Testing *In Situ* Aluminium Cell Control with the Dyna/Marc Cell Simulator

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GENISIM

In Situ Aluminium Cell Control

Plan of the Presentation

- Introduction
- Calculation of the Normalized Cell Voltage
- Smoothing/fitting the Normalized Cell Voltage
  - Moving average
  - Linear root mean square fit
  - Quadratic root mean square fit
  - Continuous transition quadratic RMS fit
- Estimation of the Alumina Concentration
- Primary Calibration Surface and Estimation of the ACD
- PID Controller
- Effect of the Change of Control Logic on the Process Efficiency
- Conclusions

Introduction

- A new approach to controlling alumina feeding in a H.H. cell, called *In Situ* aluminium cell control has been recently proposed. The core principle is quite simple, it turned out that it is possible to extract the values of both the dissolved alumina concentration and the ACD at the end of a 5 to 10 minute no feed observation period only by using the standard cell amperage and voltage data.

- Once this is done, it is possible to use a PID controller to regulate the rate of alumina feeding using only the cell voltage to calculate the error between the estimated dissolved alumina concentration and a target value for an extended period of time. After that extended period of 8 to 12 hours, a new no feed observation period must be performed in order to reestablish the value of both process variables.

- The detailed procedure will now be described.

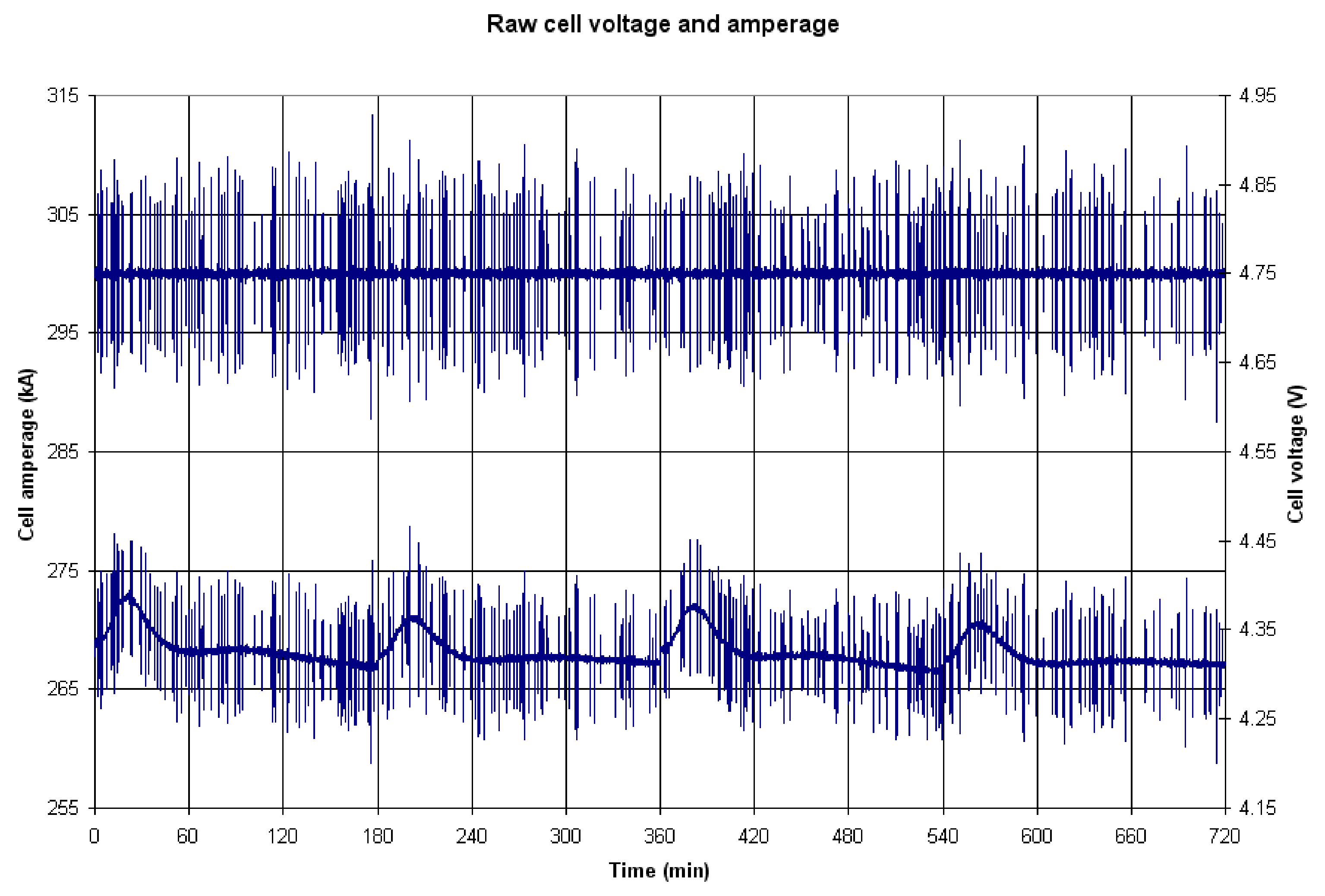
Calculation of the Normalized Cell Voltage

$$V_n = (V - \text{BEMF}) / I \; * \; I_n + \text{BEMF}$$

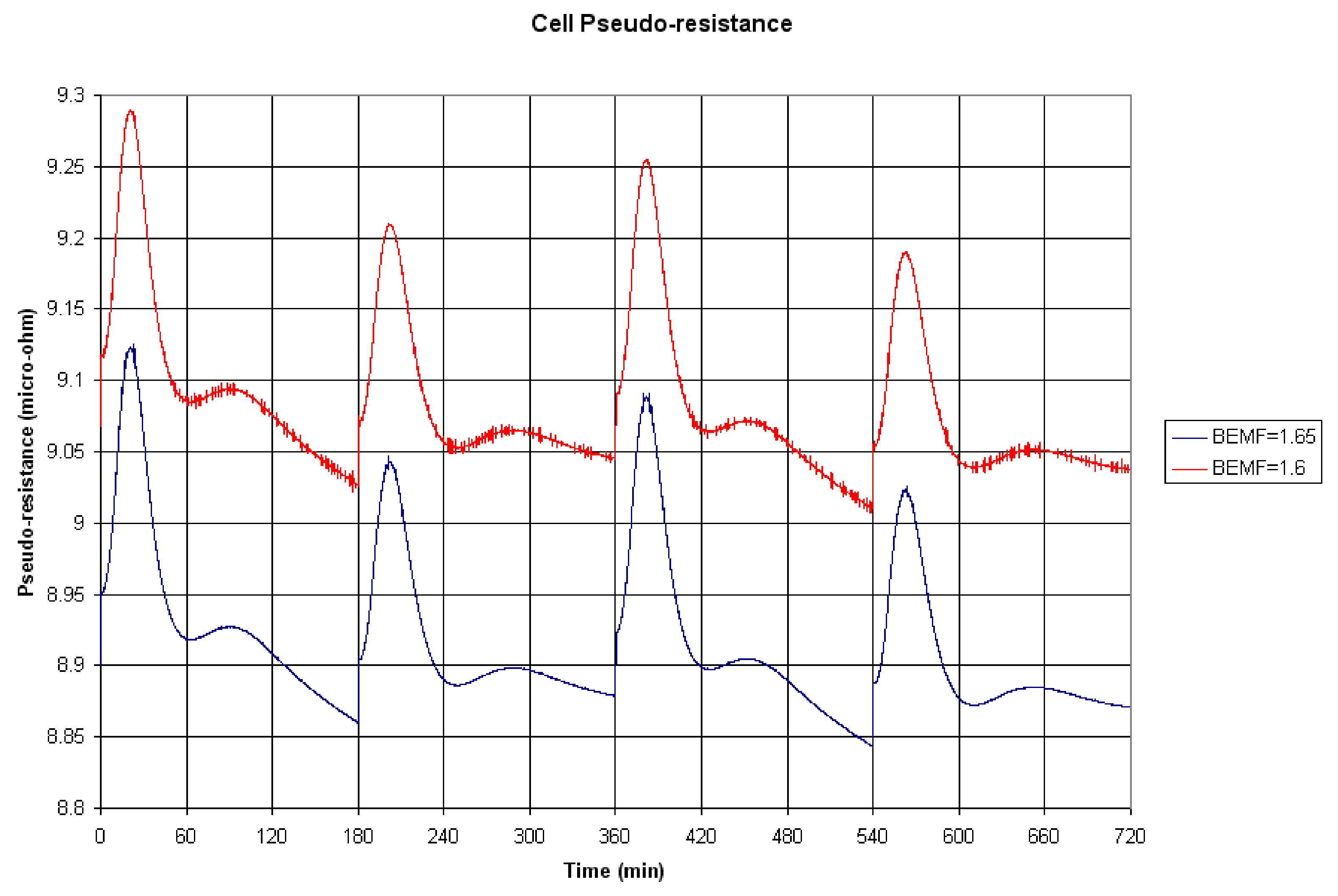
Where:

V_n	is the normalized cell voltage almost free of fluctuation due to the amperage fluctuation (V)
V	is the raw fluctuating cell voltage (V)
I	is the raw fluctuating cell amperage (kA)
I_n	is the nominal or target cell amperage (kA)
BEMF	is the extrapolated voltage at zero amperage usually set to 1.65 (V)

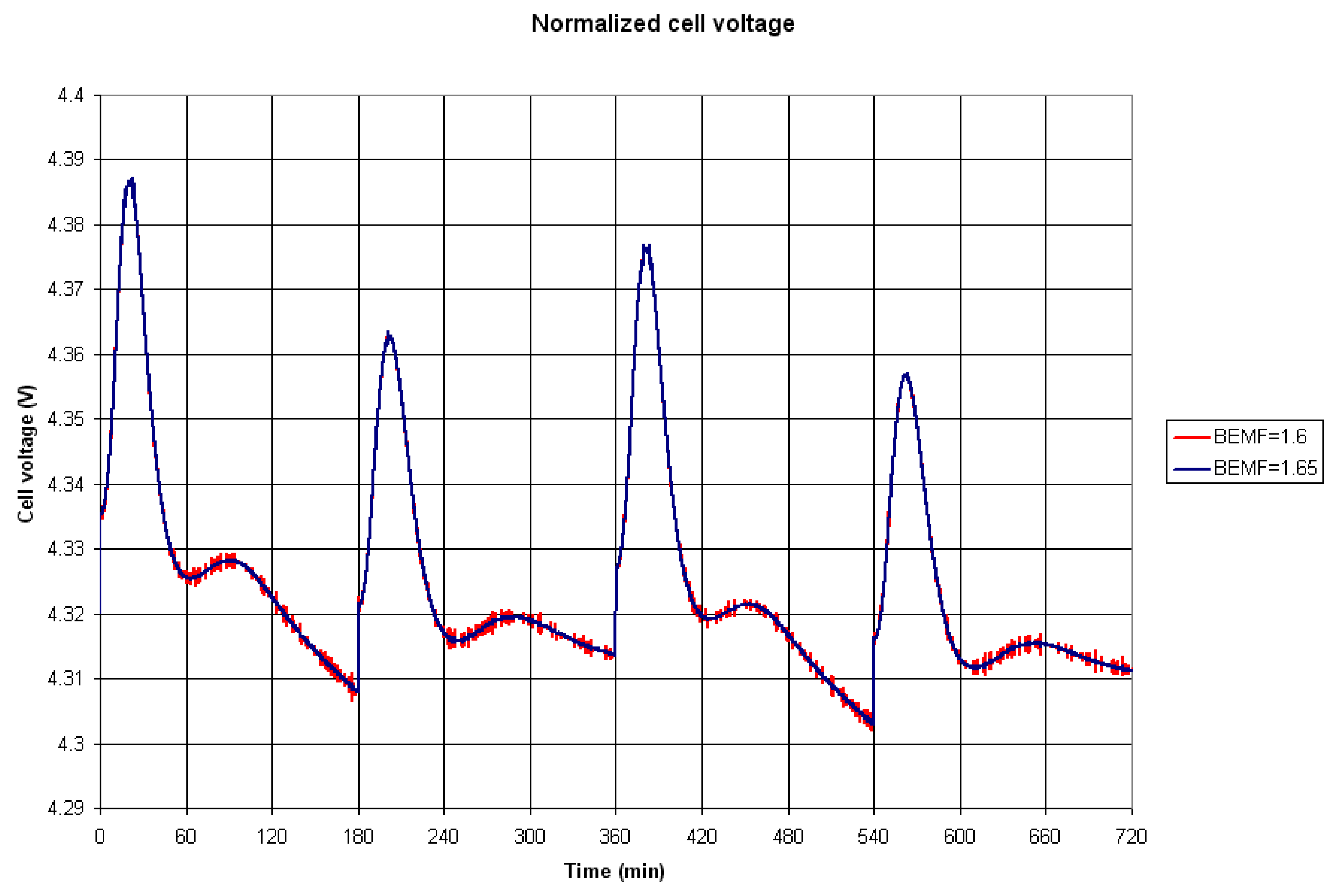
Calculation of the Normalized Cell Voltage



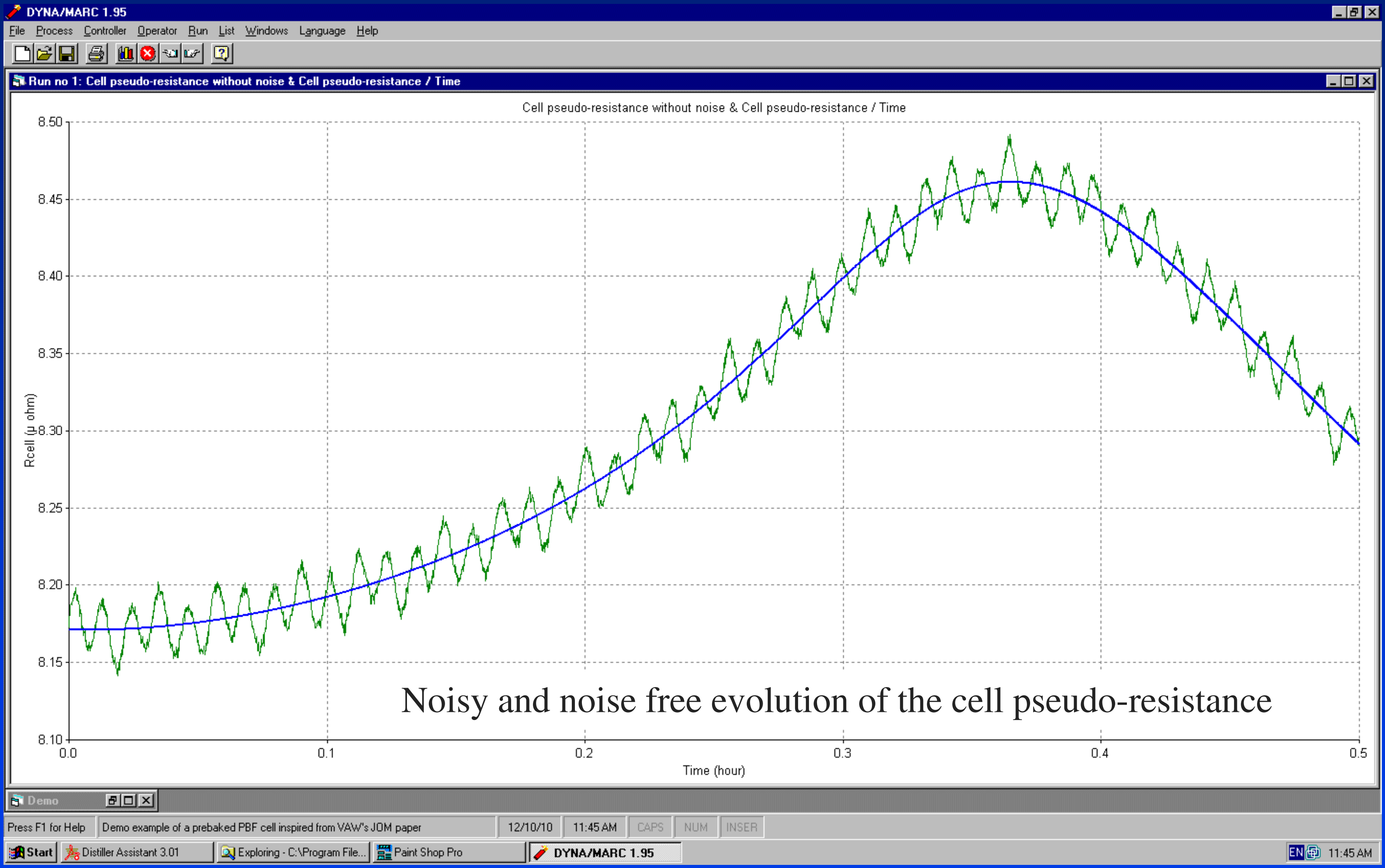
Calculation of the Normalized Cell Voltage



Calculation of the Normalized Cell Voltage



Smoothing/fitting the Normalized Cell Voltage



Noisy and noise free evolution of the cell pseudo-resistance

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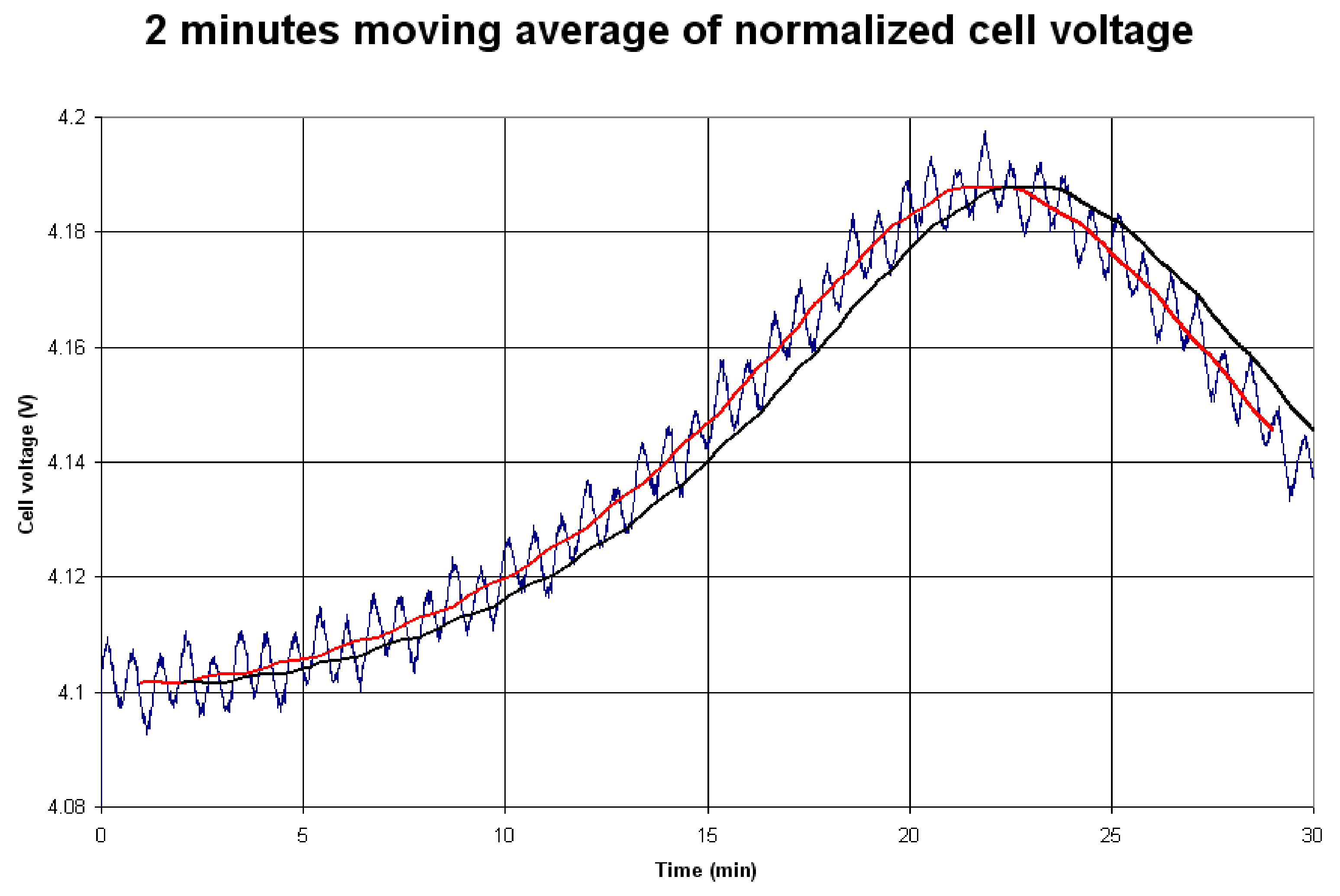
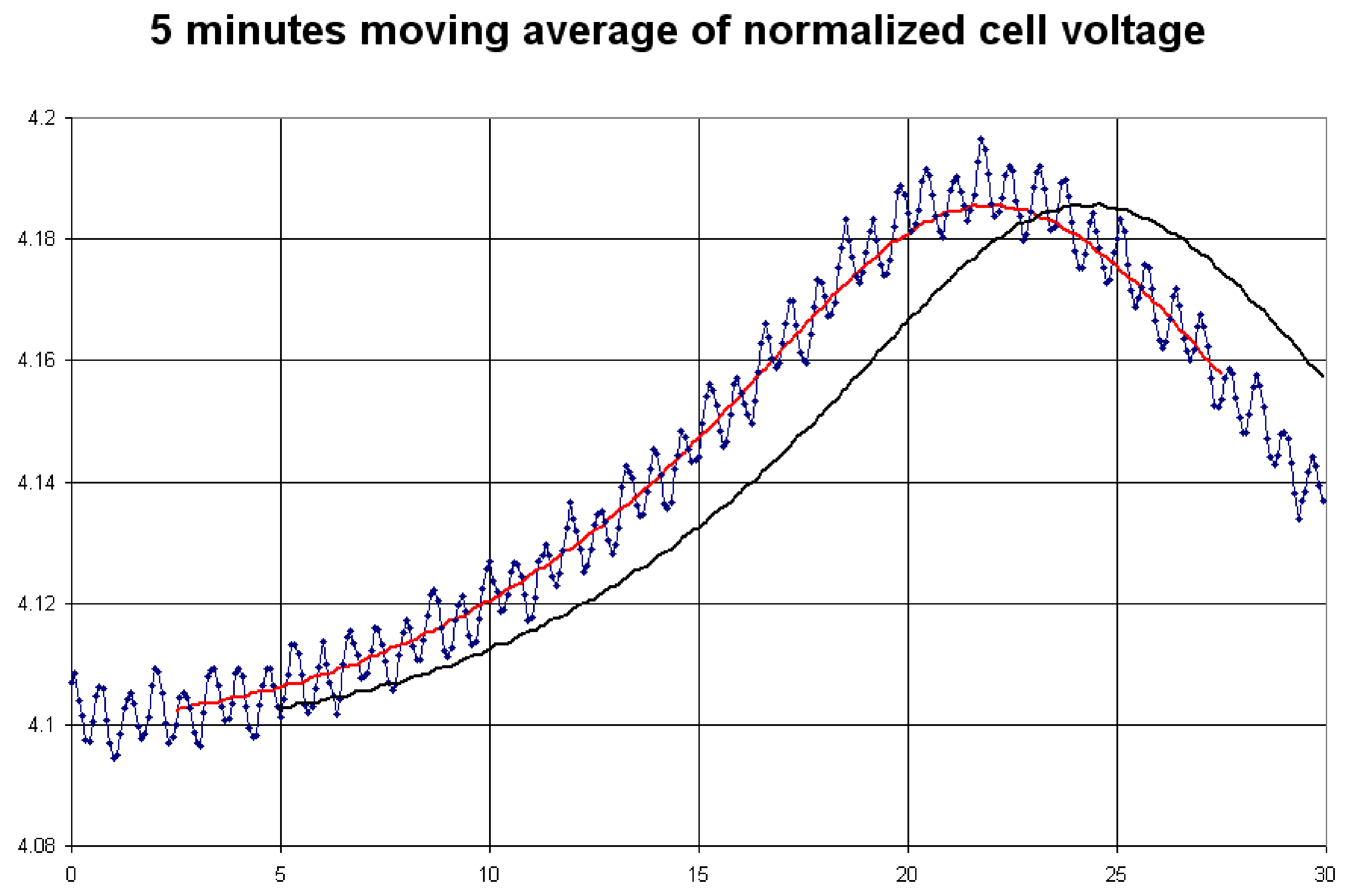
Demo example of a prebaked PBF cell inspired from VAW's JOM paper

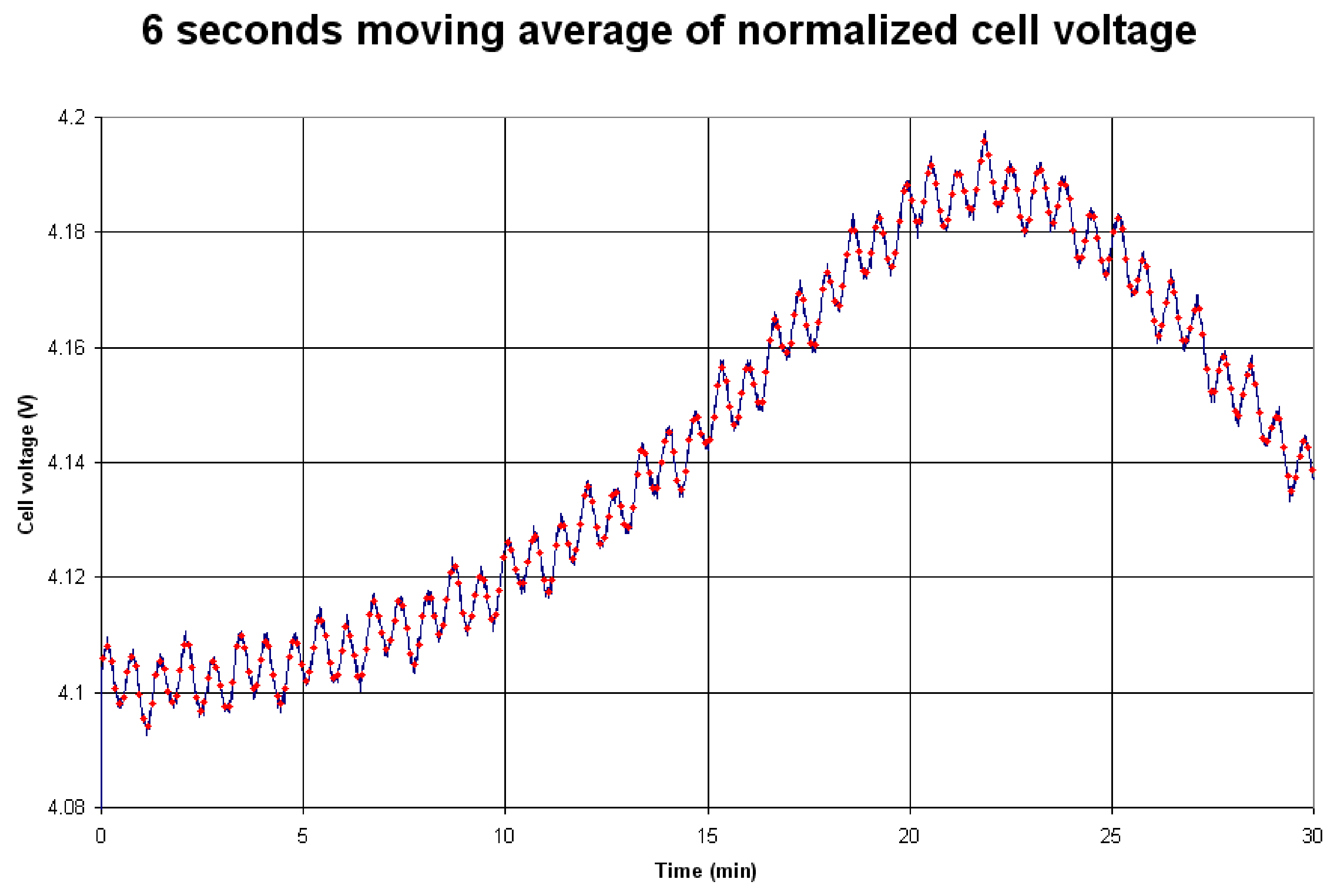
Smoothing/fitting the Normalized Cell Voltage



Smoothing/fitting the Normalized Cell Voltage



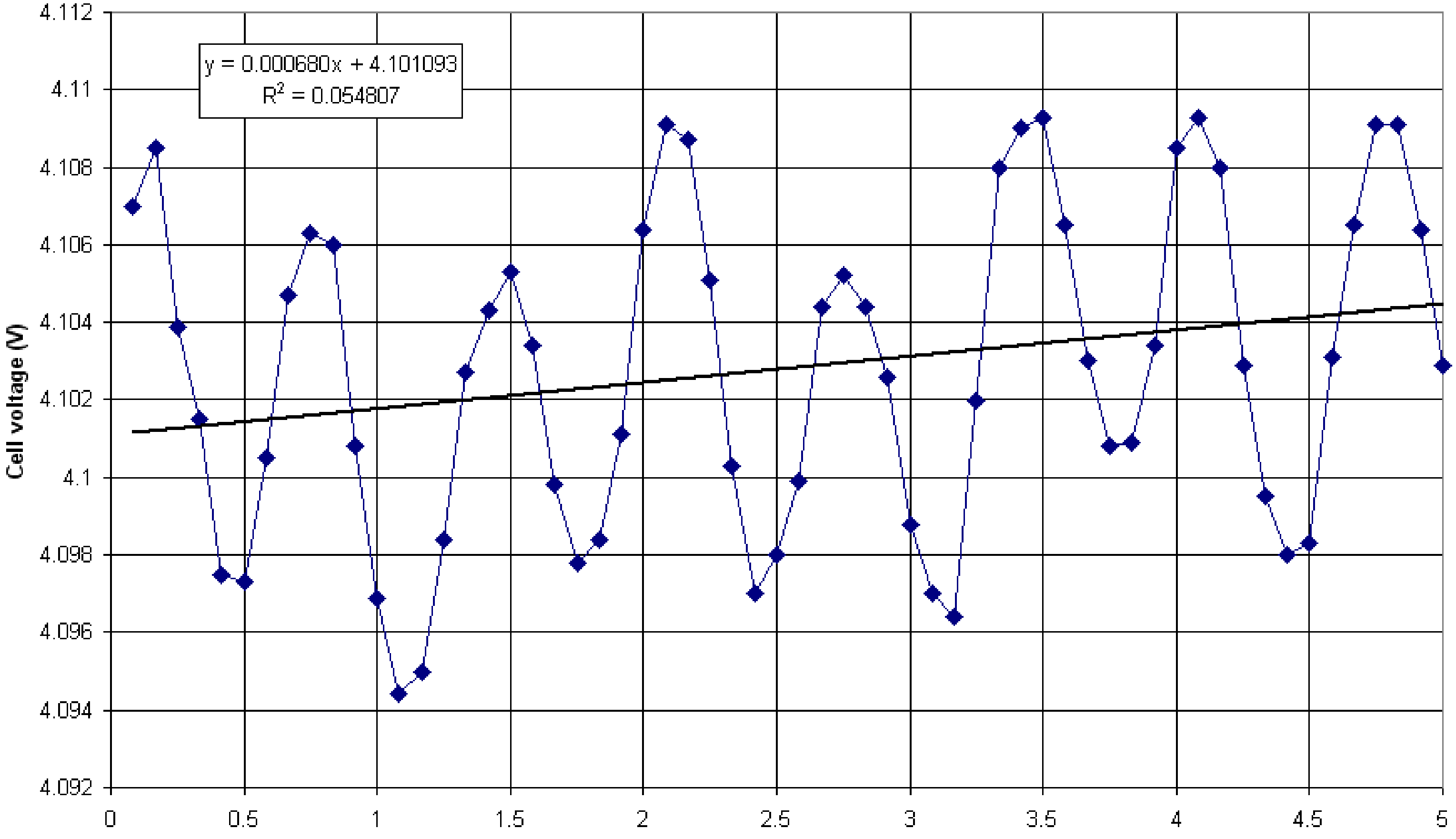
Smoothing/fitting the Normalized Cell Voltage



Smoothing/fitting the Normalized Cell Voltage

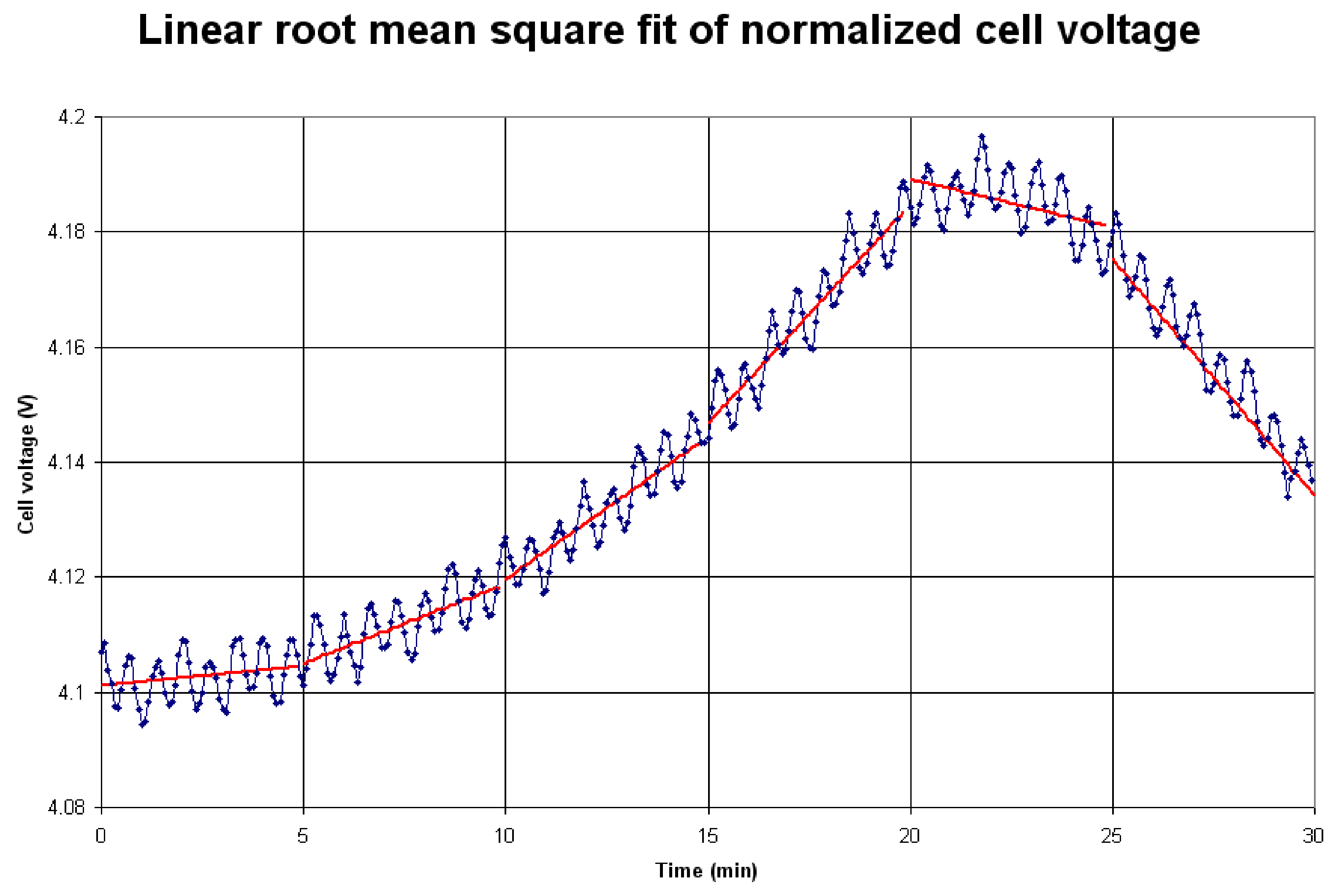
Linear root mean square fit of the normalized cell voltage

Prediction of the current noise free normalized cell voltage: 0.00068 * 5 + 4.1011 = 4.1045 V

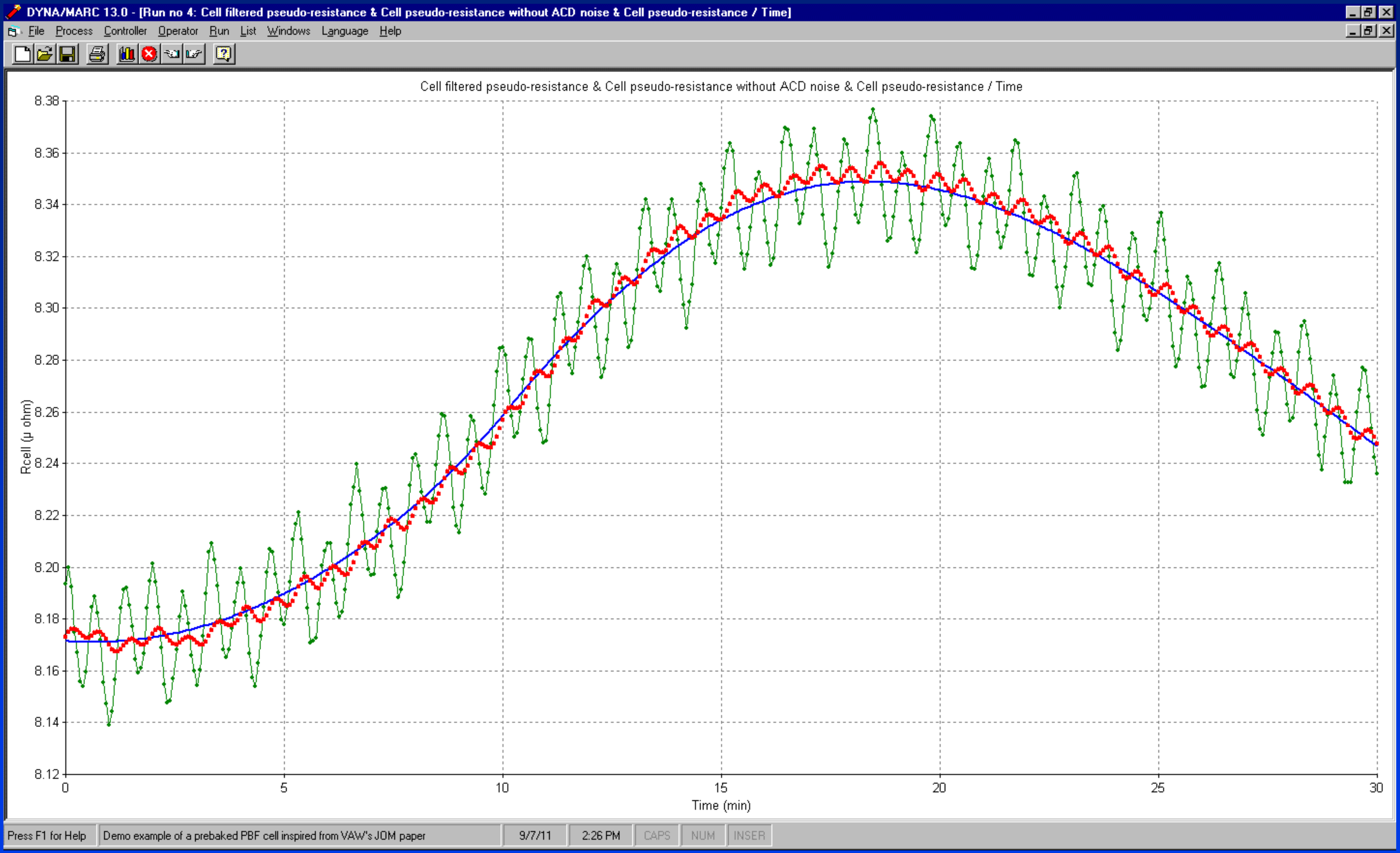


Prediction of the current noise free slope of the normalized cell voltage: 0.00068 V/min

Smoothing/fitting the Normalized Cell Voltage



Smoothing/fitting the Normalized Cell Voltage



DYNA/MARC 13.0 - [Run no 4: Cell filtered pseudo-resistance & Cell pseudo-resistance without ACD noise & Cell pseudo-resistance / Time]

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

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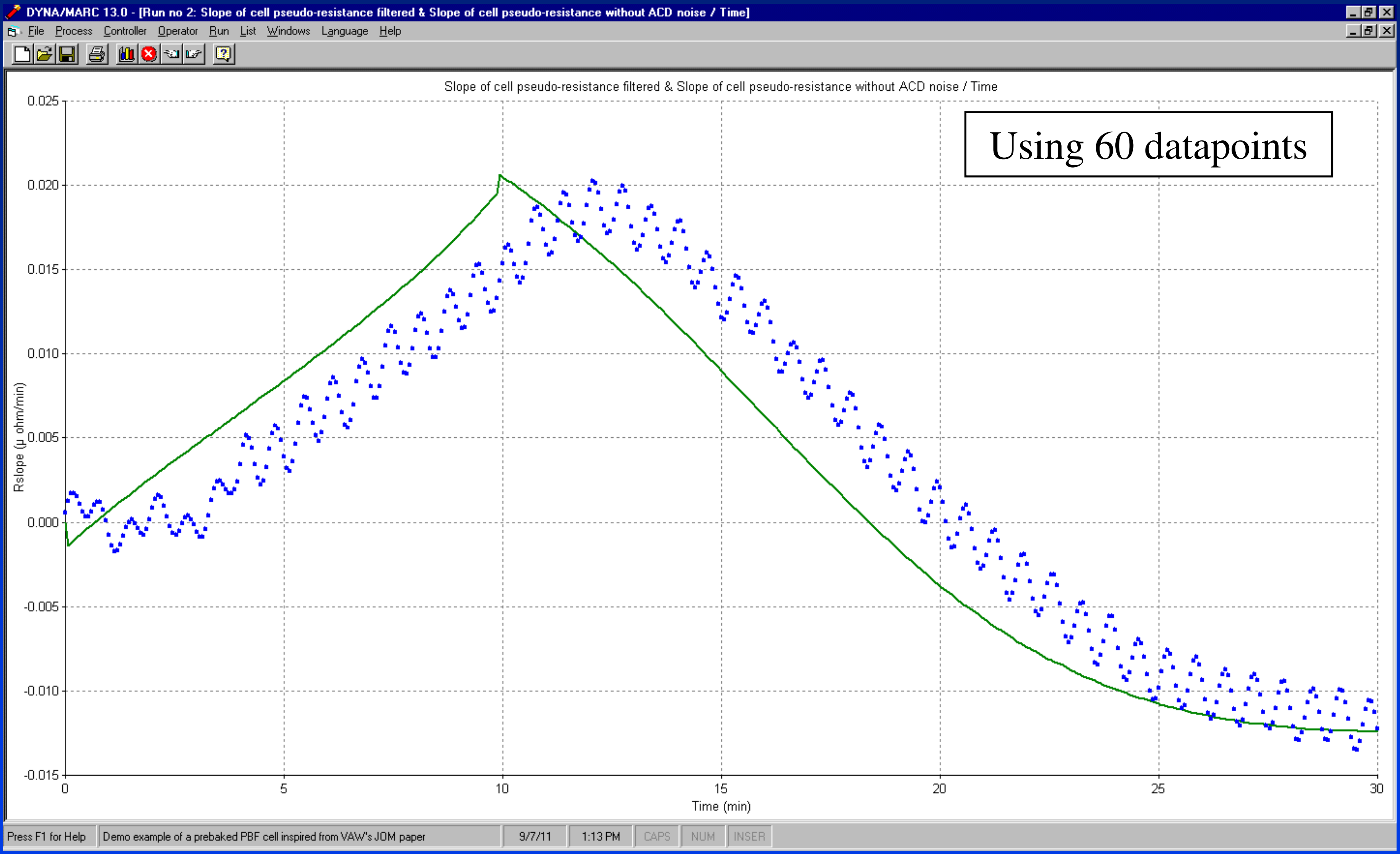
Smoothing/fitting the Normalized Cell Voltage Slope



DYNA/MARC 13.0 - [Run no 2: Slope of cell pseudo-resistance filtered & Slope of cell pseudo-resistance without ACD noise / Time]

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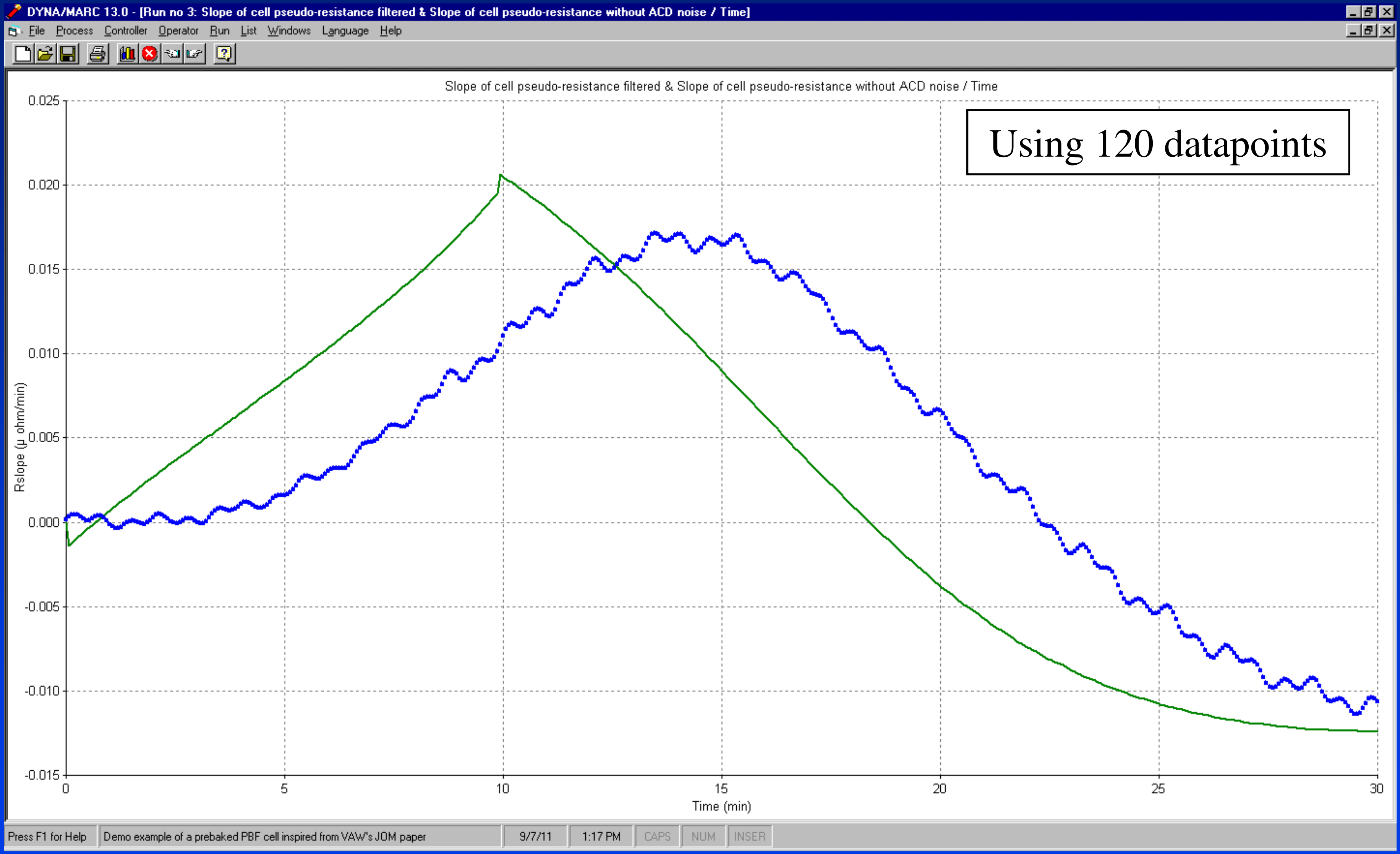
Smoothing/fitting the Normalized Cell Voltage Slope



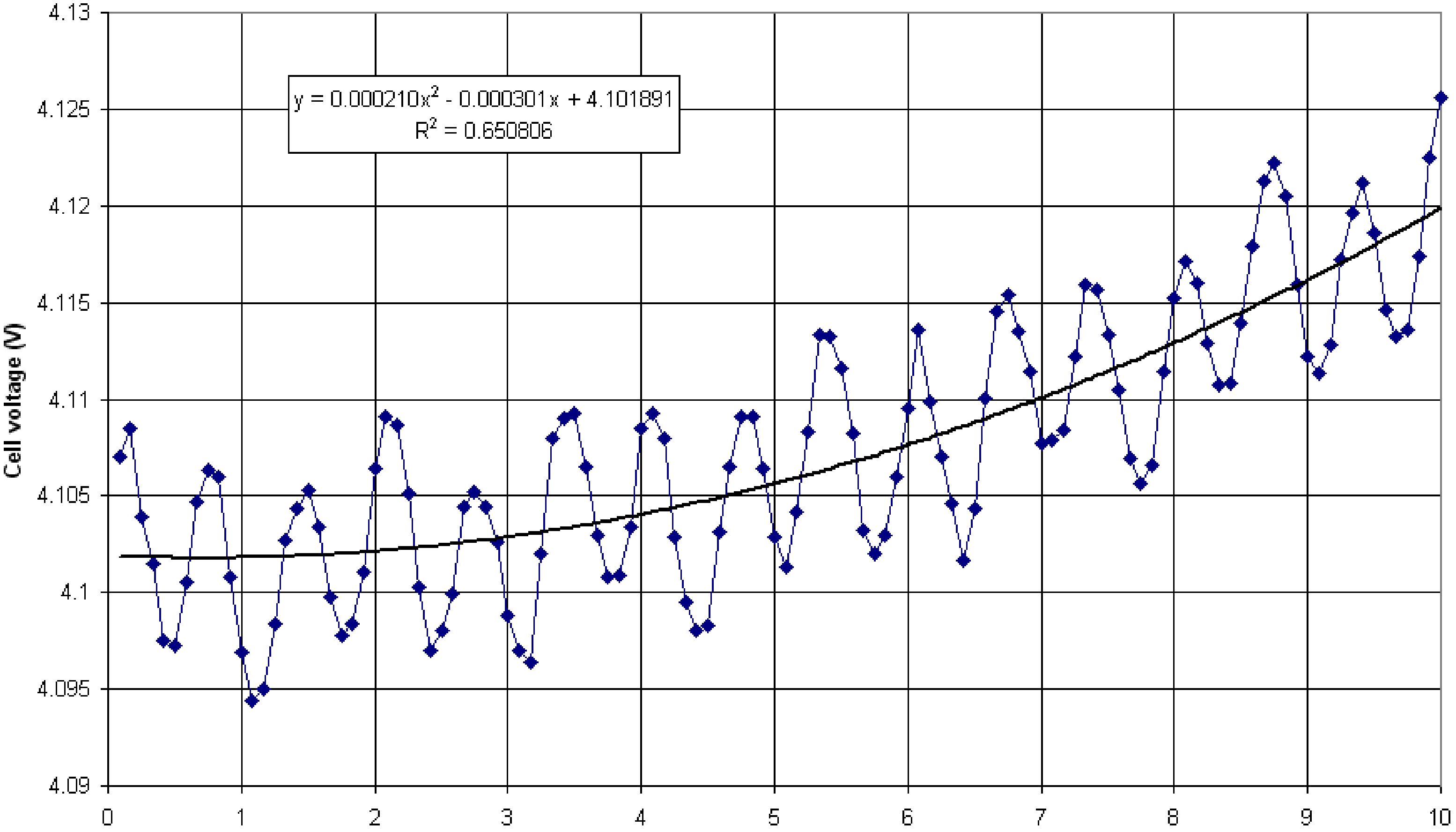
Using 120 datapoints

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

Smoothing/fitting the Normalized Cell Voltage

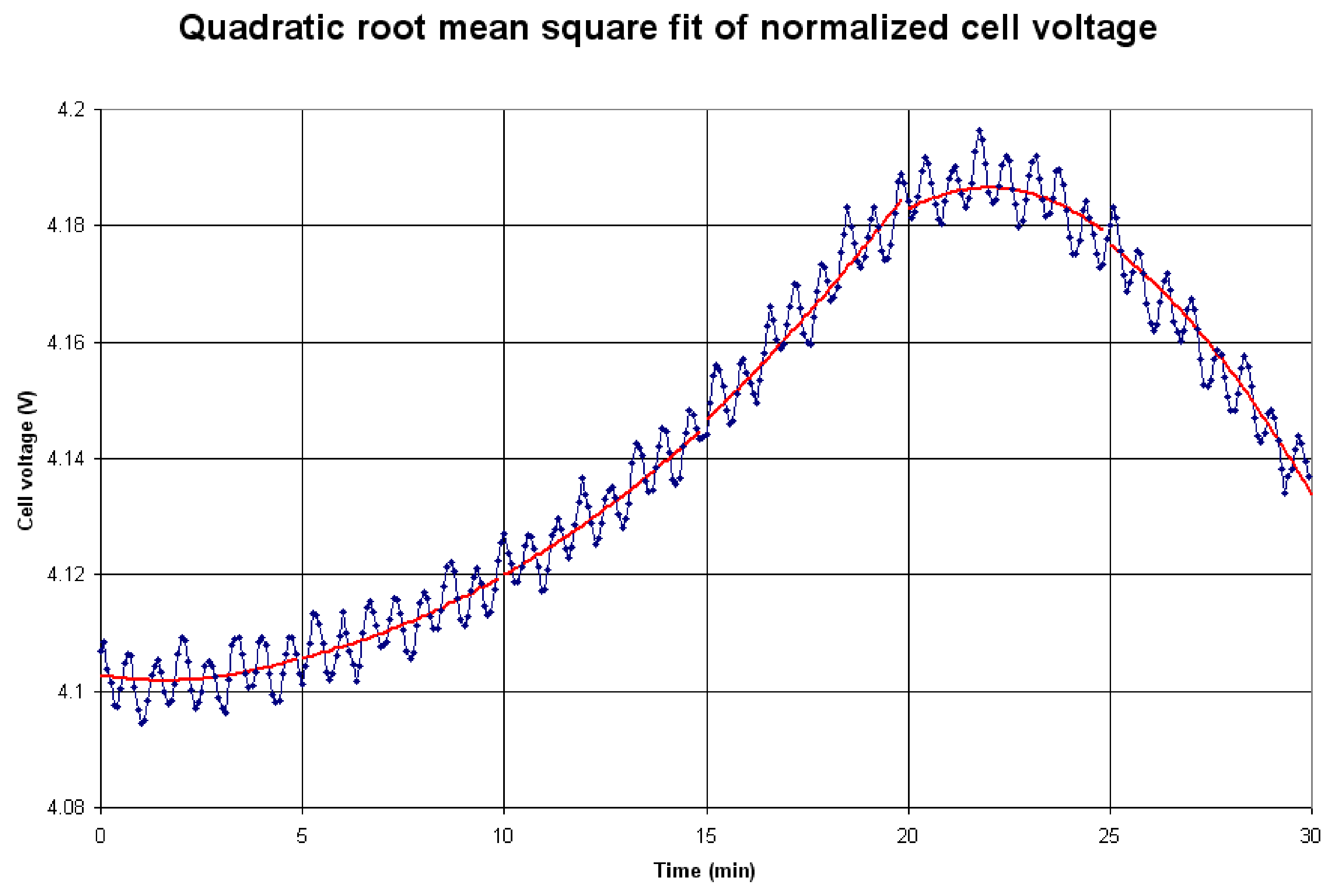
Quadratic root mean square fit of normalized cell voltage

Prediction of the current noise free normalized cell voltage: 0.00021*100-0.000301*10+4.1019 = 4.1199 V

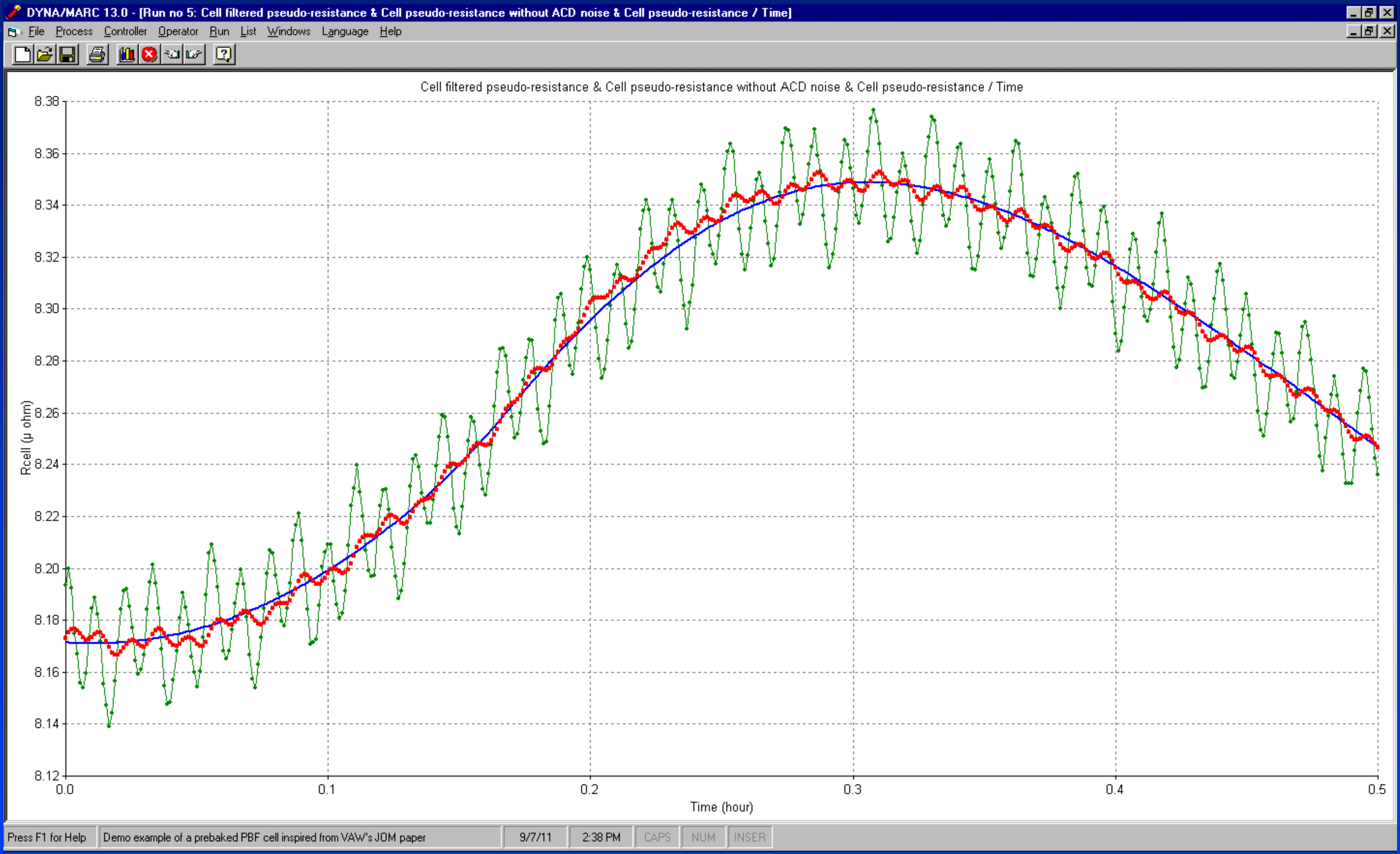


Prediction of the current noise free slope of the normalized cell voltage: 2*0.00021*10-0.000301 = 0.0039 V/min

Smoothing/fitting the Normalized Cell Voltage



Smoothing/fitting the Normalized Cell Voltage



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

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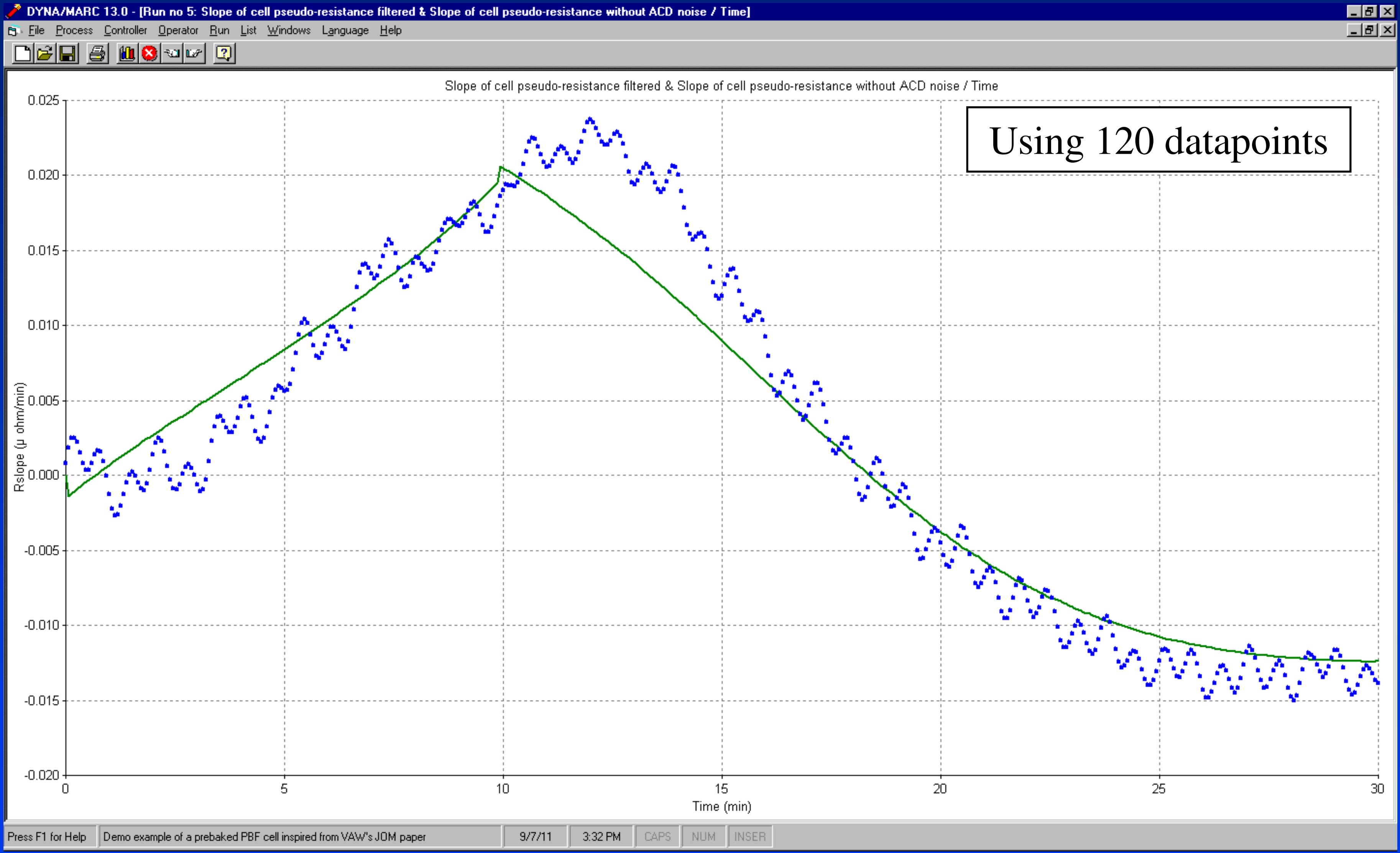
Smoothing/fitting the Normalized Cell Voltage Slope



DYNA/MARC 13.0 - [Run no 5: Slope of cell pseudo-resistance filtered & Slope of cell pseudo-resistance without ACD noise / Time]

Using 120 datapoints

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

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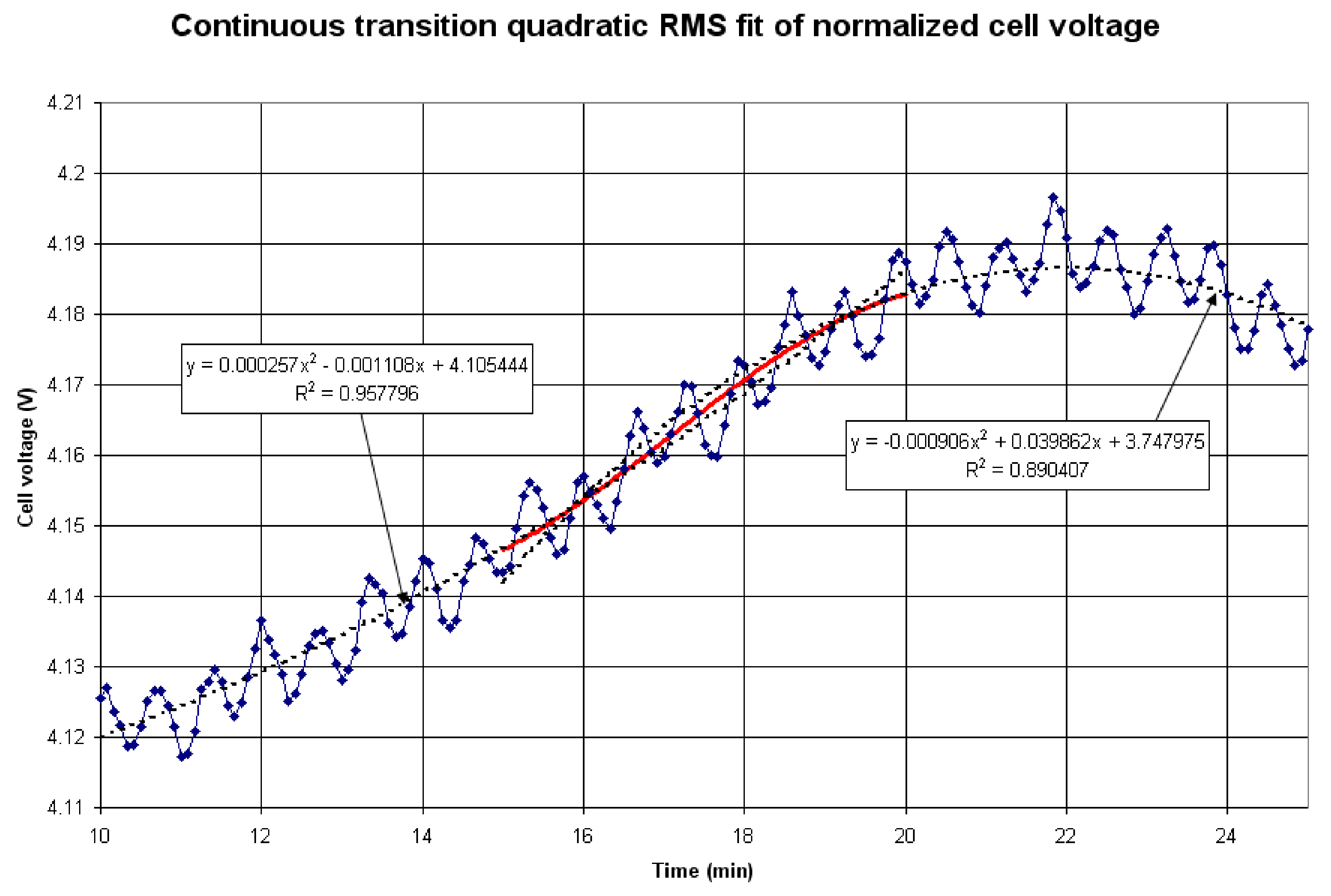
Continuous Transition Quadratic RMS Fit



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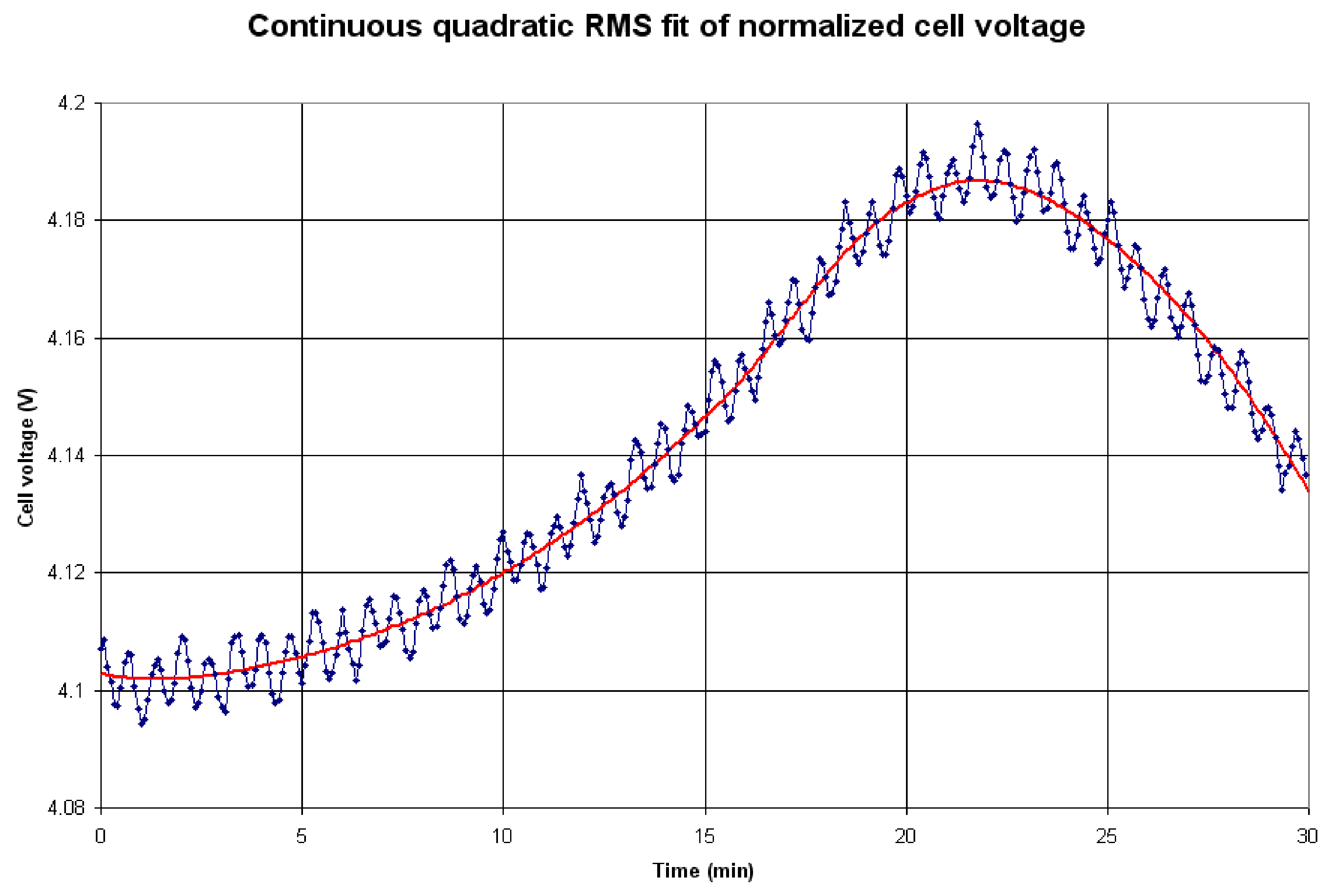
Continuous Transition Quadratic RMS Fit



Estimation of the Alumina Concentration

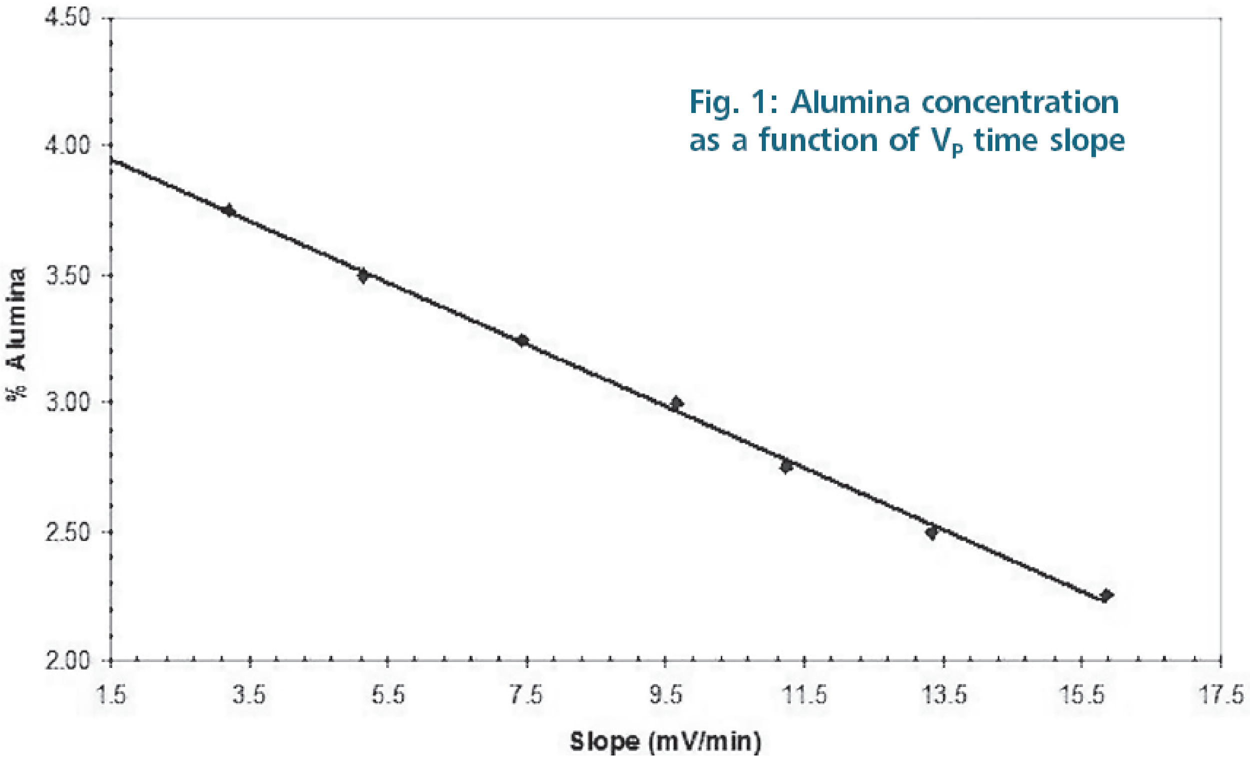
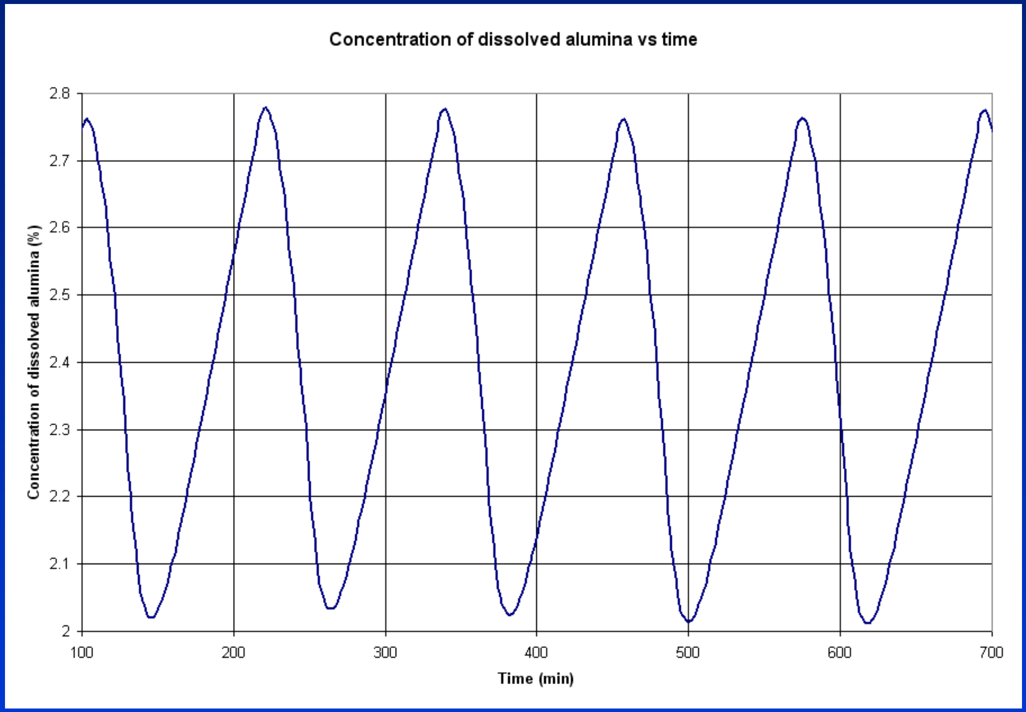
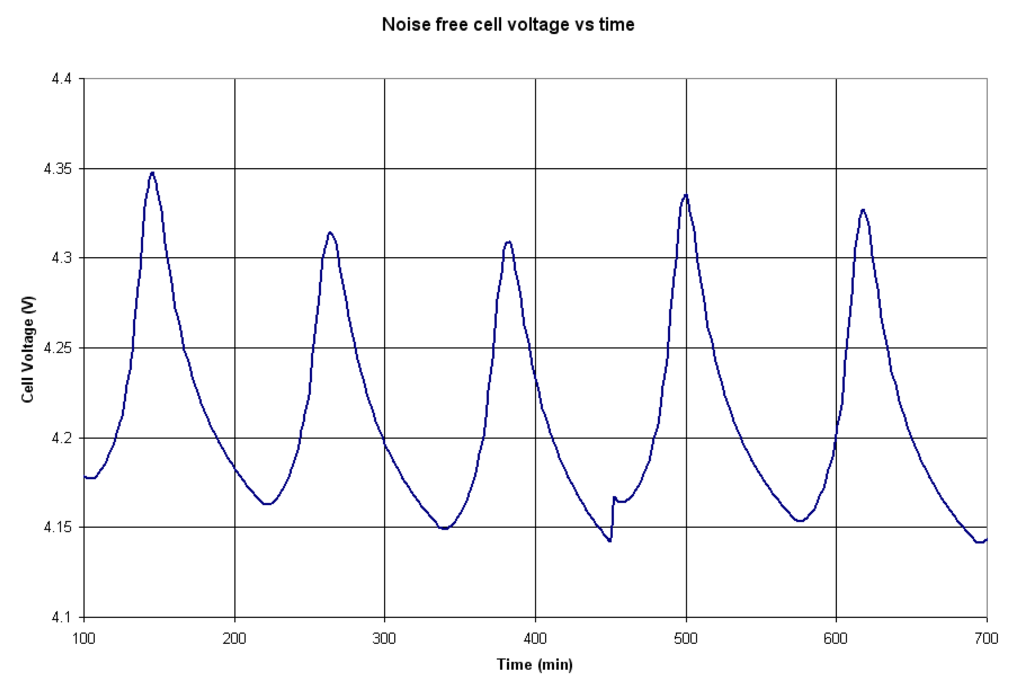


Fig. 1: Alumina concentration as a function of V_p time slope

The key concept of the *In Situ* control logic algorithm is the assumption that there is a correlation between the estimated slope of the noise free normalized cell voltage (called time slope of V_p in previous *In Situ* papers) and the alumina concentration during a no feed observation period.

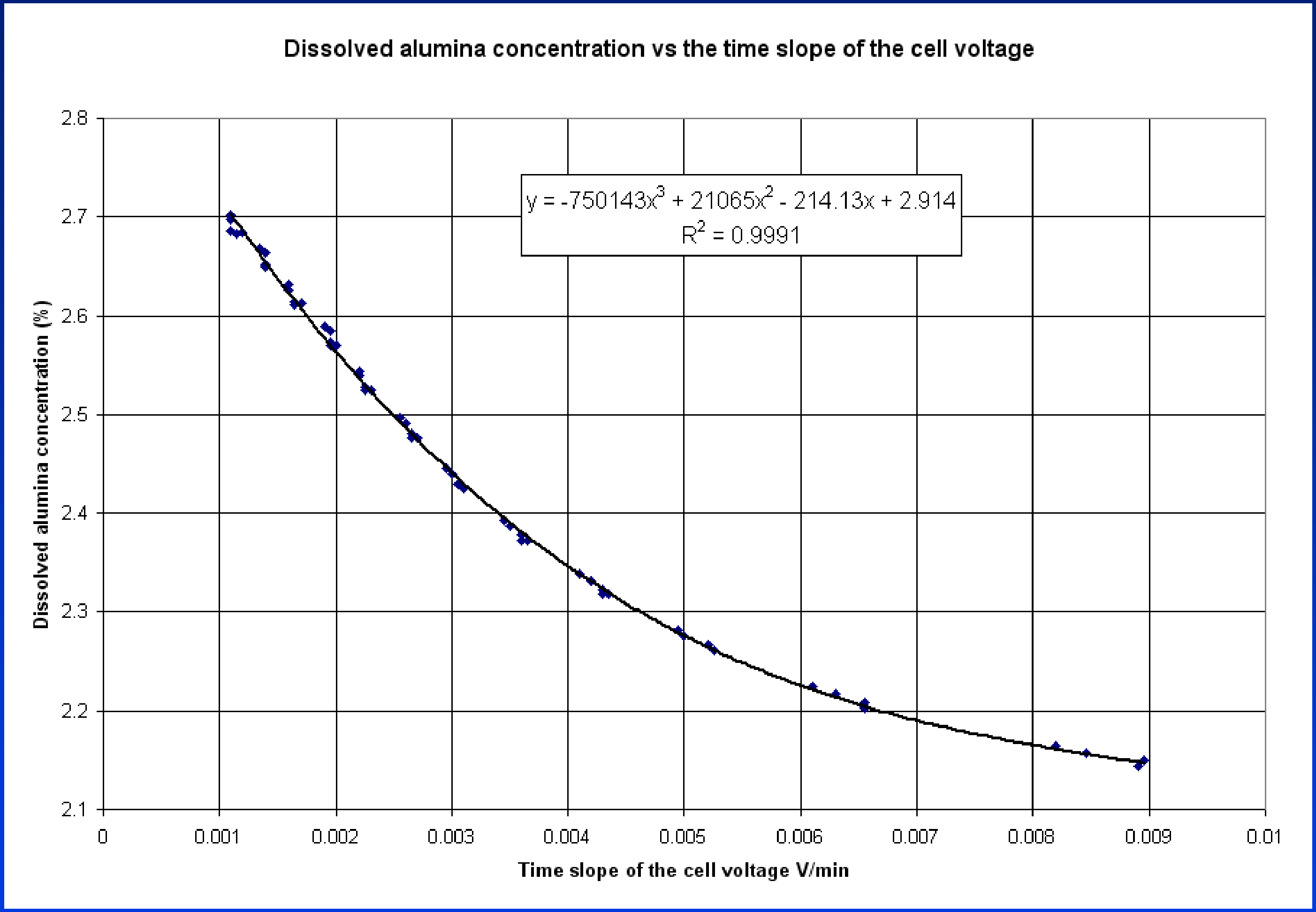
Estimation of the Alumina Concentration


Concentration of dissolved alumina vs time


Noise free cell voltage vs time

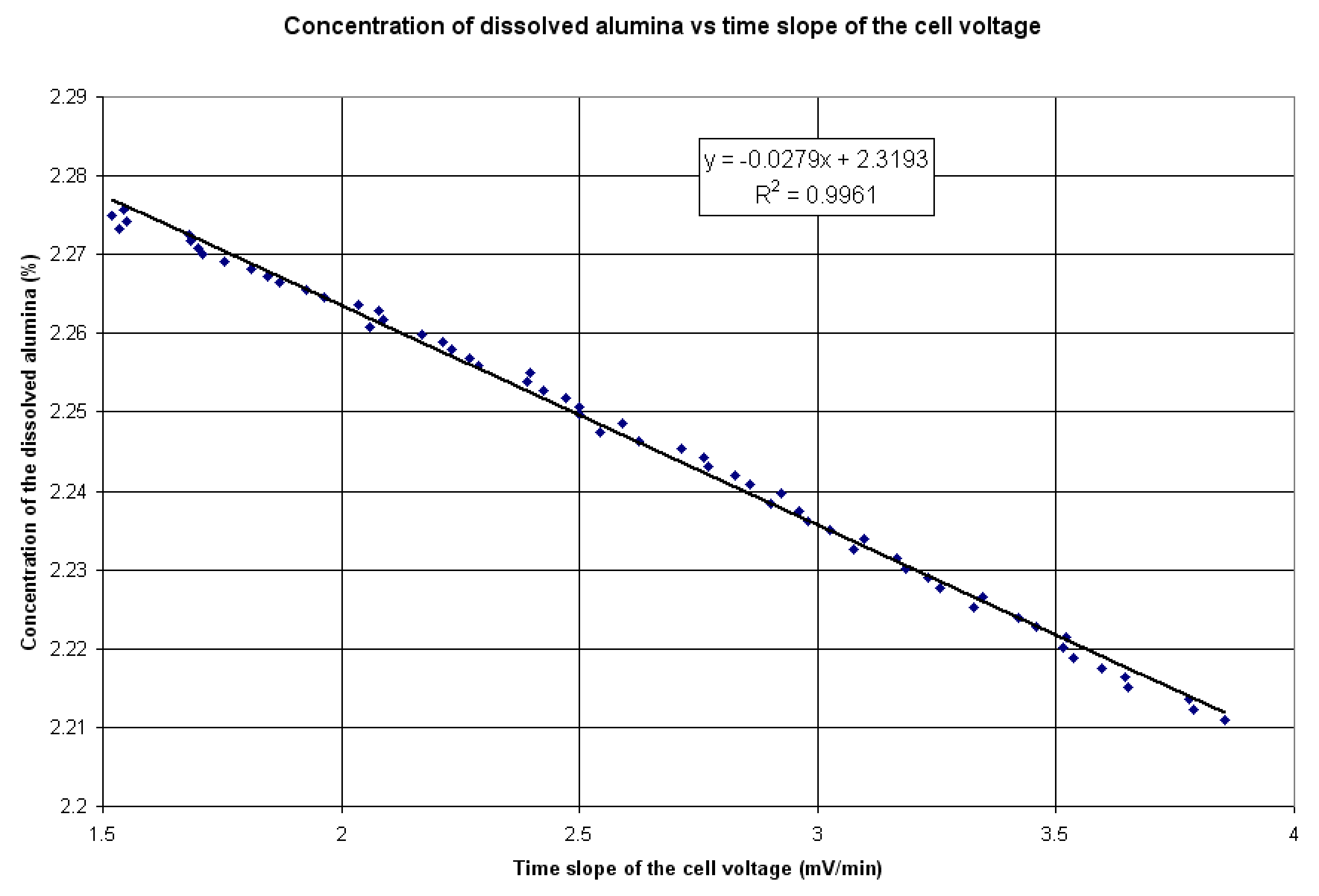
This assumption can be tested using the Dyna/Marc cell simulator

Estimation of the Alumina Concentration



Tests performed on Dyna/Marc cell simulator indicates that this correlation does exist even if it is not linear on a very wide range of alumina concentration variation and depends on a lot on factors influencing the cell resistance and the dynamics of the alumina dissolution.

Estimation of the Alumina Concentration



For a more restricted range of alumina concentration variation which corresponds to the typical range the *In Situ* controller would be able to operate the cell and for a different value of the alumina dissolution constant, a linear correlation was obtained.

Estimation of the Alumina Concentration

For example, the slope of 3.9 mV/min previously estimated after 10 minutes of no feed observation period by the quadratic RMS fit would correspond to an estimated alumina concentration of:

$$-0.0279 * 3.9 + 2.3193 = 2.21\ \%$$

Primary Calibration Surface and Estimation of the ACD

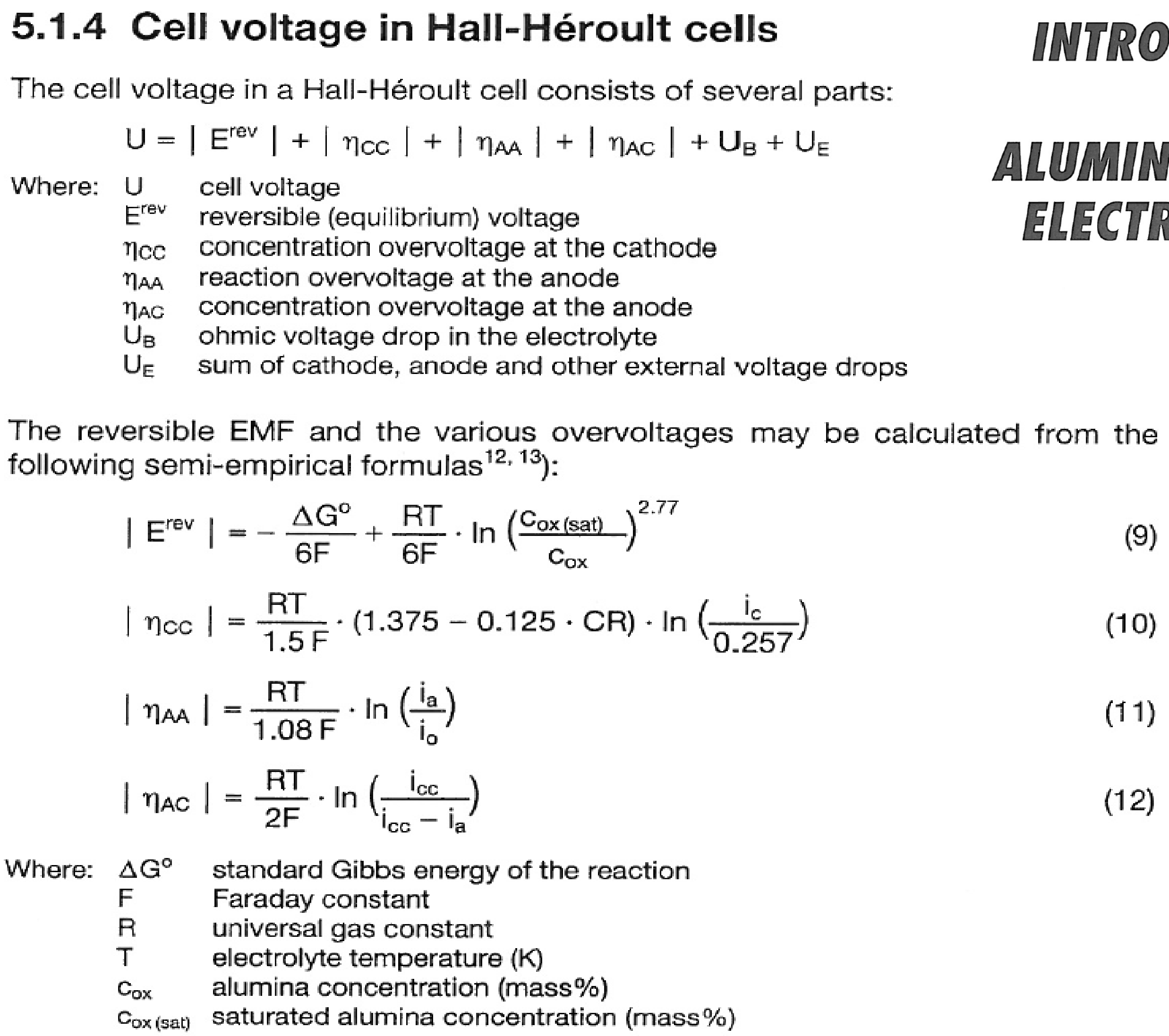
In previous *In Situ* papers, the concept of primary calibration curve is presented. It is simply the observation that when all the other variables affecting the cell voltage are kept constant, it is possible to perfectly correlate the concentration of dissolved alumina in the bath with the noise free normalized cell voltage using the following equation:

$$1 / (CAl_2O_3 - CAl_2O_3\text{-}AE) = CoeffA * EXP (CoeffB * V_n)$$

Where:

V_n	is the estimated noise free normalized cell voltage (V)
CAl_2O_3	is the estimated concentration of dissolved alumina in the bath (%)
CAl_2O_3-AE	is the estimated concentration of dissolved alumina triggering an anode effect (AE) (%)
CoeffA	is the first coefficient of the correlation
CoeffB	is the second coefficient of the correlation

Components of the Bath Voltage



5.1.4 Cell voltage in Hall-Héroult cells

The cell voltage in a Hall-Héroult cell consists of several parts:

$$U = |E^{rev}| + |\eta_{CC}| + |\eta_{AA}| + |\eta_{AC}| + U_B + U_E$$

Where:

U	cell voltage
E^{rev}	reversible (equilibrium) voltage
η_{CC}	concentration overvoltage at the cathode
η_{AA}	reaction overvoltage at the anode
η_{AC}	concentration overvoltage at the anode
U_B	ohmic voltage drop in the electrolyte
U_E	sum of cathode, anode and other external voltage drops

The reversible EMF and the various overvoltages may be calculated from the following semi-empirical formulas[12, 13]:

$$|E^{rev}| = -\frac{\Delta G^o}{6F} + \frac{RT}{6F} \cdot \ln\left(\frac{c_{ox\,(sat)}}{c_{ox}}\right)^{2.77} \quad (9)$$

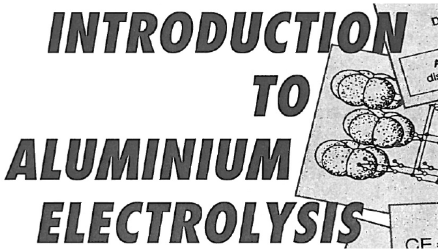
$$|\eta_{CC}| = \frac{RT}{1.5\,F} \cdot (1.375 - 0.125 \cdot CR) \cdot \ln\left(\frac{i_c}{0.257}\right) \quad (10)$$

$$|\eta_{AA}| = \frac{RT}{1.08\,F} \cdot \ln\left(\frac{i_a}{i_o}\right) \quad (11)$$

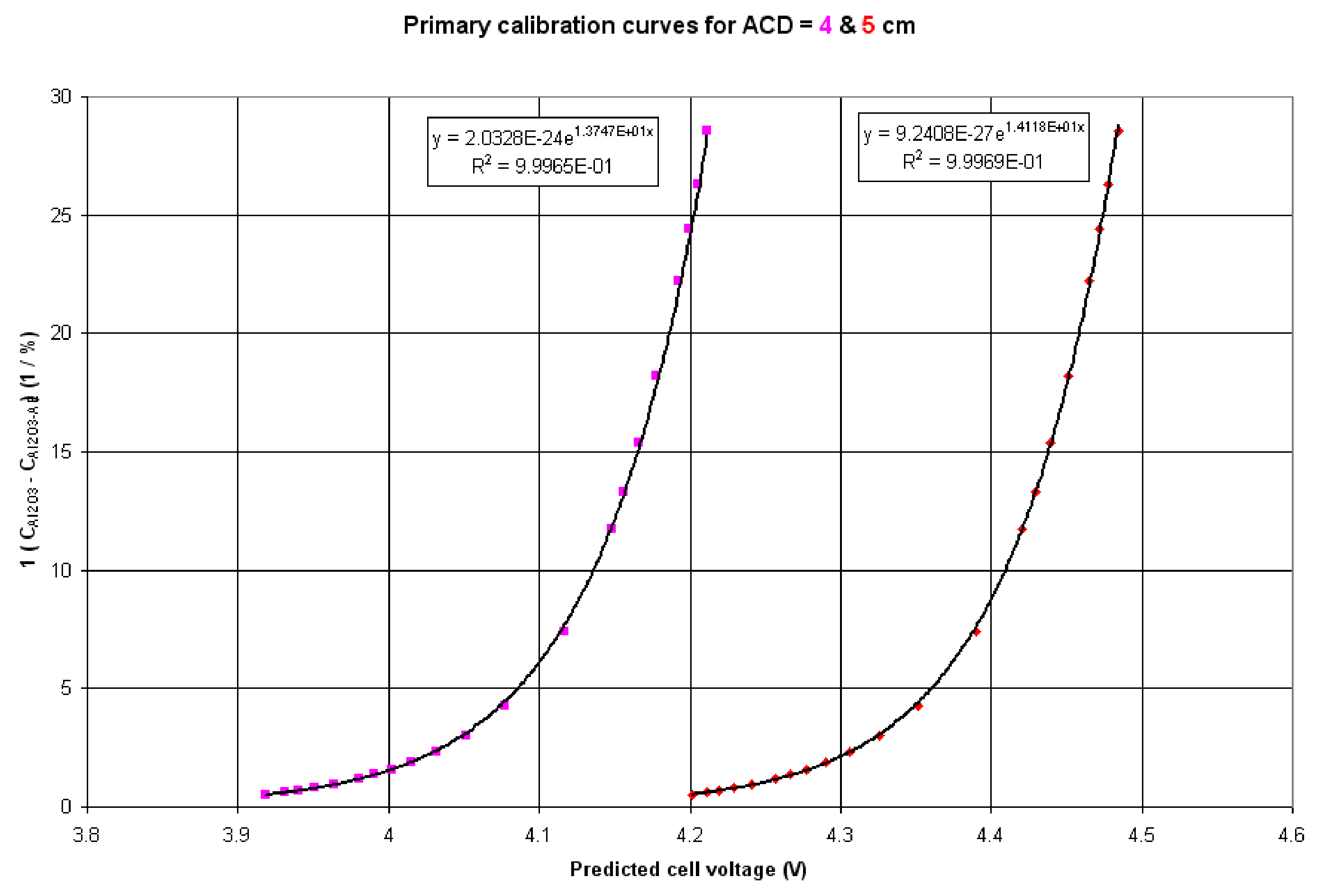
$$|\eta_{AC}| = \frac{RT}{2F} \cdot \ln\left(\frac{i_{cc}}{i_{cc} - i_a}\right) \quad (12)$$

Where:

ΔG^o	standard Gibbs energy of the reaction
F	Faraday constant
R	universal gas constant
T	electrolyte temperature (K)
c_{ox}	alumina concentration (mass%)
$c_{ox\,(sat)}$	saturated alumina concentration (mass%)



Primary Calibration Surface and Estimation of the ACD



In is quite easy to generate this correlation for any combination of cell conditions using published cell voltage break down equations like those published in Introduction to Aluminium Electrolysis: Understanding the Hall-Heroult Process, that happen to be the ones used by Dyna/Marc.

Primary Calibration Surface and Estimation of the ACD

So it turns out that for the cell conditions selected:

when ACD = 4 cm

CoeffA = 2.0328E-24

CoeffB = 13.747

when ACD = 5 cm

CoeffA = 9.2408E-27

CoeffB = 14.118

Primary Calibration Surface and Estimation of the ACD

With CAl_2O_3 = 2.21 % and AE = 1.965 %, we have:

$$1 / (CAl_2O_3 - AE) = 1 / 0.245 = 4.08$$

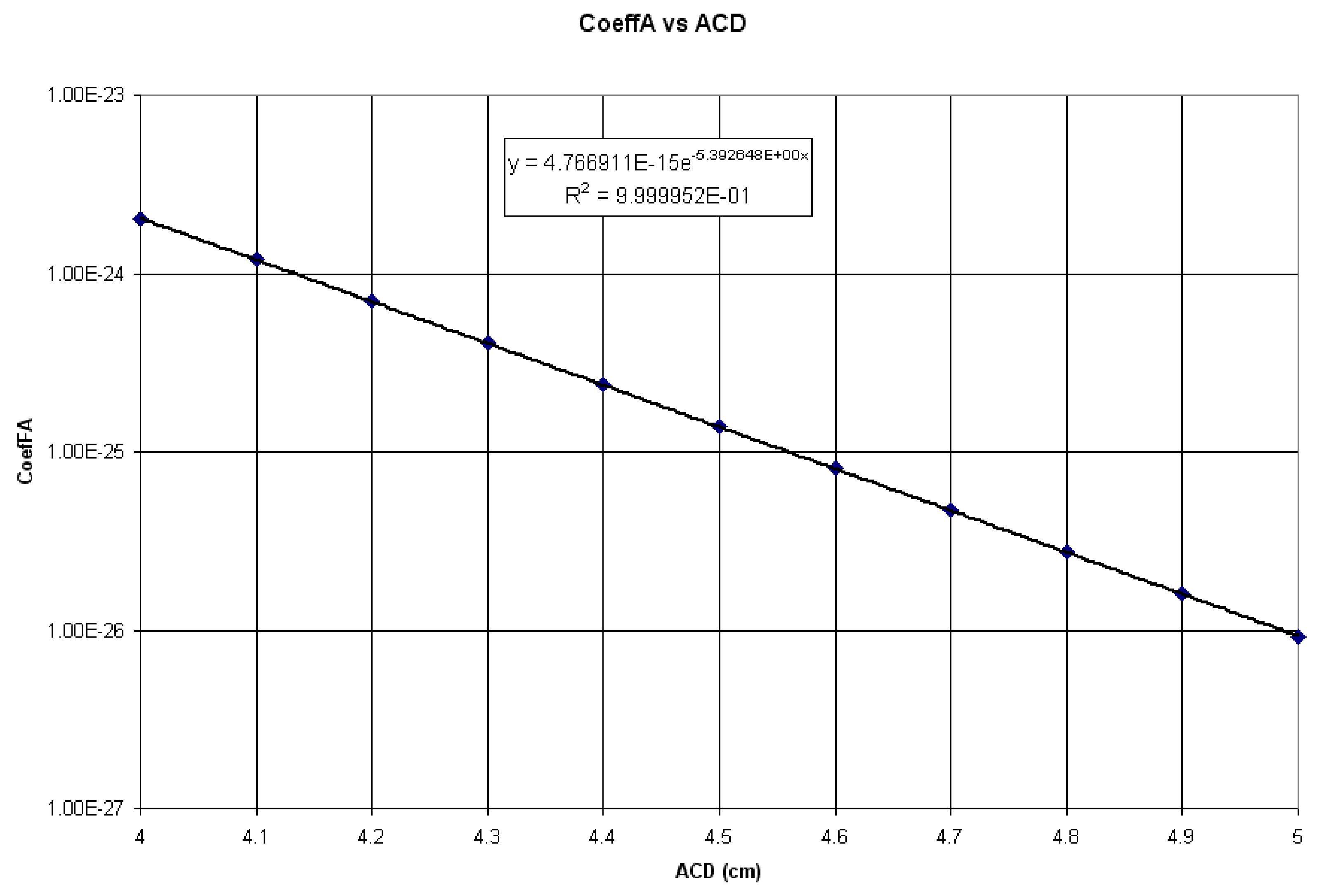
From that we can calculate that at 2.21 % of dissolved alumina, the predicted cell voltage would be at:

(LN(4.08) - LN(2.0328E-24)) / 13.747 = 4.071 V, at 4 cm ACD
(LN(4.08) - LN(9.2408E-27)) / 14.118 = 4.346 V, at 5 cm ACD

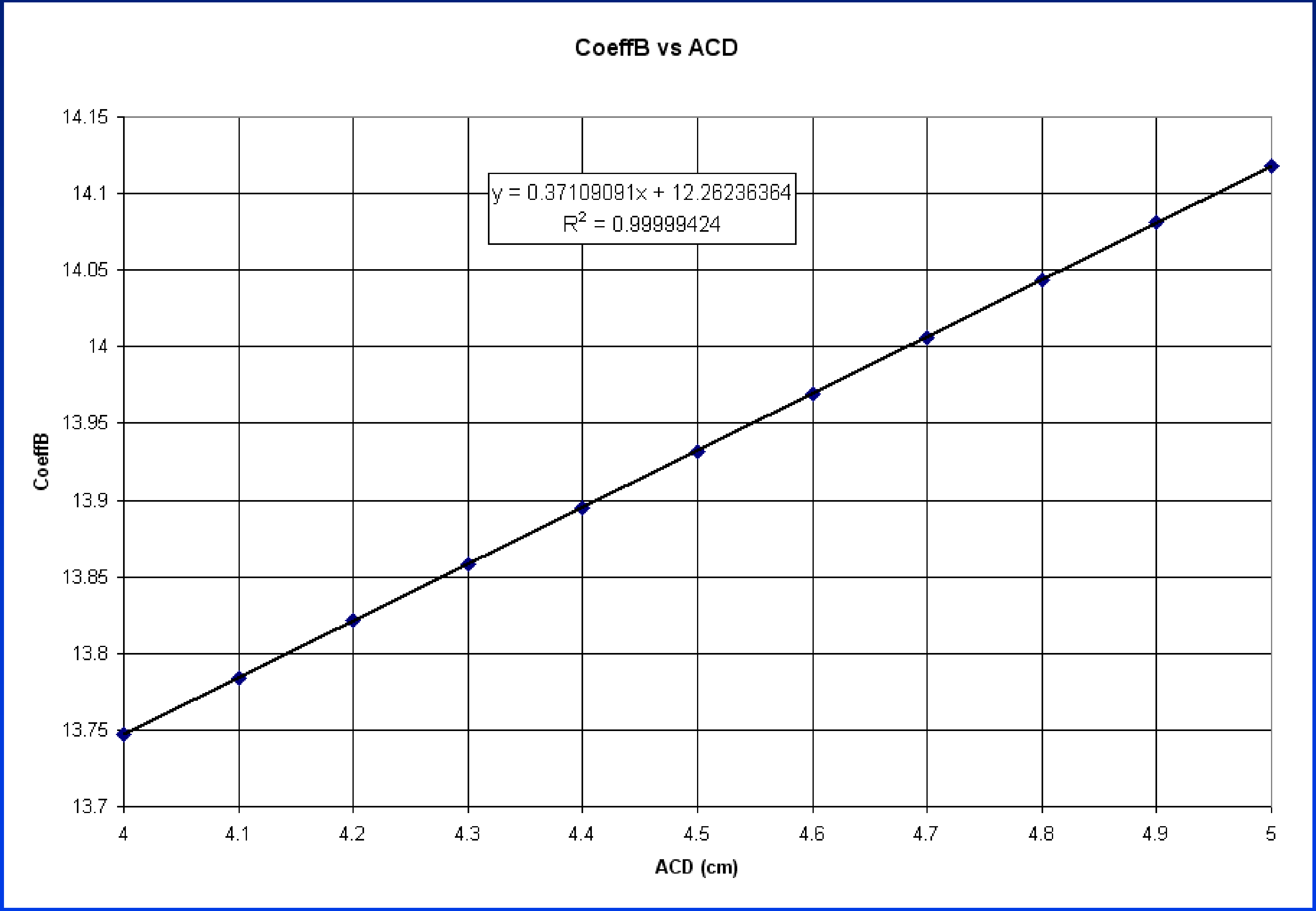
Since the estimated noise free normalized cell voltage after 10 minutes of no feed observation was previously estimated to be 4.1199 V from the quadratic RMS fit, we can calculate the estimated ACD to be:

$$4 + (4.1199 – 4.071) / (4.346 – 4.071) = 4.18 \text{ cm}$$

Primary Calibration Surface and Estimation of the ACD



Primary Calibration Surface and Estimation of the ACD



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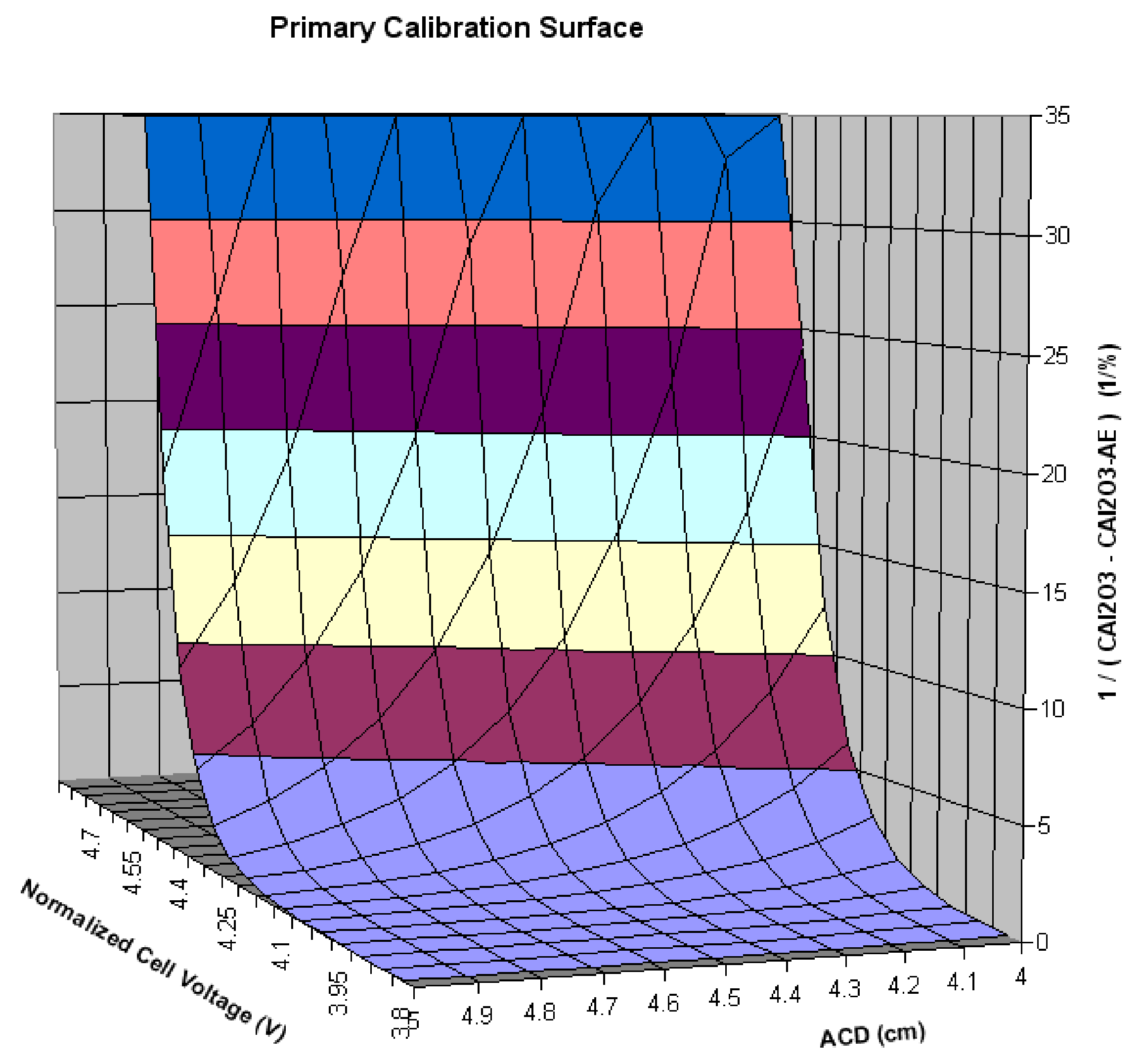
Primary Calibration Surface and Estimation of the ACD



Primary Calibration Surface and Estimation of the ACD

In the demo Dyna/Marc test case, that linear rate of change of the ACD was estimated to be about -0.00033 cm/min, which means that 3 hours after the observation, the ACD can be estimated to be:

$$4.18 - 0.00033 * 180 = 4.12 \text{ cm}$$

Using ACD = 4.12, CoeffA value can be calculated to be equal to:

$$4.766911\text{E-}15 * \text{EXP } (-5.392648 * 4.12\ ) = 1.06957\text{E-}24$$

And CoeffB value can be calculated to be equal to:

$$0.37109091 * 4.12 + 12.26236364 = 13.7913$$

If 3 hours after the last observation, the value of the noise free normalized cell voltage is estimated to be equal to 4.10 V, the concentration of the dissolved alumina can in turn be estimated to be equal to:

$$1.06957\text{E-}24 * \text{EXP } (13.7913 * 4.10\ ) = 3.8557$$

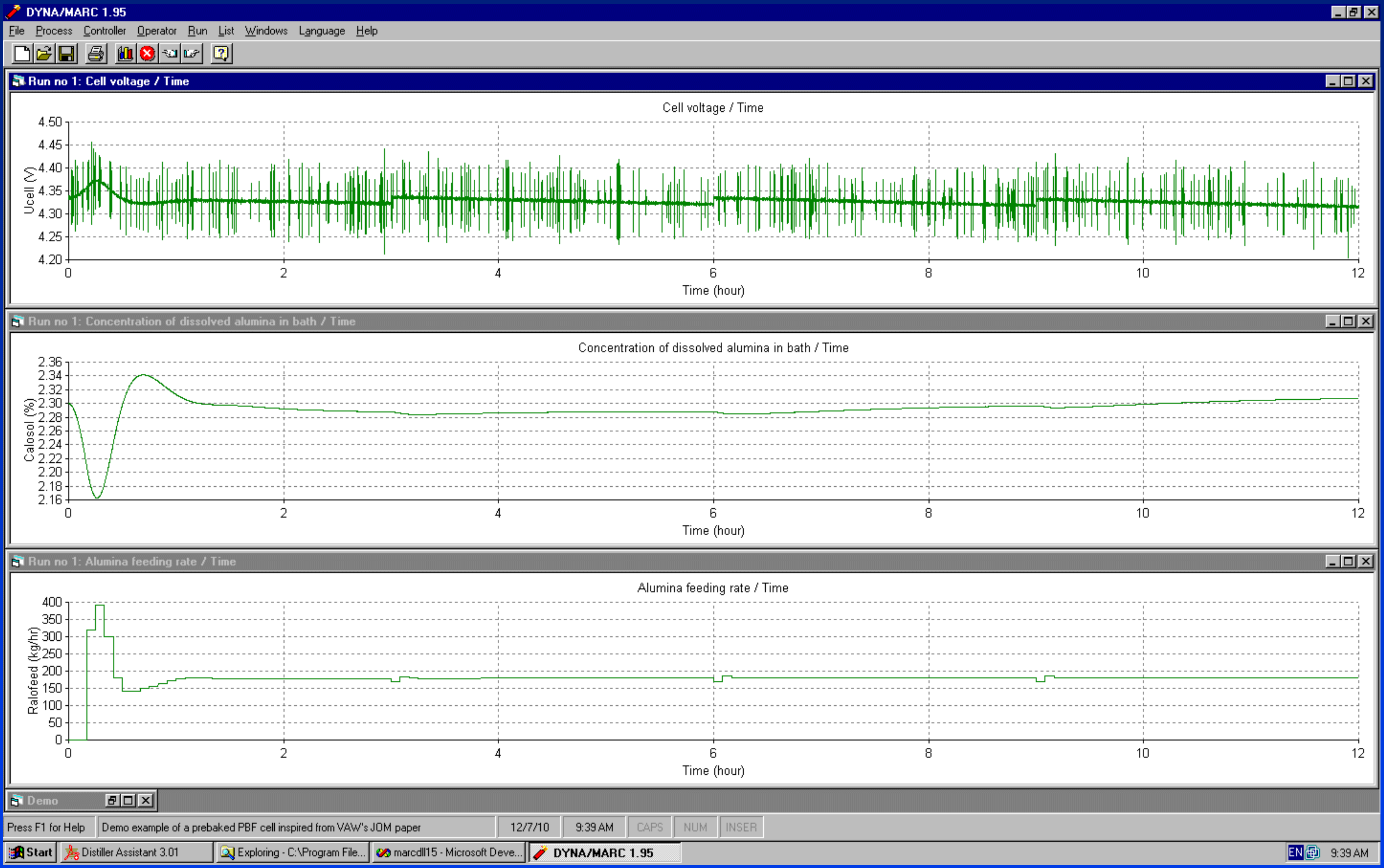
$$1\ /\ 3.8557 + 1.965 = 2.22\ \%$$

PID Controller

The last part of the *In Situ* control logic is quite straightforward, after a no feed observation period, the concentration of the dissolved alumina in the bath is estimated every 5 minutes or so. Next, the error between a selected target value and the current estimated value is used to adjust the alumina feeding rate using the standard PID controller equation:

$$\mathrm{Output(t)} = K_p \left(e(t) + K_{ip} \int_0^t e(\tau)\, d\tau + K_{dp} \frac{de}{dt} \right)$$

Testing *In Situ* Control with Dyna/Marc Cell Simulator



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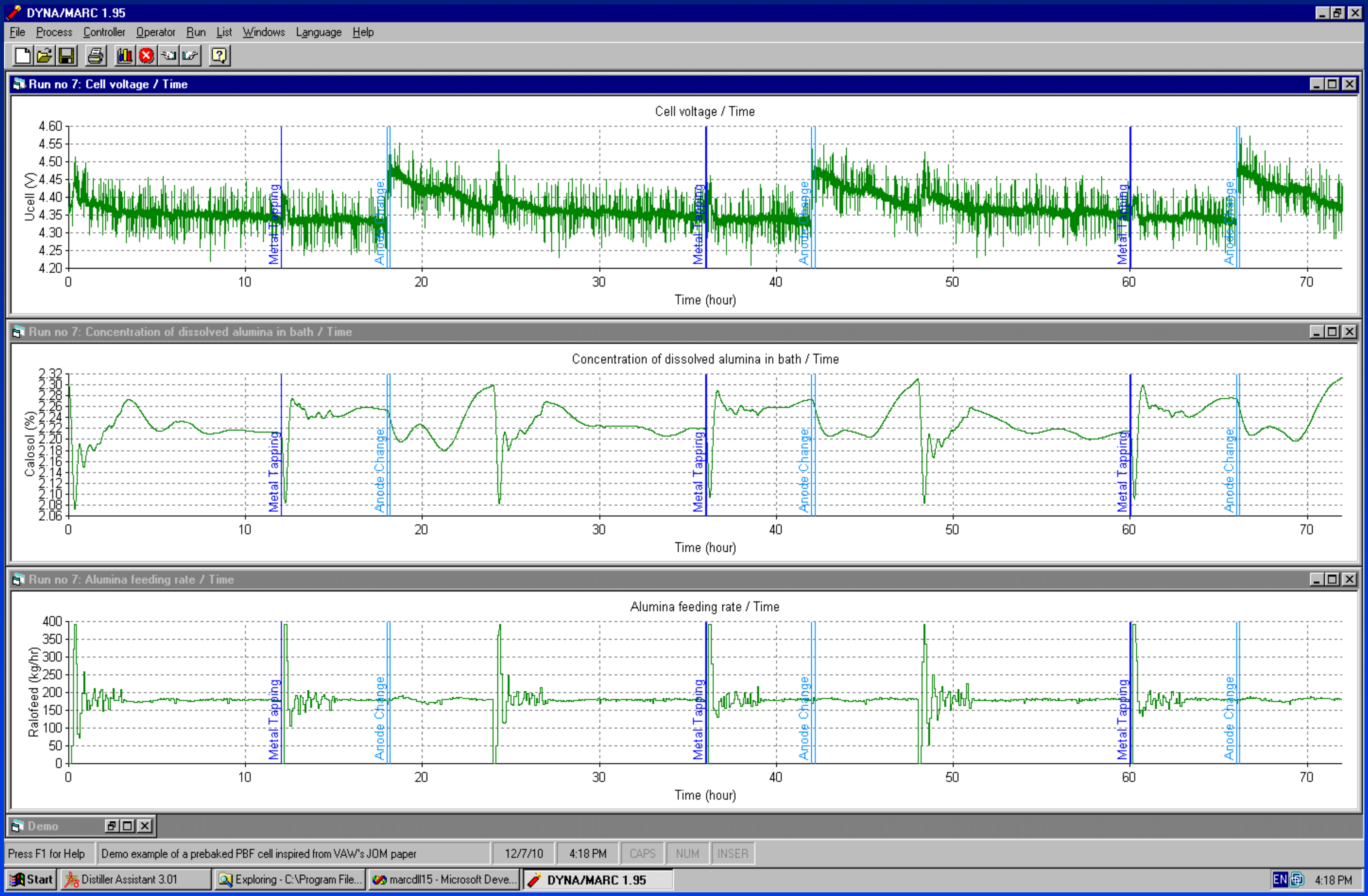
Testing *In Situ* Control with Dyna/Marc Cell Simulator



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

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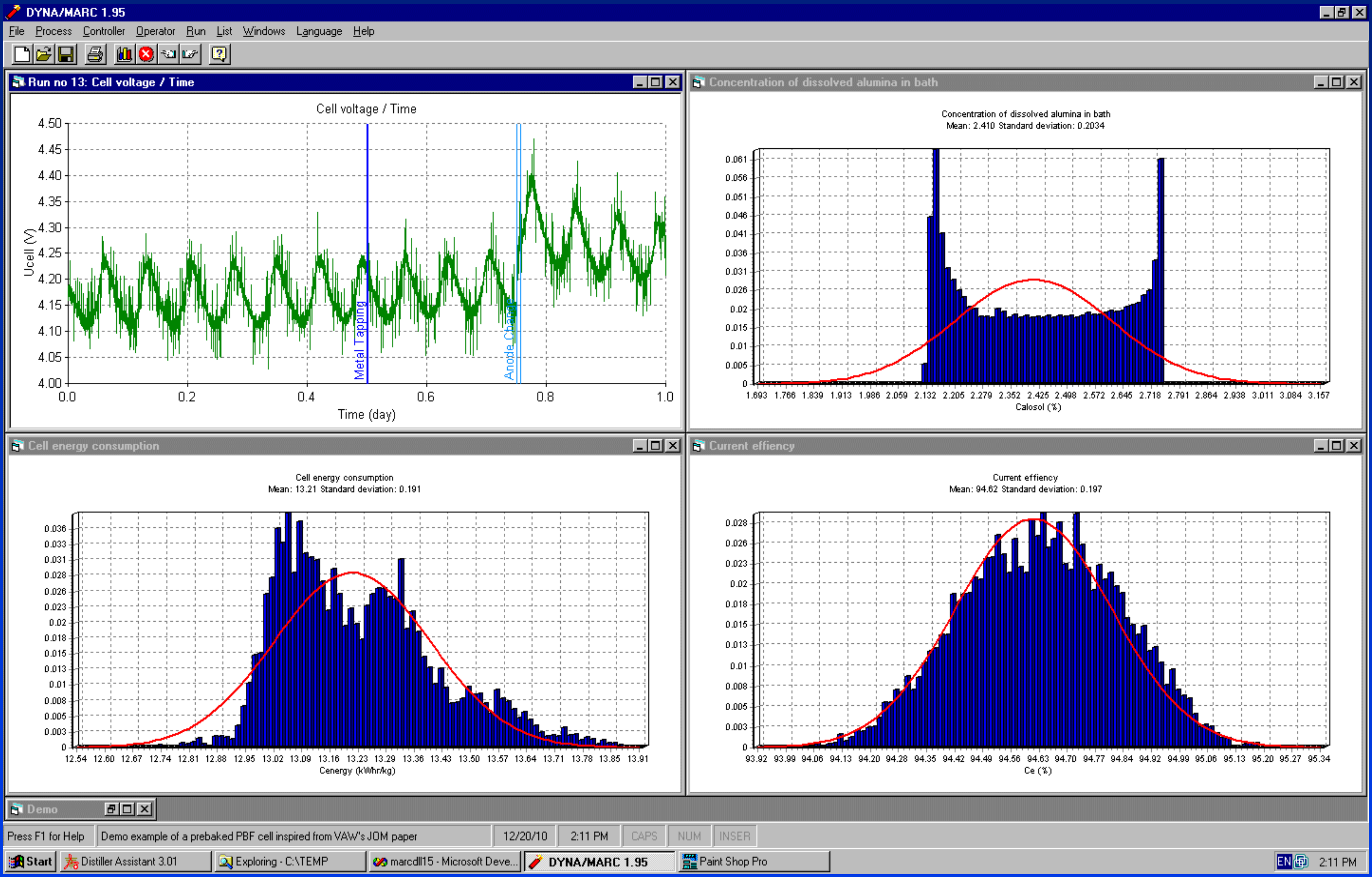
Effect of the Change of Control Logic on the Process Efficiency



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

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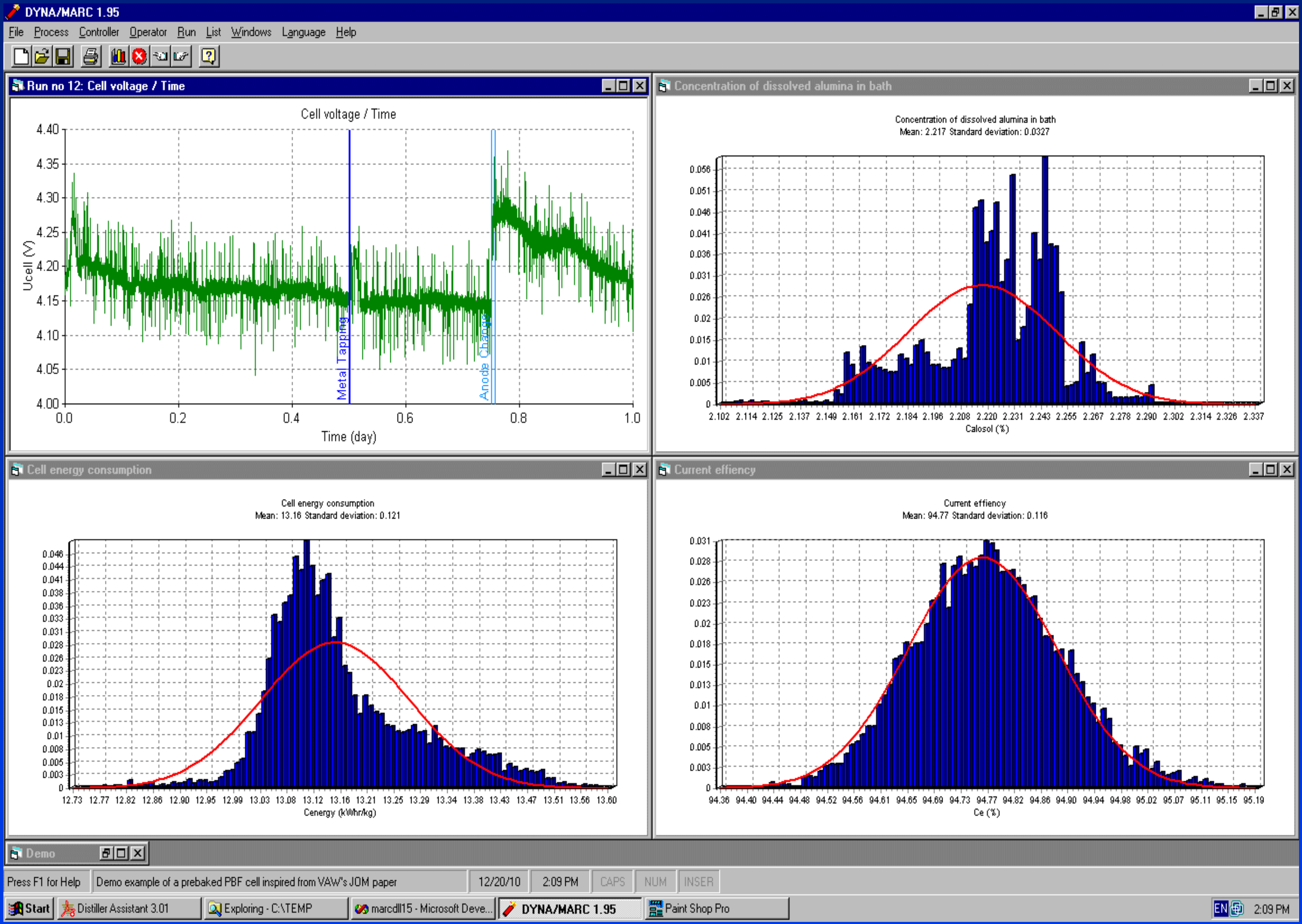
Effect of the Change of Control Logic on the Process Efficiency

Using a typical continuous tracking control logic, the average dissolved alumina concentration obtained is 2.41 % with a standard deviation of 0.20 %, the average power efficiency is 13.21 kWhr/kg with a standard deviation of 0.19 kWhr/kg and an average current efficiency obtained is 94.62 % with a standard deviation of 0.20 %.

Effect of the Change of Control Logic on the Process Efficiency



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

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Effect of the Change of Control Logic on the Process Efficiency

Using the new *In Situ* control logic, the average dissolved alumina concentration obtained is 2.22 % with a standard deviation of only 0.03 %, the average power efficiency is 13.16 kWhr/kg with a standard deviation of 0.12 kWhr/kg and an average current efficiency obtained is 94.77 % with a standard deviation of 0.12 %.

Conclusions

- The newly proposed *In Situ* control logic has been presented in full details. The core principle is quite simple, the values of both the dissolved alumina concentration and the ACD can be estimated at the end of a 5 to 10 minute no feed observation period only by using the standard cell amperage and voltage data. Once this is done, it is possible to use a PID controller to regulate the rate of alumina feeding using only the cell voltage to calculate the error between the estimated dissolved alumina concentration and a target value for an extended period of time.
- The *In Situ* control logic has been coded in Fortran, added to Dyna/Marc kernel as an additional control subroutine and fully tested. It worked exactly as planned, the dissolved alumina concentration is effectively controlled with an impressive accuracy only using standard line amperage and cell voltage signals as feedback control inputs. That drastic reduction of the process variation of the concentration of the dissolved alumina, leading to the possibility of reducing the averaged value without increasing the risk of anode effect, had a positive impact on both the current efficiency and the power efficiency.