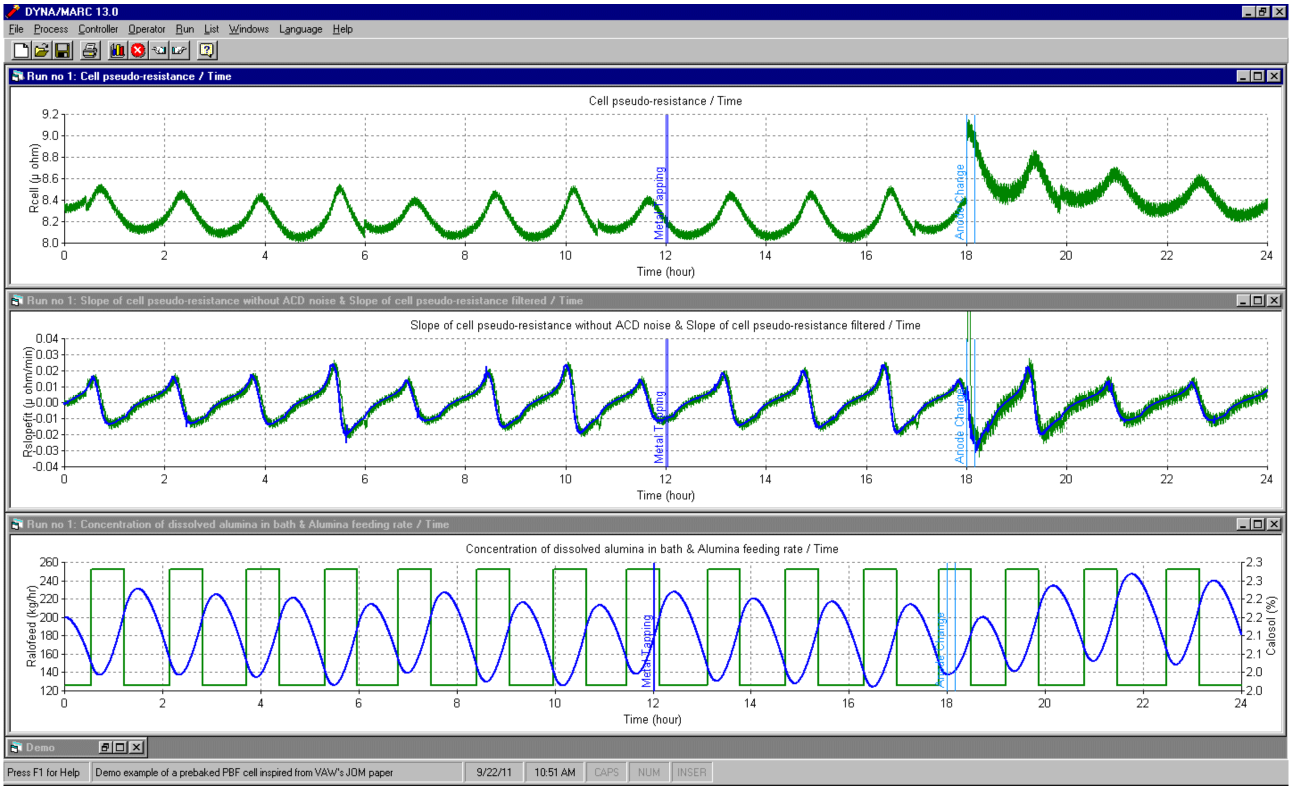

Figure 5: 24 hours Dyna/Marc simulation using the Pechiney Tracking Feed Control, shorter cycles

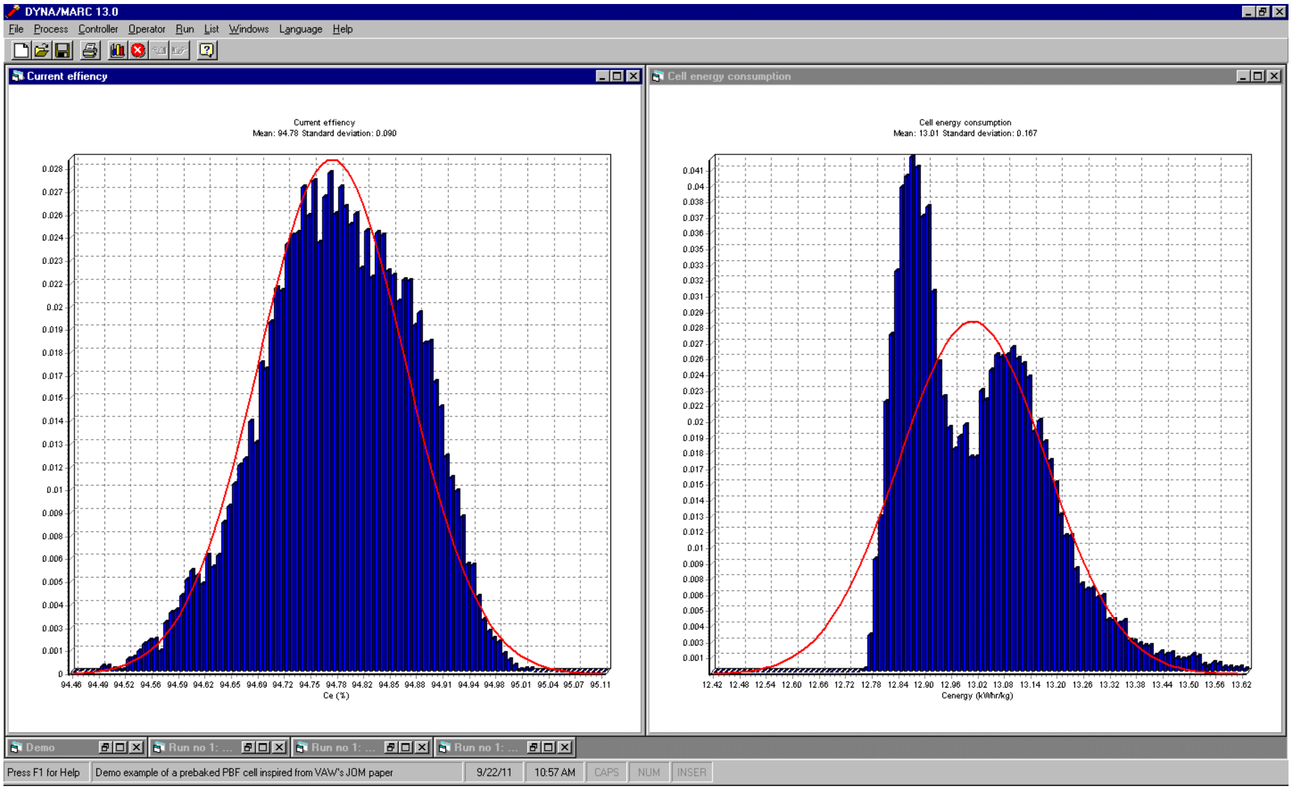

Figure 6: Predicted 24 hours averaged cell power and current efficiency, using the Pechiney Tracking Feed Control, shorter cycles

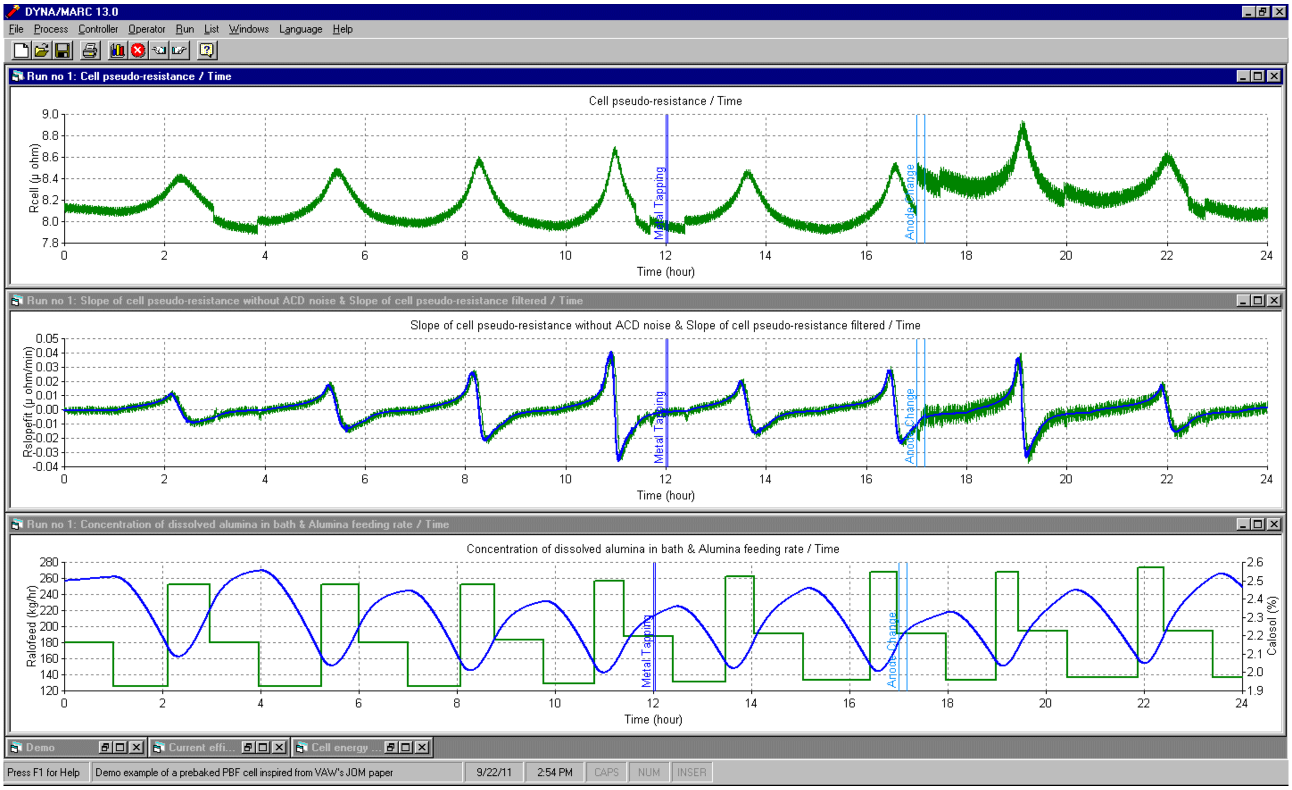

Figure 7: 24 hours Dyna/Marc simulation using the Demand Tracking Feed Control

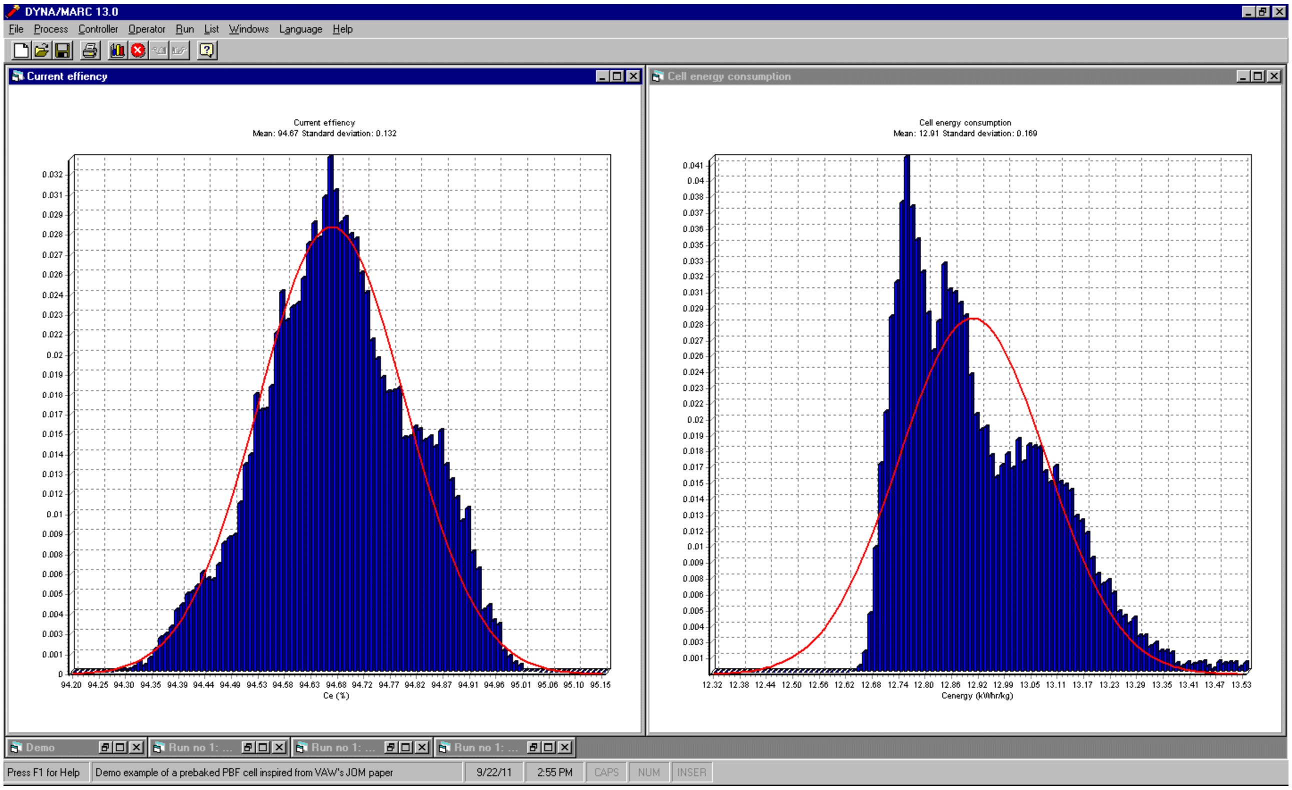

Figure 8: Predicted 24 hours averaged cell power and current efficiency, using the Demand Tracking Feed Control

Figure 9: 24 hours Dyna/Marc simulation using the Demand Tracking Feed Control, shorter cycles

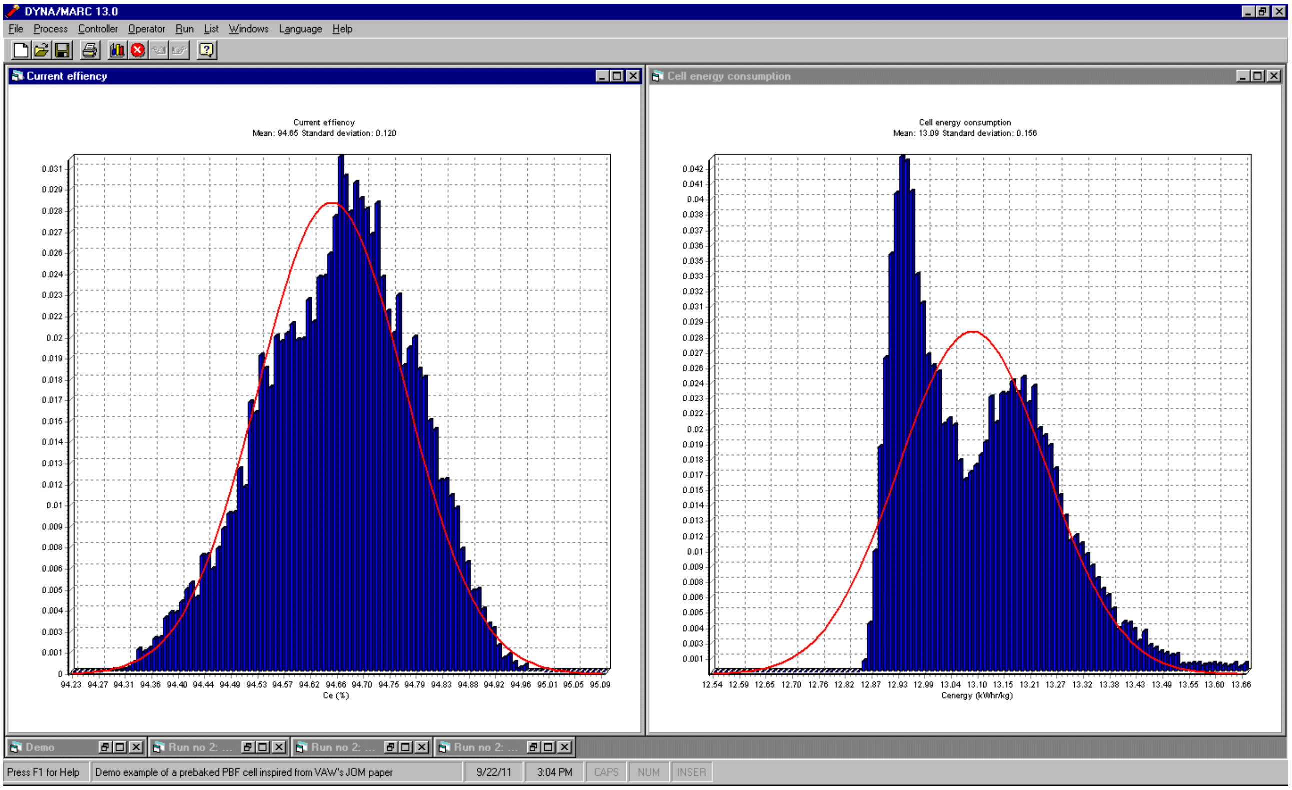

Figure 10: Predicted 24 hours averaged cell power and current efficiency, using the Demand Tracking Feed Control, shorter cycles

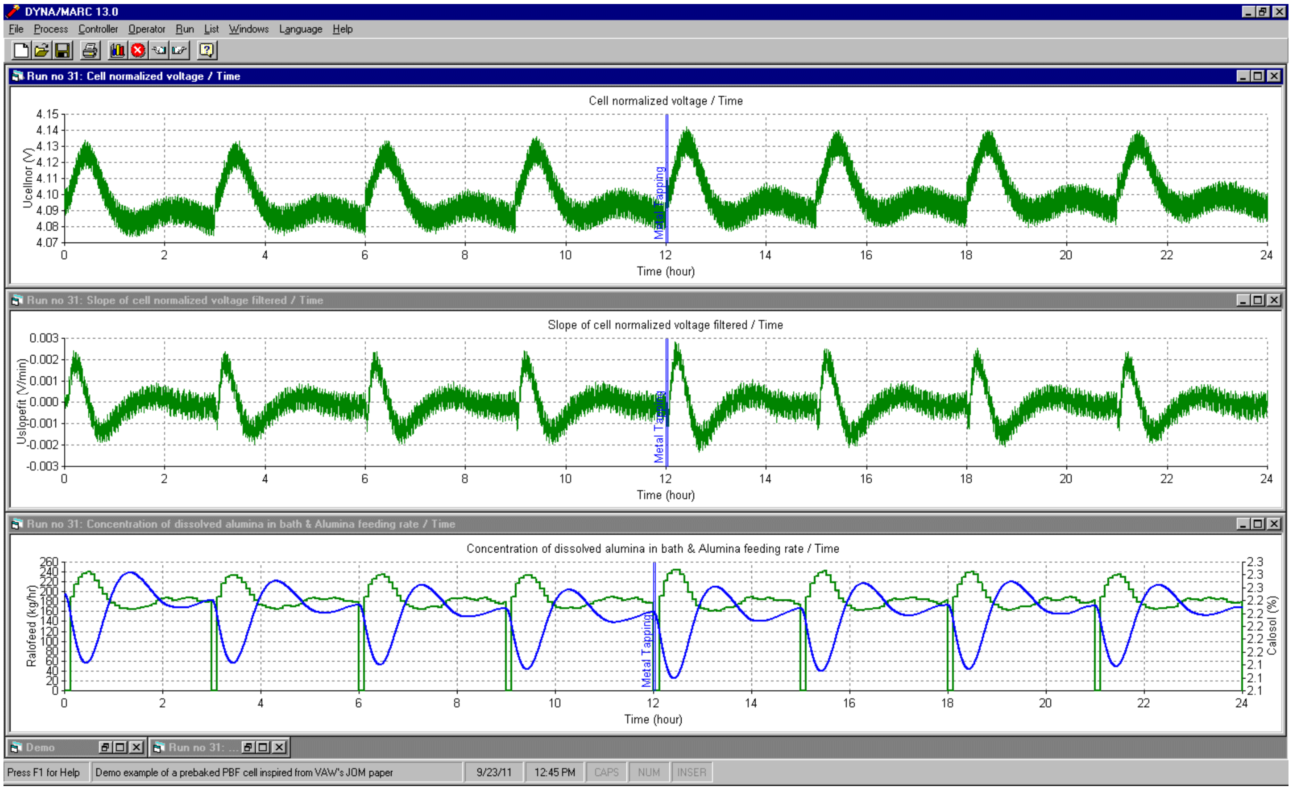

Figure 11: 24 hours Dyna/Marc simulation using the *In Situ* Feed Control

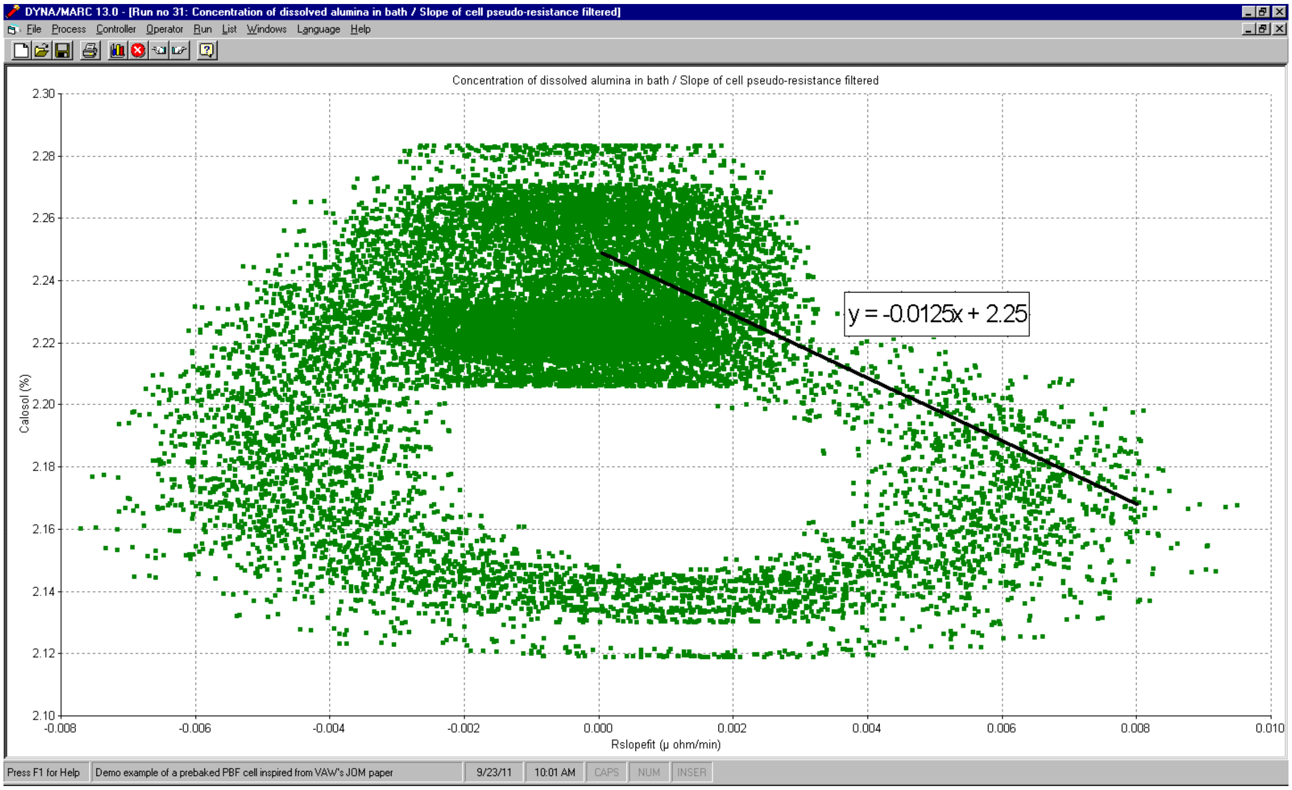

Figure 12: Correlation between the slope of the normalized cell voltage and the dissolved alumina concentration for that 24 hours simulation

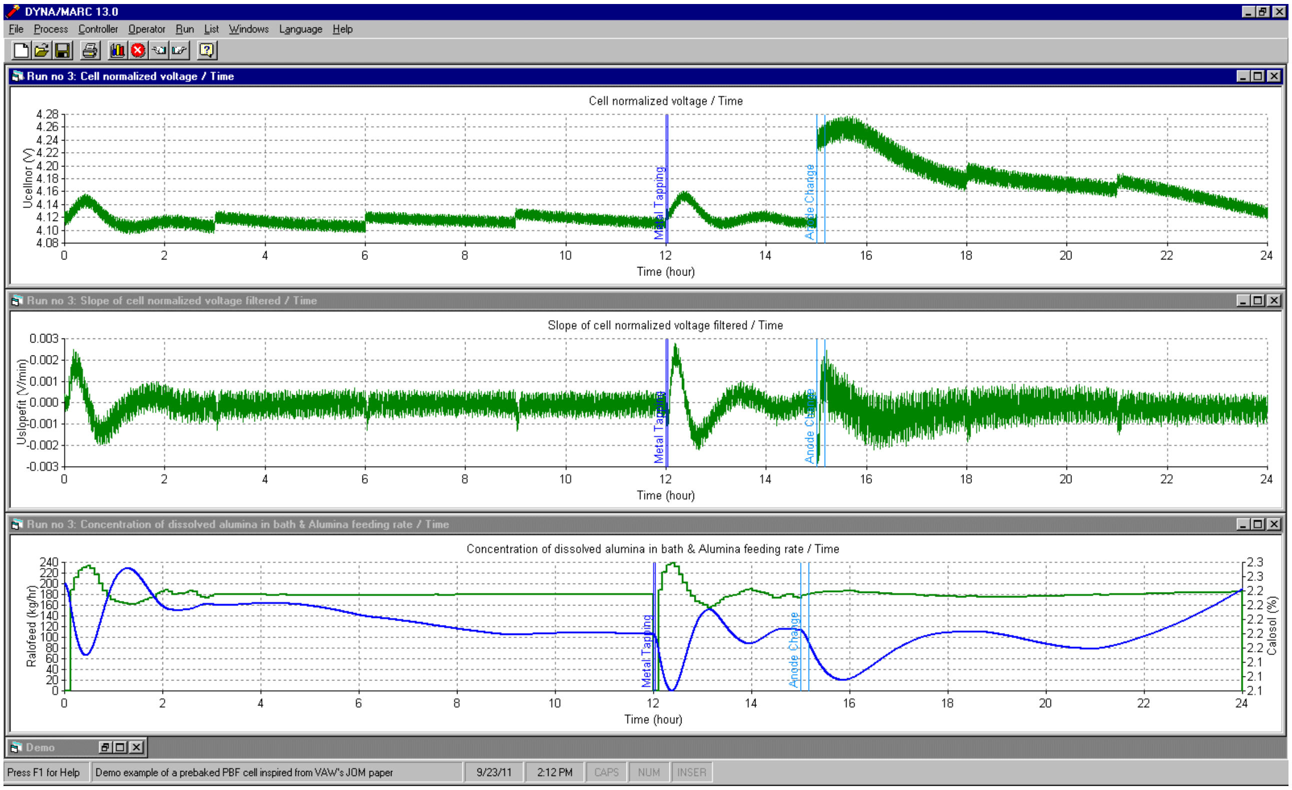

Figure 13: 24 hours Dyna/Marc simulation using the *In Situ* Feed Control with normal anode change event

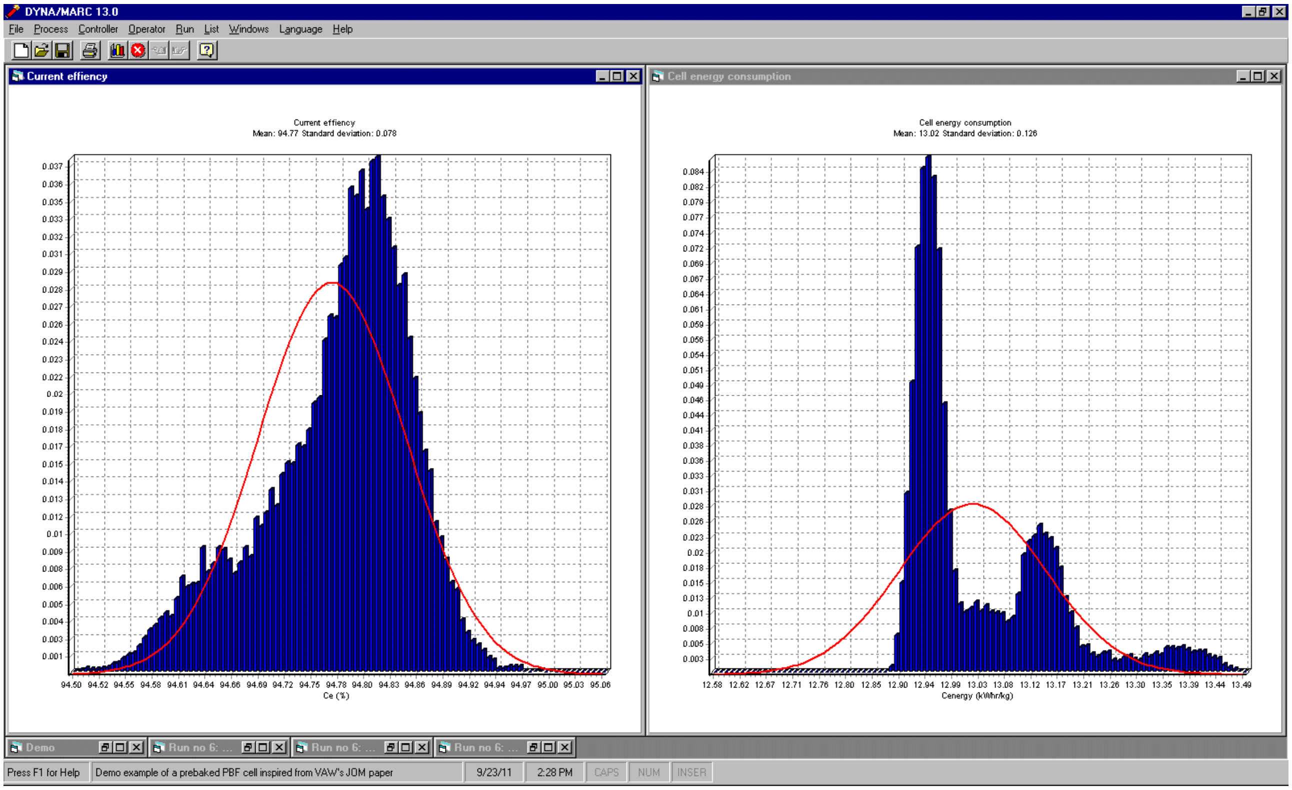

Figure 14: Predicted 24 hours averaged cell power and current efficiency, using the *In Situ* Feed Control