COMPARISON OF CLASSICAL TOOLS AND MODERN FINITE ELEMENT MODELING IN THE ELECTRICAL DESIGN OF SLAG RESISTANCE FURNACES

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Innovation and Creativity

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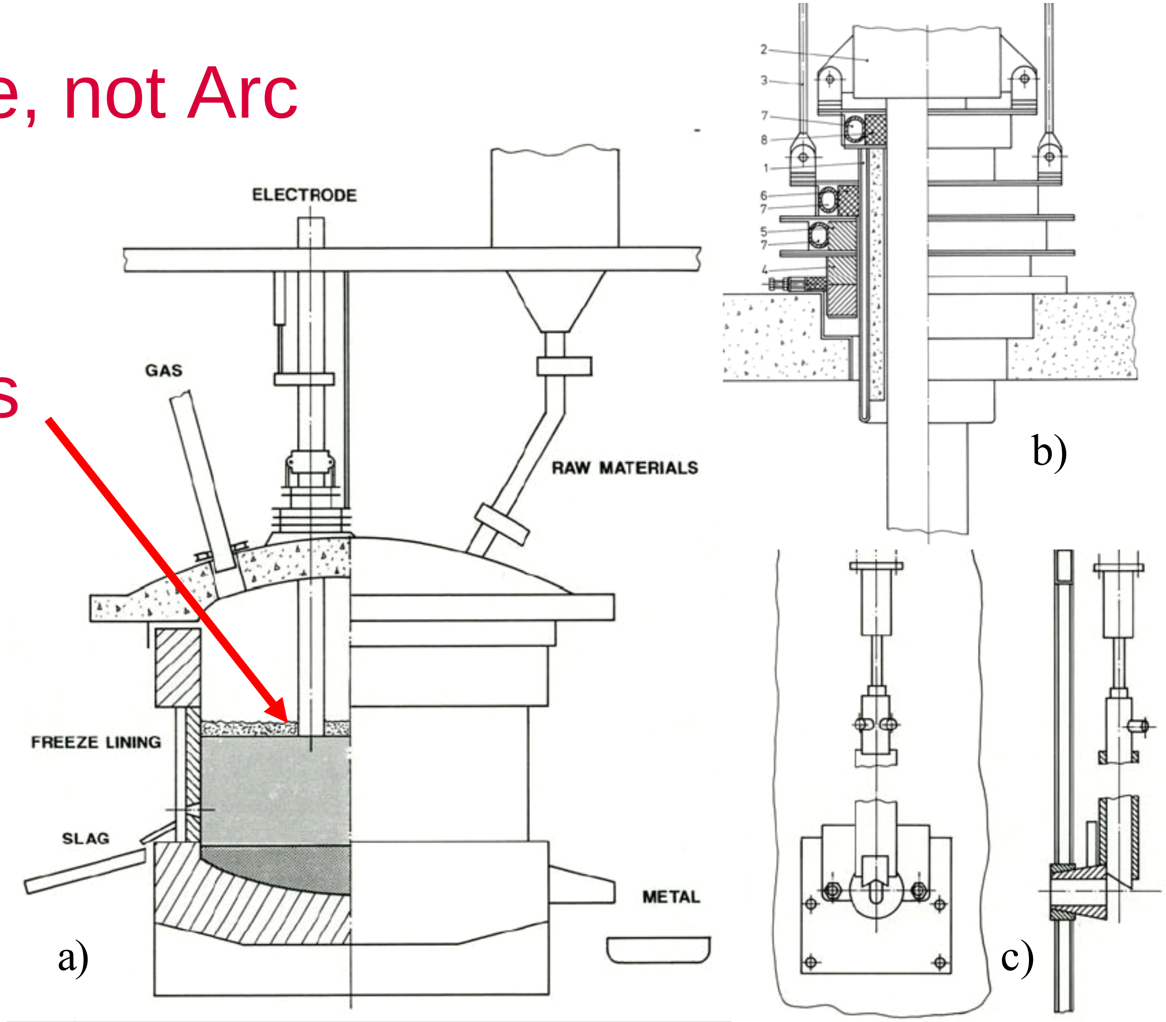
Outline

- Background on modern slag furnace designs
- 3-phase power/resistance relationships
- Basic ‘cell’ resistance
- Furnace analytical resistance models
- Actual pilot and demonstration scale plant data
- Comparison of analytical and 3D FEM model results
- Speculate on what the differences tell us about the errors in our modelling approaches

A Modern High Intensity Slag Furnace

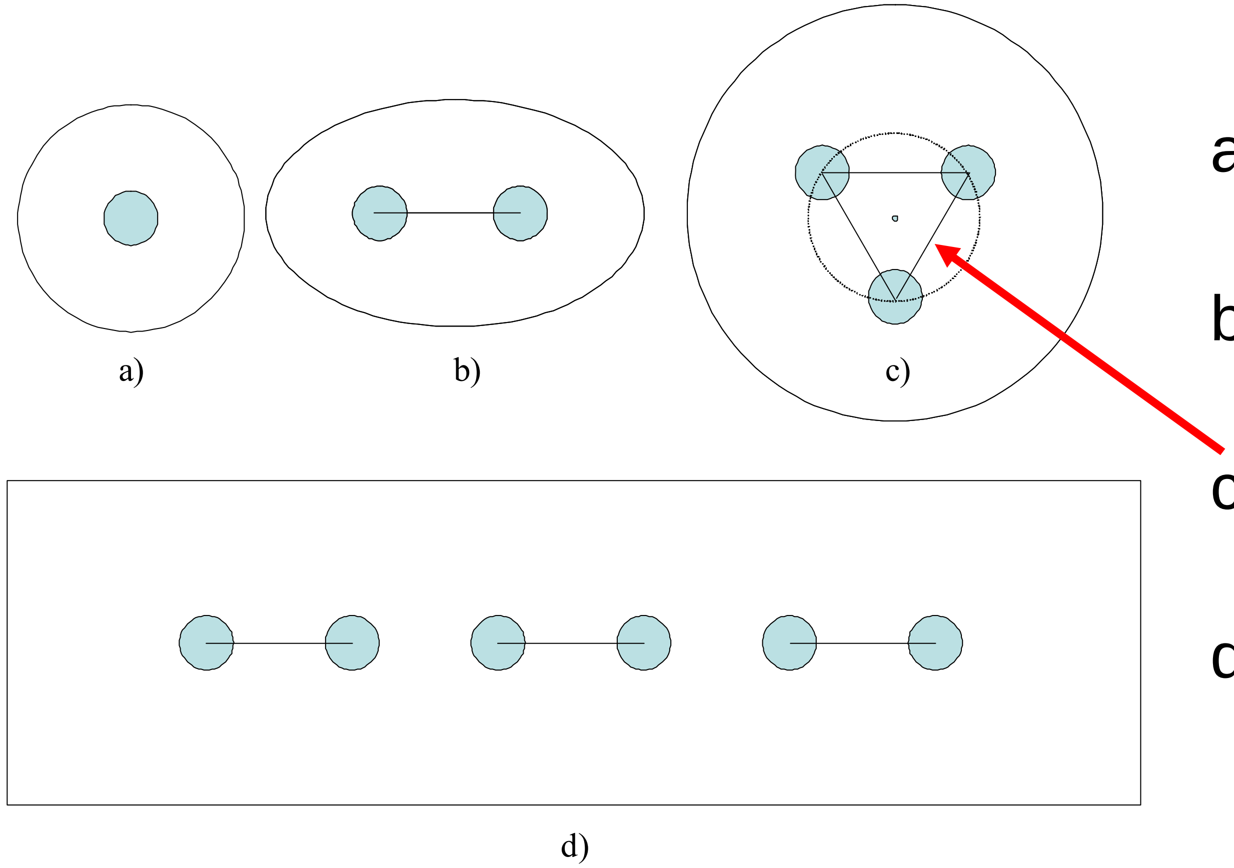
Resistance, not Arc

Immersed Electrodes



Elkem Multi-Purpose Furnace®

Typical Electric Furnace Electrode and Furnace Body Arrangements

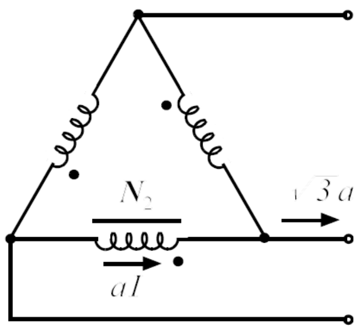


- a) single top entering electrode (1-phase),
- b) two electrodes (1-phase),
- c) three electrodes (3-phase), and
- d) six-in-line electrodes (3-single phase).

Basic Furnace Power/Resistance Modelling

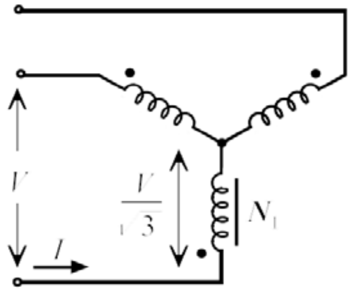
$$P_{furnace} = NP_{phase}$$

N = 1 for single phase or 3 for 3-phase



$$P_{phase} = I^2_{phase} R_{phase}$$

$$R_{phase} = R_{delta} = 3\ R_e = 3\ R_{wye}$$



Furnaces are often thought of as ’wired’ in a ’wye’, due to the control system, secondary coils are in ‘delta’.

Basic Furnace Power/Resistance Modelling

$$R_{phase} = \frac{l}{a}\frac{1}{\sigma} = \frac{l}{a}\rho$$

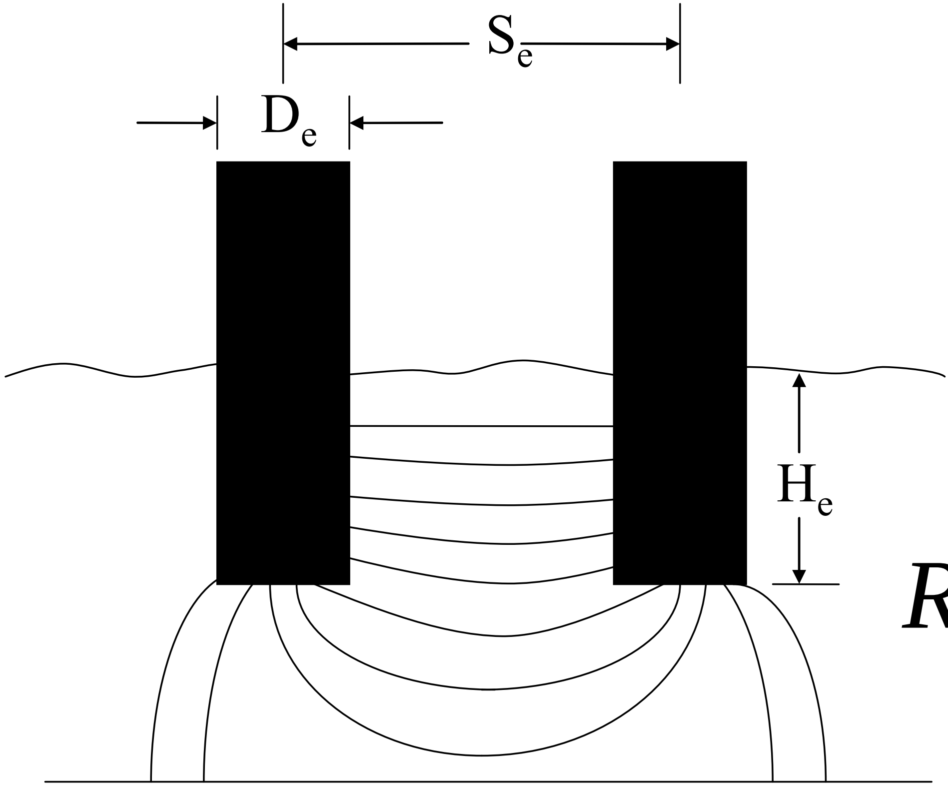
"Geometric Constant"

Slag Resistivity

$$\sigma_{T_a} = Cnst \exp^{-\frac{E}{RT_a}}$$

$$\rho_T = \rho_{ref}\left(1+\alpha_{ref}\left[T - T_{ref}\,{}^oC\right]\right)$$

Typical Current Paths in an Electric Furnace and Important Dimensions



$$R_{phase} = \frac{l}{a}\frac{1}{\sigma} = \frac{l}{a}\rho$$

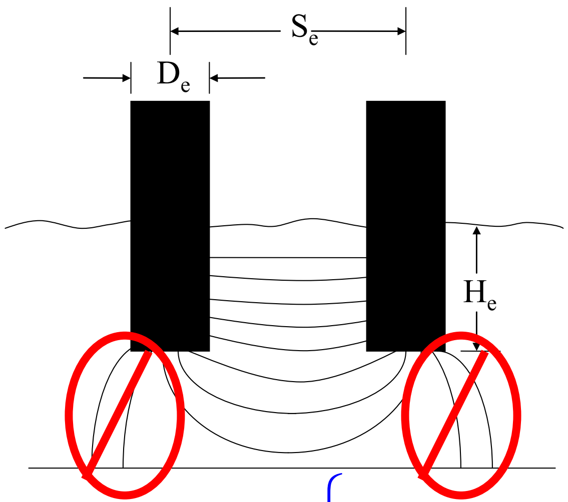
The first resistance model

Andræ, 1933:

$$R_{phase} = 3R_{electrode} = 3\frac{k}{\pi D_e}$$

Ignores immersion!

Downing and Urban Equation (1965)

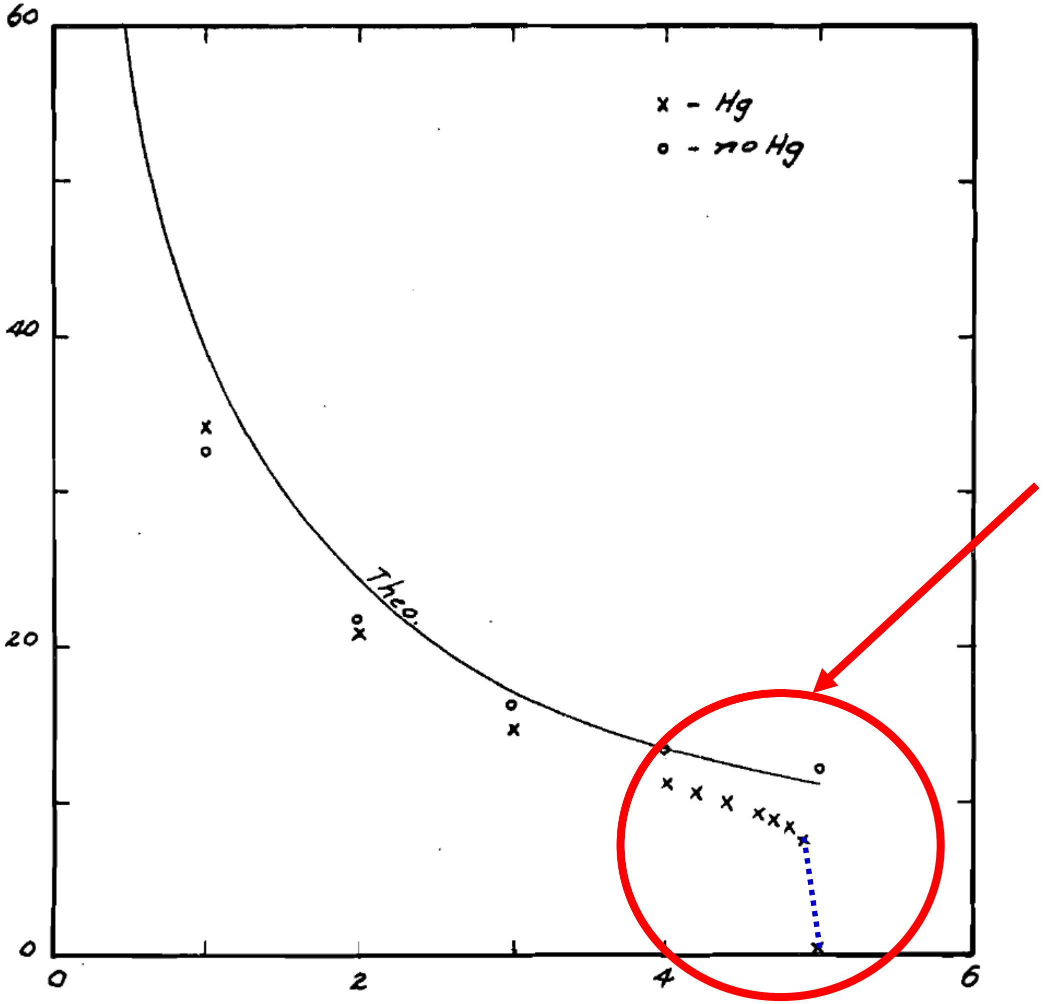


Based on the analytical solution for the capacitance of a hemi-sphere and an **infinite** cylindrical conductor in an **infinite medium**.

$$R_{phase} = \frac{1}{\sigma}\left\{ \frac{\pi H_e}{\ln\left(\frac{S_e}{2r_e} + \sqrt{\left(\frac{S_e}{2r_e}\right)^2 - 1} \right)} + \pi r_e \left(1 + \frac{r_e}{S_e} + \left[\frac{r_e}{S_e}\right]^2 + \left[\frac{r_e}{S_e}\right]^3 + \ldots \right) \right\}^{-1}$$

Downing and Urbain Equation ignores conduction to the bottom!!!

Conductive Bottom Effect

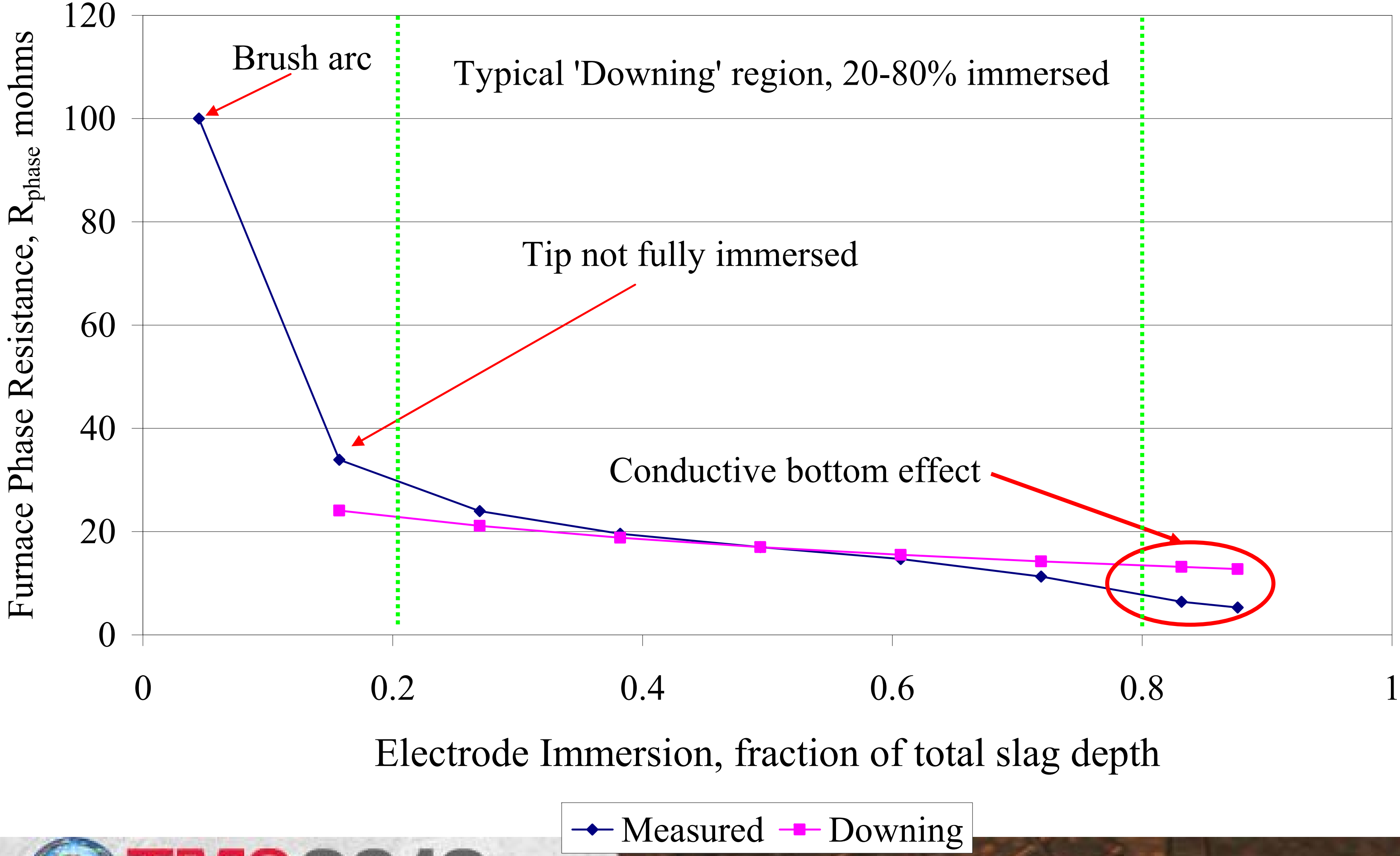


Downing and Urban:

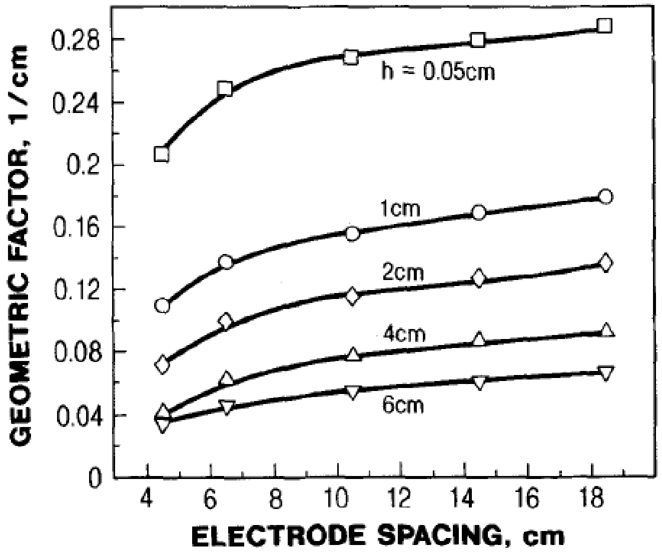
Found that the conductive bottom could not be detected until **~80% immersion!**

Not compatible with 'wye' conduction assumption.

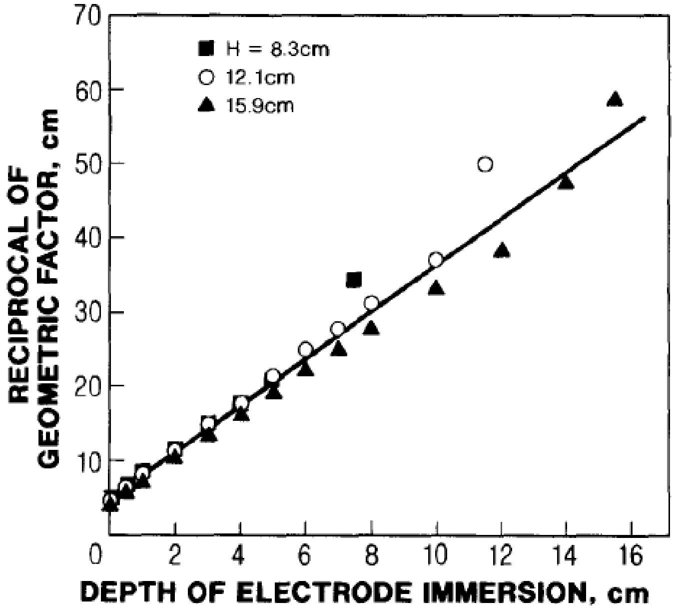
Example Dip Test, showing 'Downing Region'

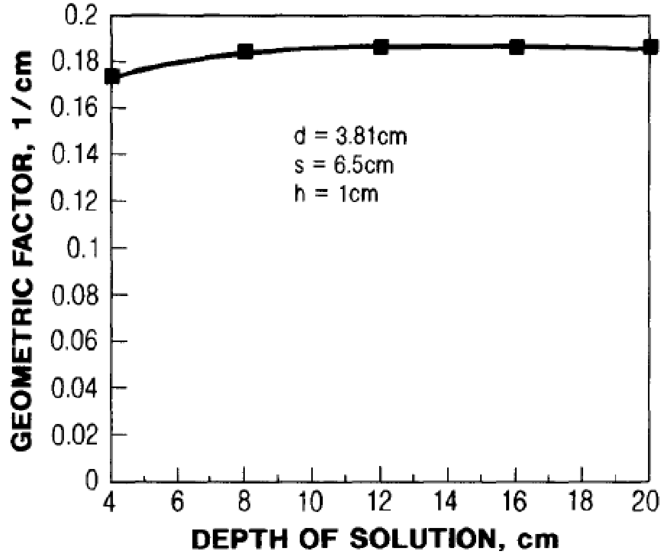


Why is Electrode Resistance Nearly Independent of Depth of 'Slag' Under the Electrode?



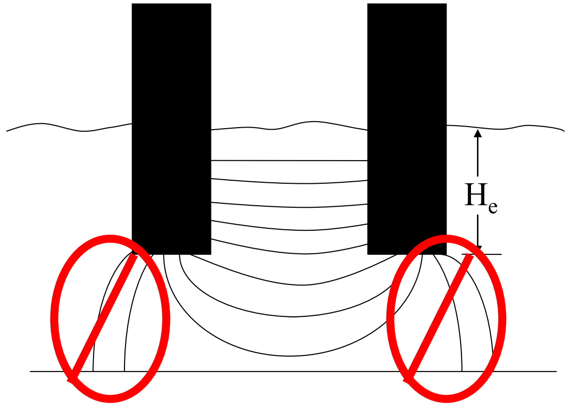
Does not fit the 'wye' assumption!





Jiao and Themelis, 1991

Modified Downing And Urbain Equation (Kennedy *et al.* 2012)



Modified here for better accuracy with fewer terms

$$a = \pi - (\pi - 2)\left(\frac{r_{tip} - r_e}{r_{tip}}\right)$$

a = 2, flat tips

a = π, hemisphere

$$R_{phase} = \frac{1}{\sigma}\left\{\frac{\pi H_e}{\ln\left(\frac{S_e}{2r_e} + \sqrt{\left(\frac{S_e}{2r_e}\right)^2 - 1}\right)} + a r_e \left(\frac{1}{1 - \frac{r_e}{S_e}}\right)\right\}^{-1}$$

Jens Westly's C_3 and the X-Graph Concept

$$I_e = C_3 \; P_{furnace}^{\,X}$$

$$R_e = C_2 \, P_{furnace}^{\,(1-2X)}$$

$$V_e = C_1 \, P_{furnace}^{\,(1-X)}$$

$$P_{furnace} = 3 \, I_e^2 \, R_e$$

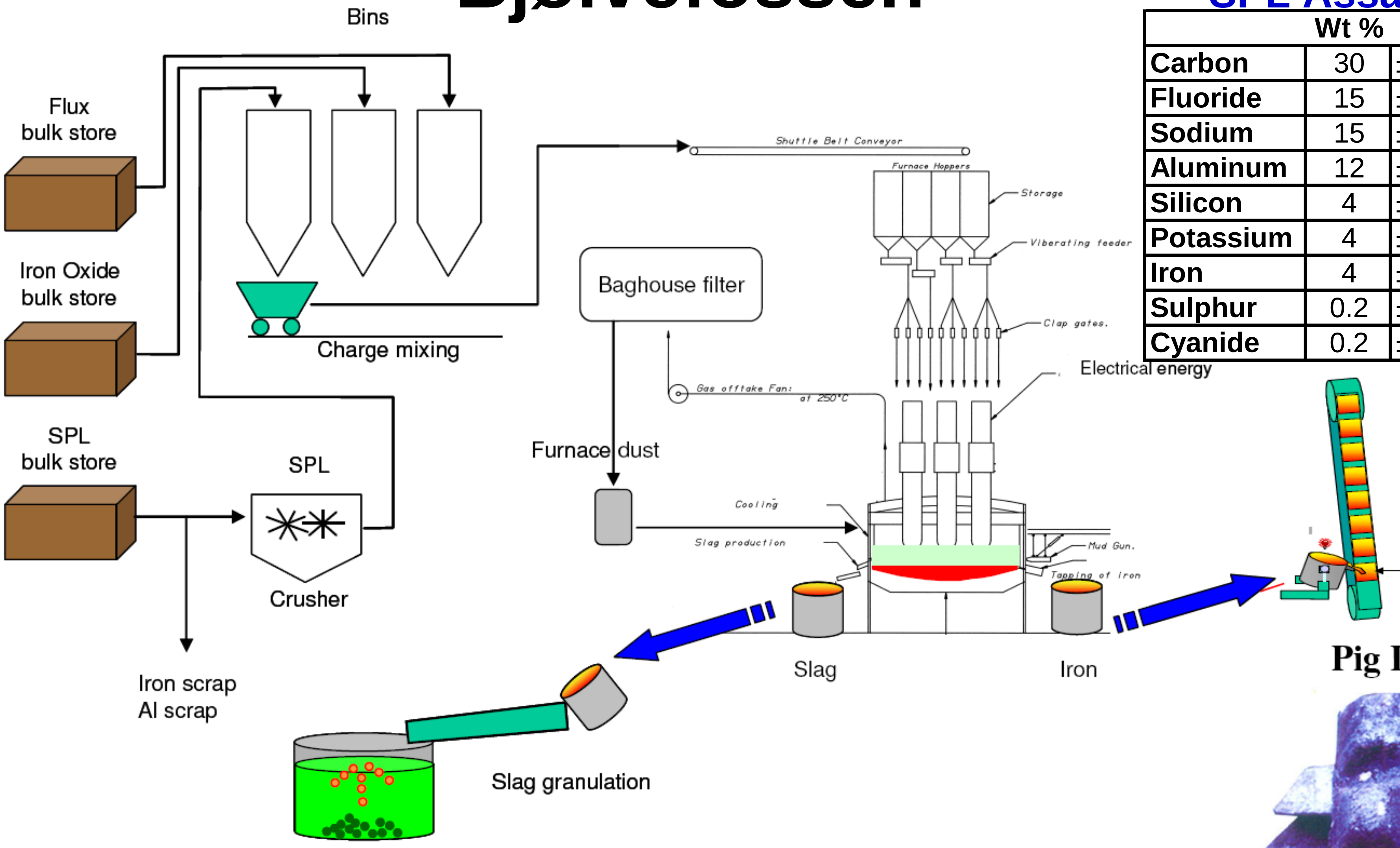
but $R_e(P_{furnace})$*!*

X has a characteristic value for a given slag furnace and process.

X is from 0.5-1.0 for slag furnaces (typically 0.6-0.9).

X=~2/3 for submerged arc furnaces.

SPL Demonstration Elkem Bjølvefossen

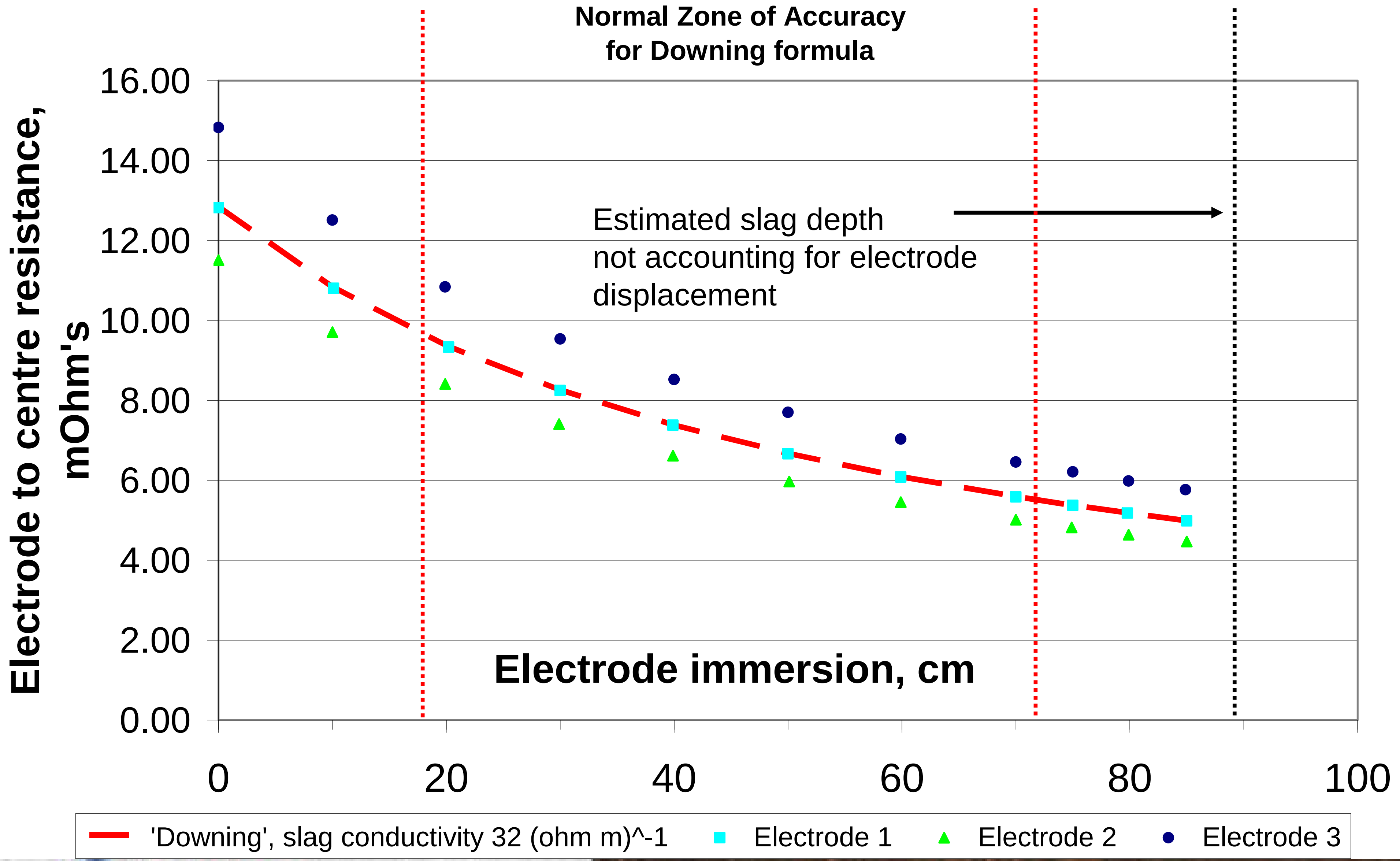


SPL Assay

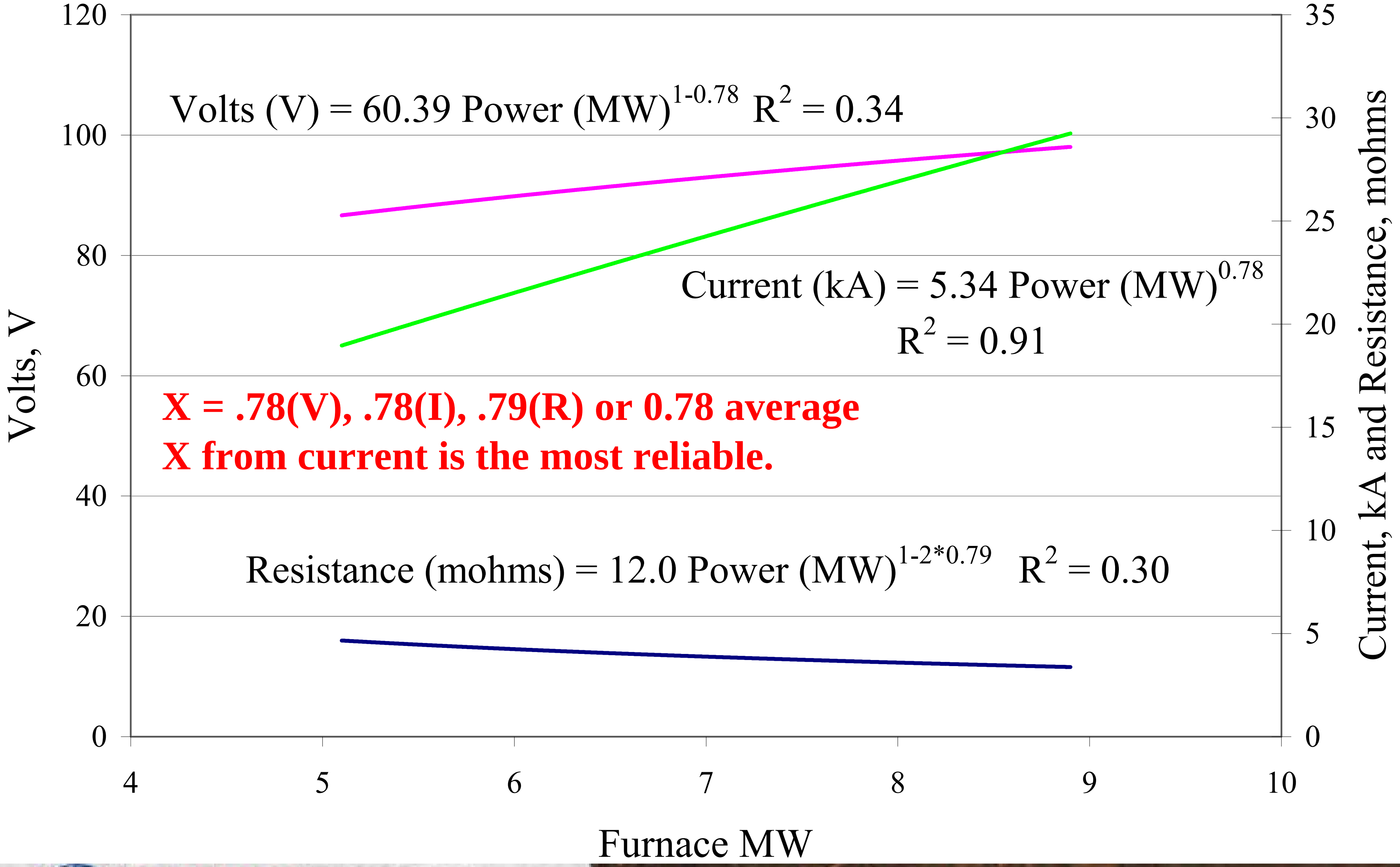
	Wt %	
Carbon	30	± 5
Fluoride	15	± 3
Sodium	15	± 5
Aluminum	12	± 5
Silicon	4	± 2
Potassium	4	± 2
Iron	4	± 3
Sulphur	0.2	± 0.1
Cyanide	0.2	± 0.2

Pig Iron

SPL Demonstration Dip Test



SPL Demonstration X-graph



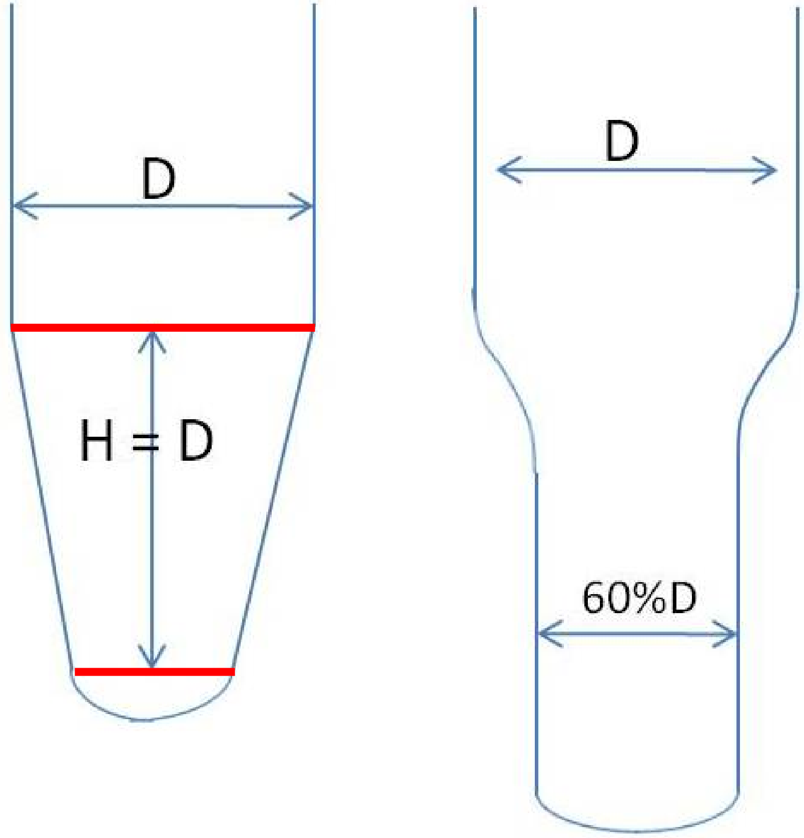
Slag Properties from Pilot and Demonstration

Large Discrepancy Between Pilot and Demonstration Conductivities

What has gone wrong?

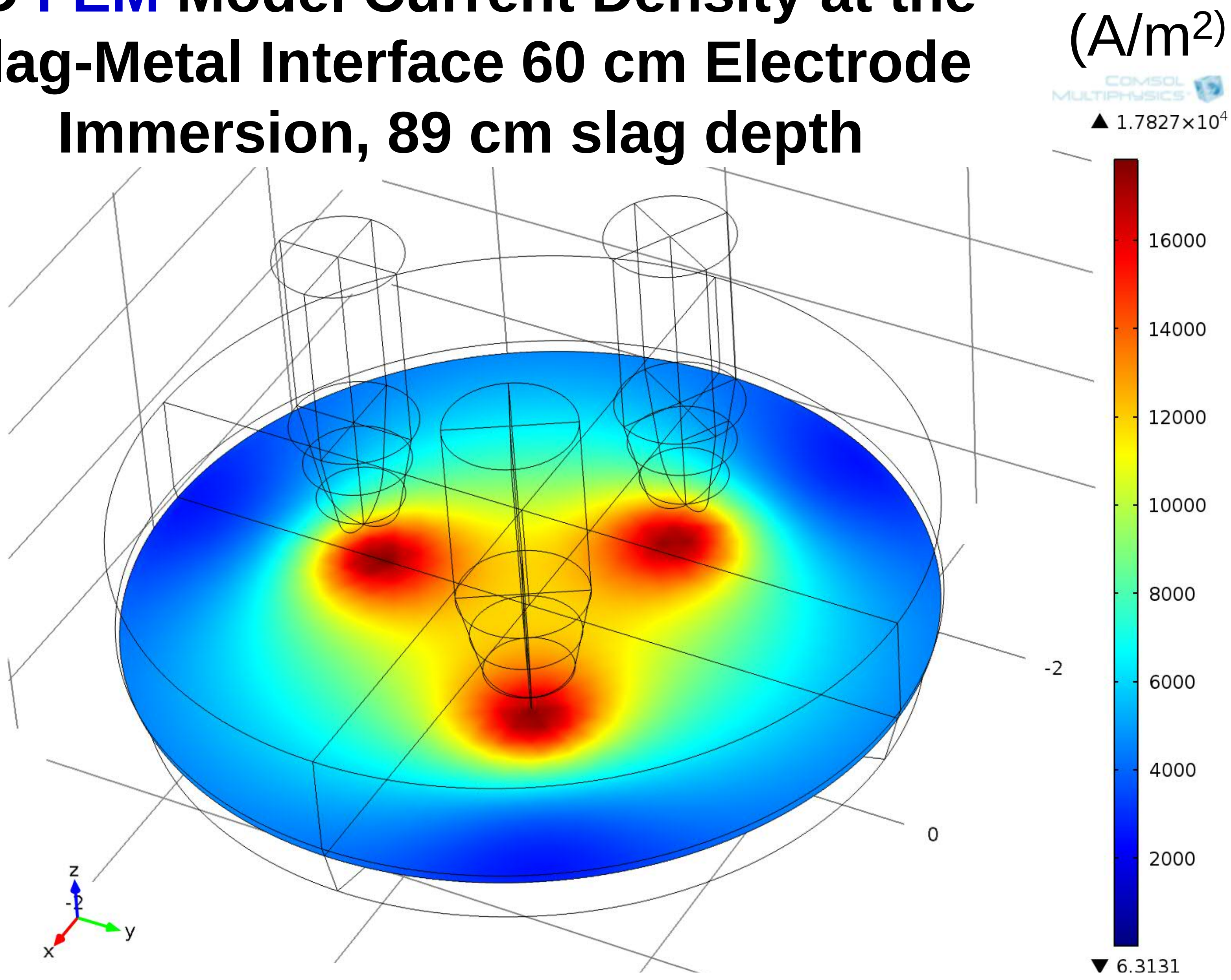
Slag Component	Pilot (wt%)	Demonstration (wt%)
F	5.9	7.0
FeO	8.7	8.1
SiO_2	43.0	44.7
CaO	3.3	5.9
Na_2O	19.3	13.9
Al_2O_3	17.2	21.7
K_2O	0.3	1.6
MgO	1.3	1.2
Slag conductivity, $(\text{ohm cm})^{-1}$	154	32
Temperature, °C	1377	1390

Real, Typical and Model 'Standard' Shapes for Electrodes

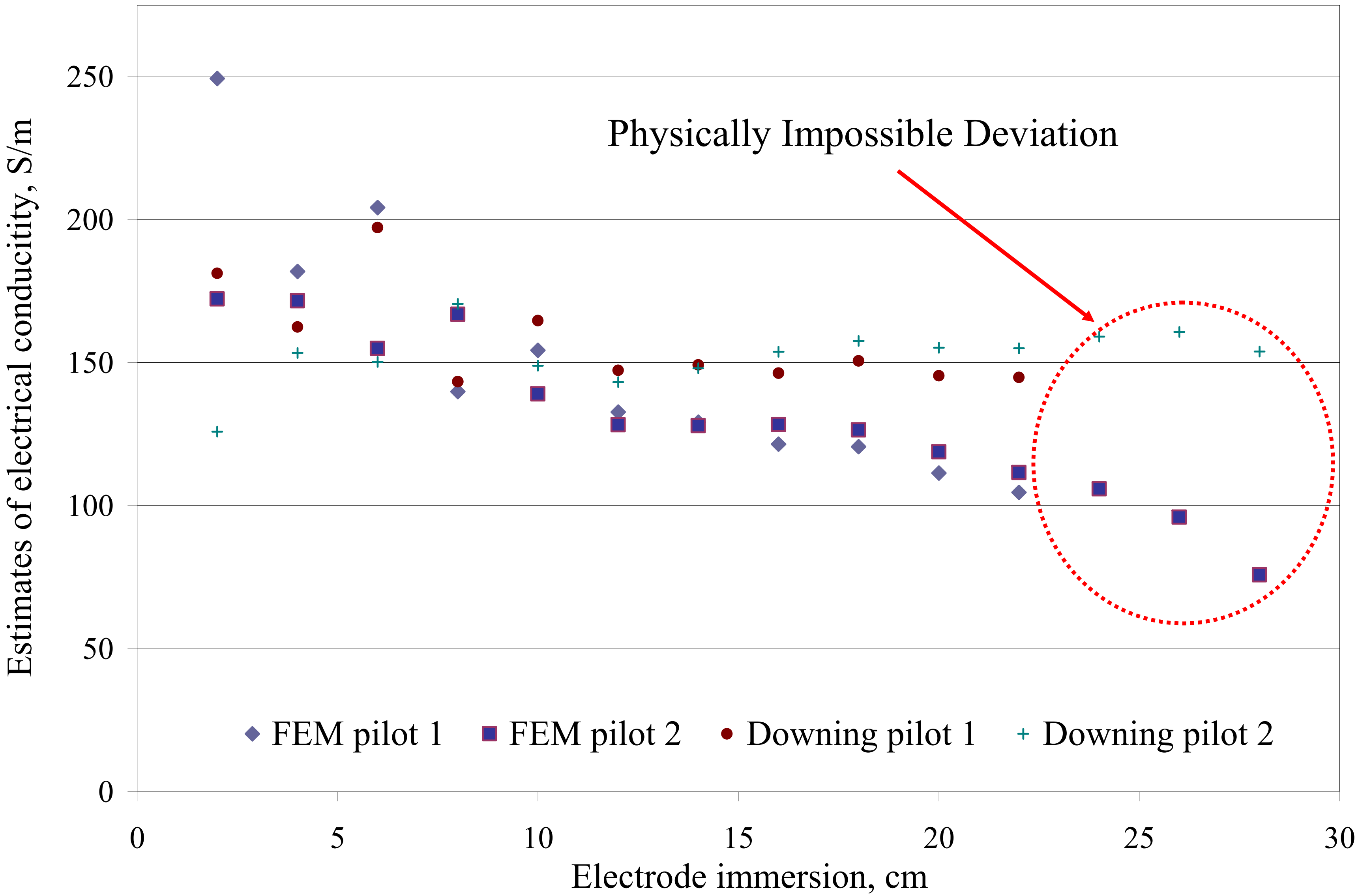


a = 2.5

3D FEM Model Current Density at the Slag-Metal Interface 60 cm Electrode Immersion, 89 cm slag depth

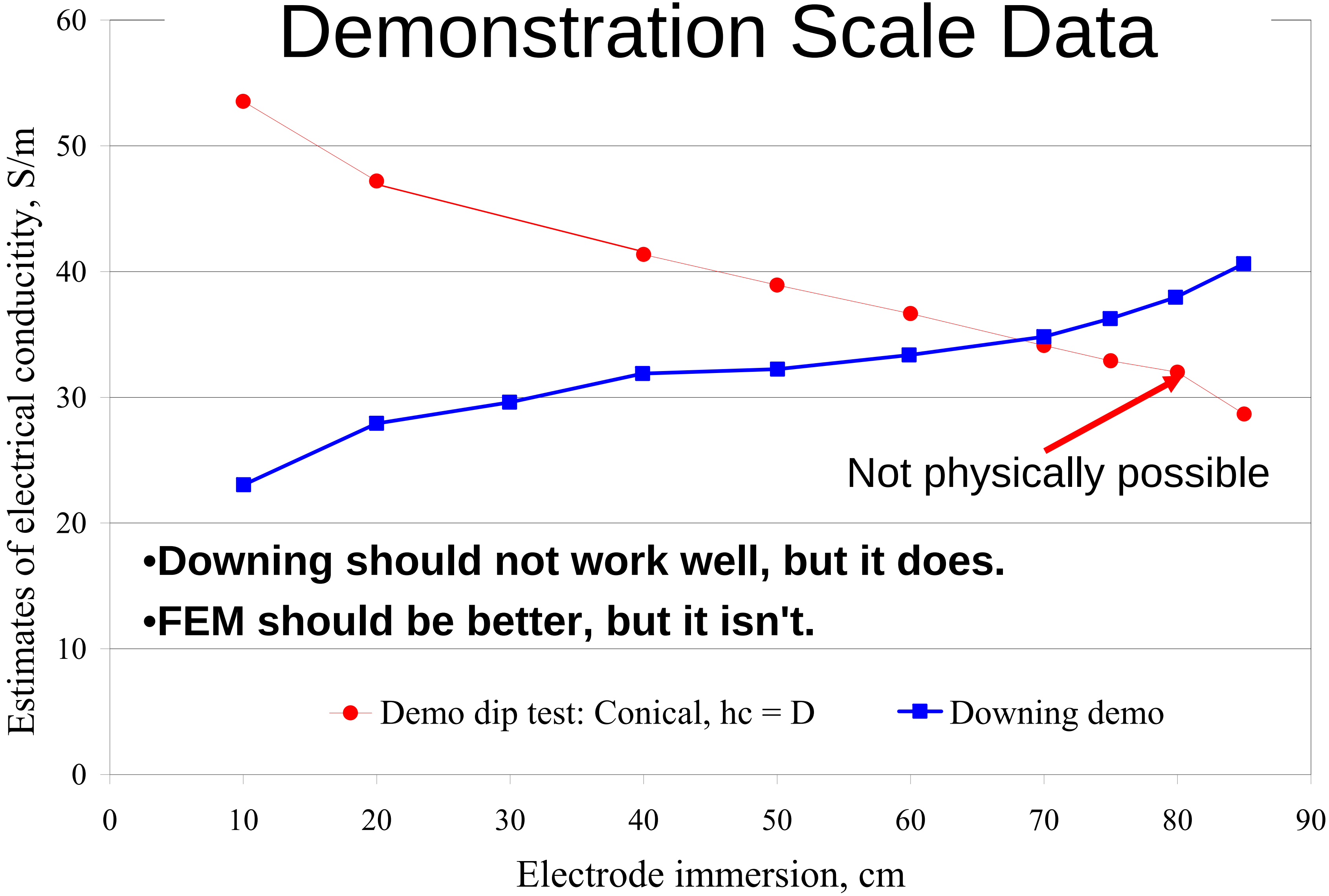


Elkem SPL Pilot Scale Data



Elkem Bjølvefossen

Demonstration Scale Data



- **Downing should not work well, but it does.**
- **FEM should be better, but it isn't.**

Conclusions

- **Acceptable agreement for engineering purposes is found between 3D FEM solutions and the Downing and Urban Equation on average.**

- **The behavior of the electrical models provide indications that the simplistic slag conduction model is incomplete.**

Conclusions

- **Lack of understanding of the nature of conduction and impedance in slags (e.g. electronic vs. ionic conductivity), limit our ability to generate accurate electrical models and to design optimized power supplies.**

- **Westly's formulae can be used to adjust predicted resistance for changes in power intensity in the absence of in-furnace temperature readings.**

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Conductivity of Different Furnace Materials

Species	Electrical Conductivity $(ohm\ m)^{-1}$	Temperature (oC)
Oxide materials:		
Al_2O_3	384	2127
CaF_2	600	1500
CaO	1500±50%	2580
MgO	1500 ±50%	2800
SiO_2	10^{-2}	2000
ZrO_2	1500 ±50%	2600
Molten matte and metals:		
$25\%Cu_2S/75\%FeS$	$\sim 9.5E^4$	1200
Cu	$4.76E^6$	1084
Fe	$7.2E^5$	1727