Models for Electrical Conditions in Submerged Arc Furnaces.

M. Sparta, V. K. Risinggård, U. Thisted, M. Fromreide

03.11.2025

NORCE is an independent research institute that conducts research for both public and private sectors, to facilitate informed and sustainable choices for the future.

1200 mill NOK | **850** employees | **50** nationalities

RESEARCH

These are some of our key research areas:

Digitisation AI

Energy of the Future: energy transition, low-emission oil and gas production, CO_2 storage, and renewable energy.

Safe and Good Societies: youth exclusion, innovation in municipal services, primary healthcare services, regional innovation and business development, space and space debris, defense, societal security, and emergency preparedness.

Climate and Environmental Risk: climate models, river restoration, the marine environment, geohazards, and microplastics.

Sustainable Seas and Coasts: sustainable feed, aquaculture, circular economy, and monitoring technology.

Our commercialization division strengthens industry through licensing agreements or the creation of new spin-off companies.

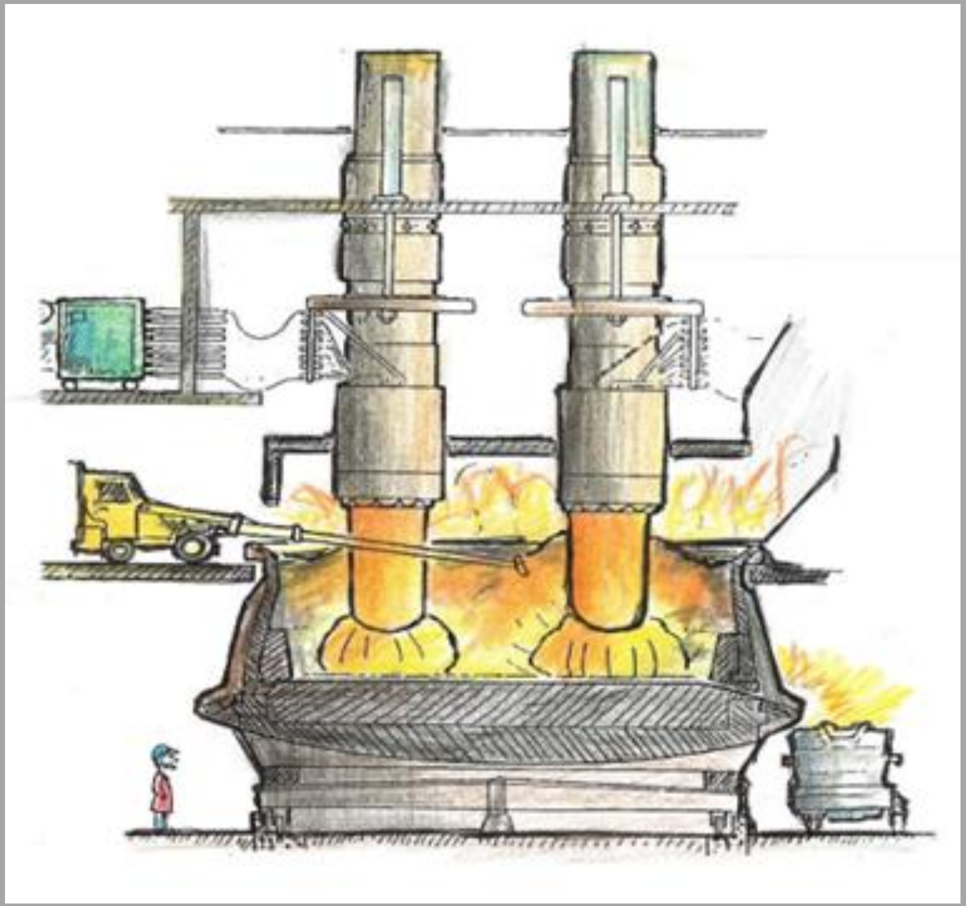
INFRASTRUCTURE

Our infrastructure includes:

- Ullrigg Test Centre
- NORCE Technology Park Risavika
- OpenLab Drilling
- NORCE Marine Research Centre
- Research aircraft and drones
- Model systems for social science research
- NBioC -The National Bioprocessing and Fermentation Centre
- INES - Infrastructure for Norwegian Earth System Modelling
- LFI – Laboratory for Fresh Water Ecology and Inland Fisheries
- Multiphase Flow Loop

Submerged arc furnaces are vital for primary metal production

- It's difficult to optimize these furnaces for **performance**, energy **efficiency**, product **quality**, and **environmental impact** due to the extreme heat and harsh internal conditions.
- Direct observation and experimental surveys are at best challenging.
- Numerical modeling is a powerful tool for analyzing these complex systems.
- FEM simulations provide insights into the furnace's internal environment that are otherwise impossible to get through physical experimentation.



Submerged arc furnace for the production of ferrosilicon. (Courtesy of T. Hannesson, *The Si process - Drawings*, Elkem Iceland, 2016.)

10+ years of COMSOL modeling thanks to Competence building projects

Electrical Conditions and their Process Interactions in High Temperature Metallurgical Reactors (ElMet)

Duration: 5 years, 2015-2020

Industrial partners: Elkem, Eramet Norway

Electrical Conditions in Submerged Arc Furnaces – Identification and Improvement (SAFECI)

Duration: 4.5 years, 2021-2025

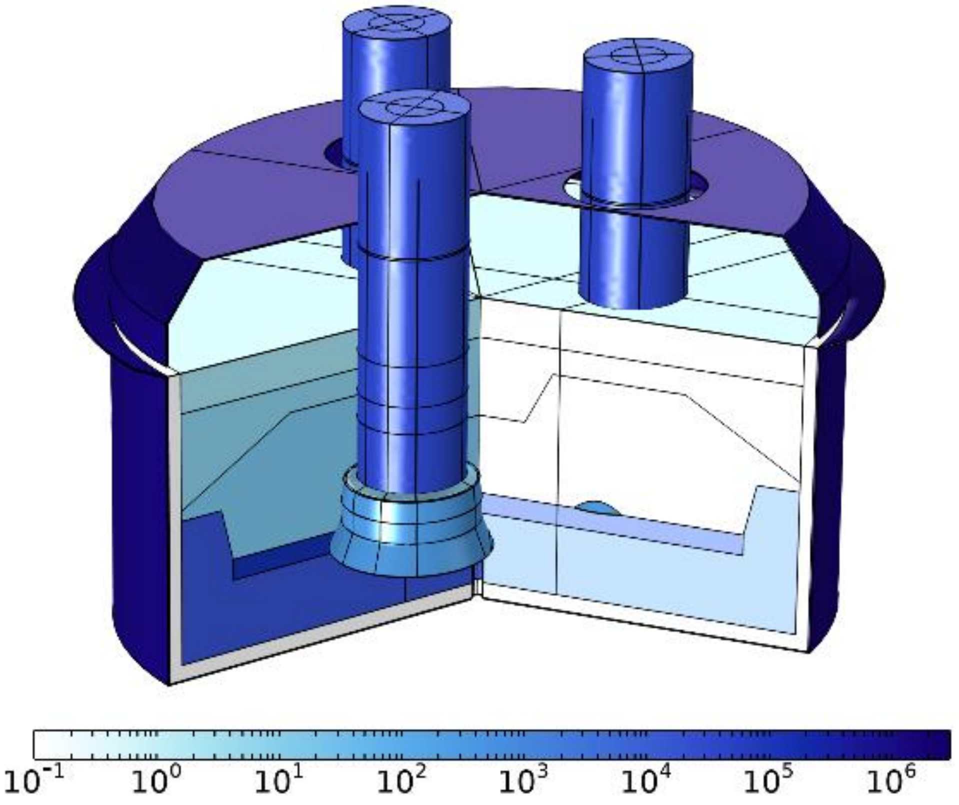
Industrial partners: Elkem, Eramet Norway, Finnfjord and Wacker Chemicals Norway

Submerged-arc furnaces: Improved electrical conditions for increased energy efficiency and decarbonization (SAPPHIRE)

Duration: 4 years, 2025-2029

Industrial partners: Elkem, Eramet Norway, Finnfjord and Wacker Chemicals Norway

The “base” model



Schematic representation of the model. The electrical conductivity on a logarithmic color scale in S/m.

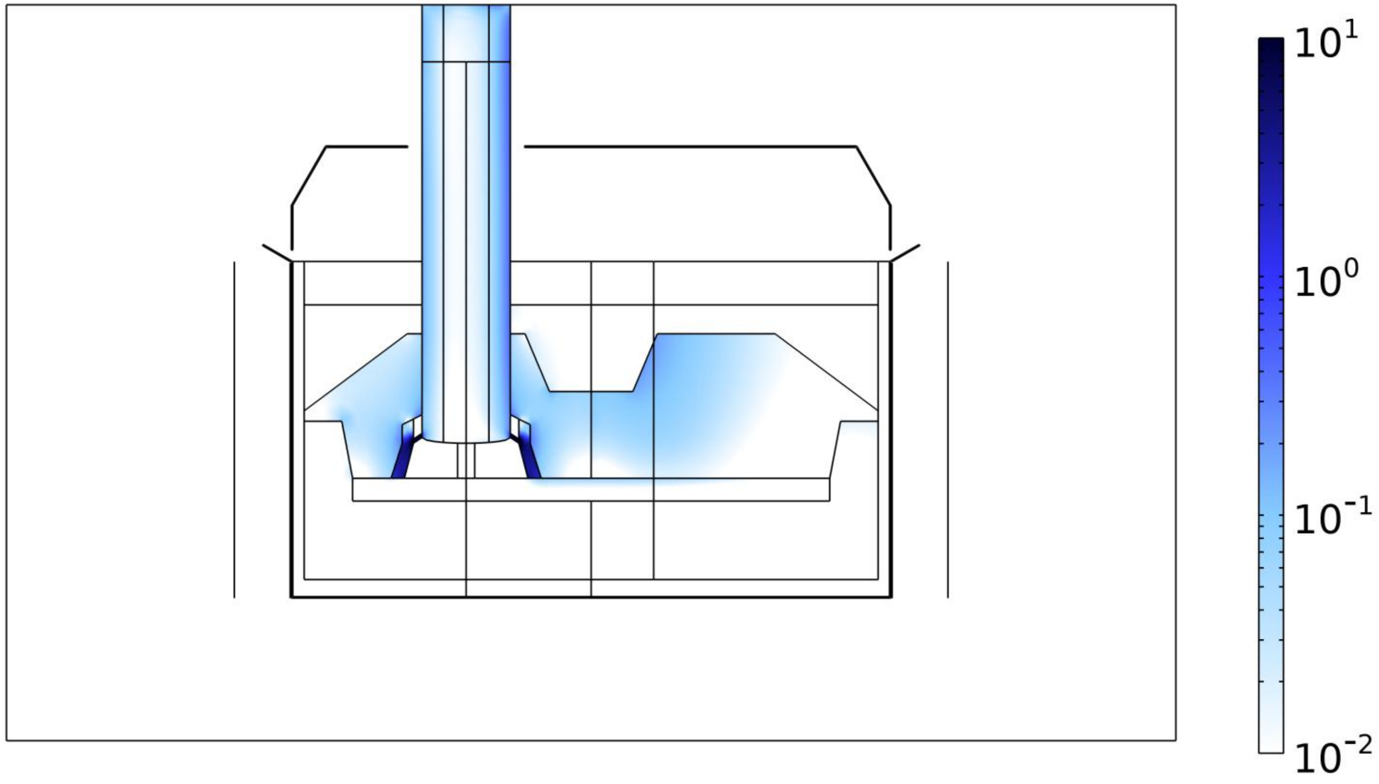
Geometrical Representation: The model accurately represents an industrial three-phase electric smelting furnace. It includes three electrodes arranged in an equilateral triangle, a surrounding steel shell, a non-conductive insulation layer, and a conductive carbon lining. Internal domains include charge banks with varying resistivity; either coke beds (with adjustable diameter and resistivity) or craters (with non-conductive gas and resistive arcs), depending on the specific process being modeled.

Electrical Simulation:

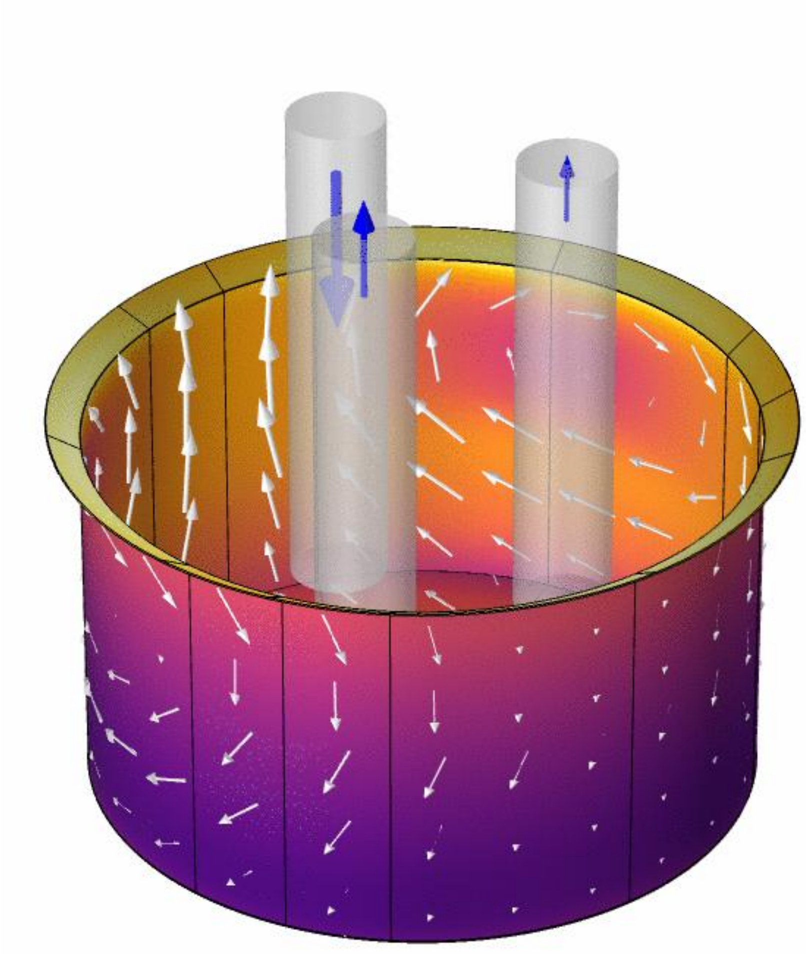
- The AC/DC - Magnetic and Electric Fields (mef) interface was used to establish the electrical conditions.
- An Electrical Circuit (cir) model was integrated to track the true power for each phase, offering insight into power flow.

SAMPLE RESULTS

Active and reactive powers, currents, magnetic field…



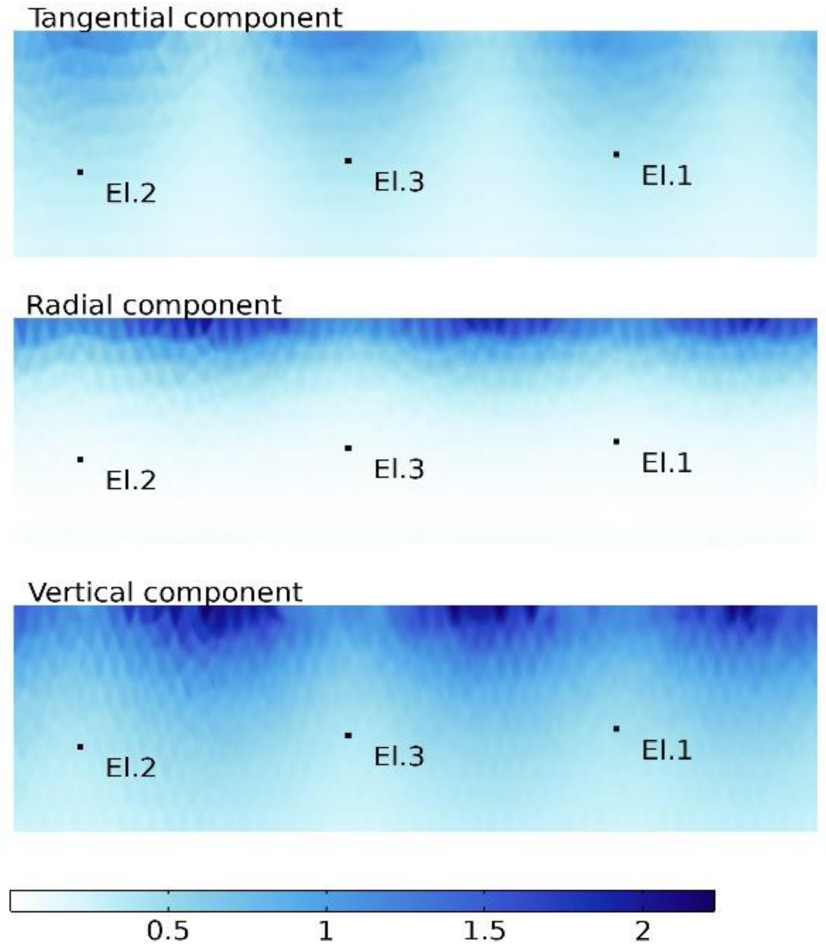
Active Power density (MW/m³)



Electrode currents and induced shell currents

Virtual magnetometers

- The furnace models predict the magnetic field at any point in space, which is critical for optimizing data collection.
- Analyzing the magnetic field patterns can help develop new methods for real-time measurements.
- Visualizing the magnetic field, such as a 2D map of its components, can help identify the best strategies for collecting data on the furnace's internal state.



Projection of a cylindrical probe surface into a 2D map of the tangential, radial and vertical components of the magnetic field (mT) around the furnace. The points on the probe surface closer to the tip of the electrodes are marked.

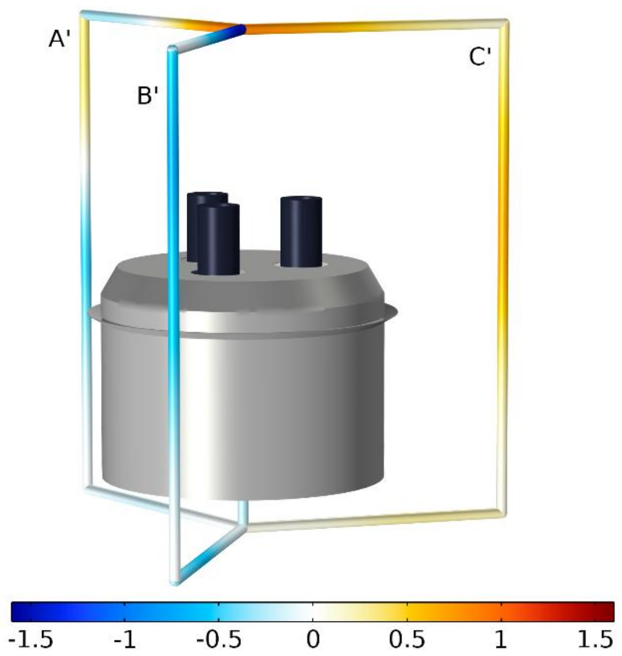
Assessment of Traditional Multi-Lead Measurement Methods

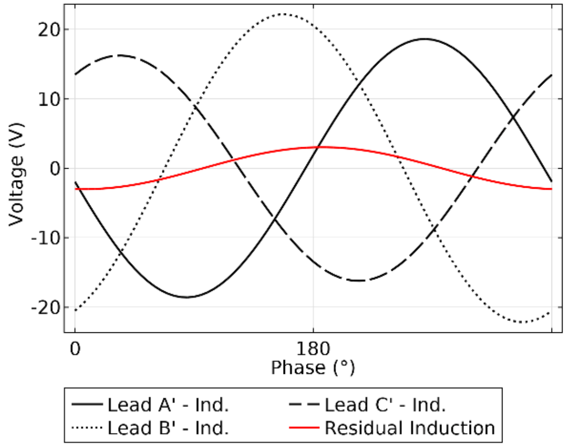
The Bøckman system is a technique used to improve the accuracy of core voltage measurements by dividing the measurement leads into three path to cancel out induced voltages through destructive interference.

Numerical models were used to analyze the effectiveness and limitations of this and similar multi-lead measurement methods under different operating conditions.

Simulations revealed the shortcomings of the destructive interference method, particularly when there is asymmetry in the lead placement.

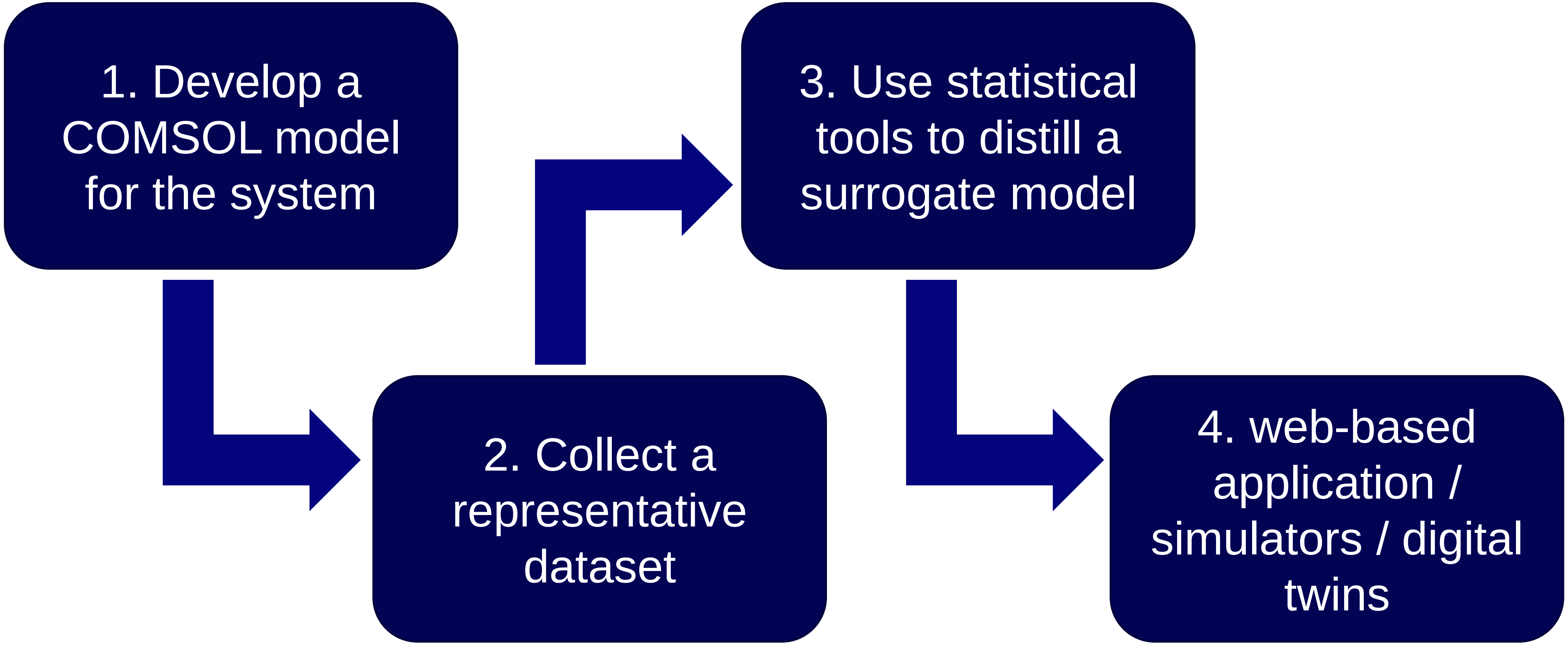
The system can be calibrated to compensate.





Top: Asymmetry in the placement of the leads - instantaneous amplitude of the tangential electric field (V/m). Bottom: Induction in the leads and effect on the partial destructive interference (red).

Development of surrogate models that retains the capabilities of a FEM model but that solves instantly



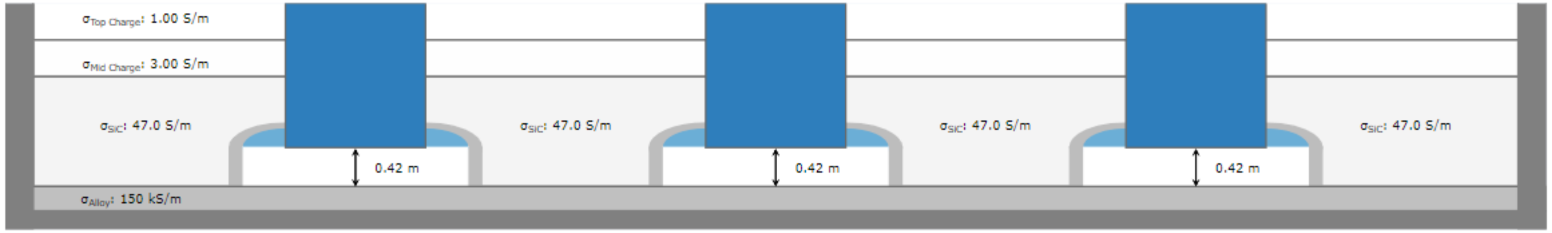
M. Sparta, M. Fromreide, V.K. Risinggård, and S.A. Halvorsen, “Electrical conditions in submerged arc furnaces: A web-based simulator” , Proceedings of the Silicon for the Chemical & Solar Industry XVI (NTNU, Trondheim, 2022) , https://doi.org/10.2139/ssrn.4118651

SAFECI - Silicon Furnace Electrical Conditions Metamodel

lome FeSi2022 FeSi2023

v.2023.03.01

Input Data



Electrode Positions [m]

1 — 0.1m — 0.425m — 0.75m — 0.425
2 — 0.1m — 0.425m — 0.75m — 0.425
3 — 0.1m — 0.425m — 0.75m — 0.425

RMS Voltage at Transformer [V]

250V — 300V — 275

Crater wall thickness [cm]

10cm — 15cm — 20cm — 15

Crater Wall Conductivies [S/m]

1 — 75S/m — 187 S/m — 300S/m — 187
2 — 75S/m — 187 S/m — 300S/m — 187
3 — 75S/m — 187 S/m — 300S/m — 187

Silicon Carbide banks Conductivities [m]

1-2 — 20S/m — 47 S/m — 75S/m — 47
2-3 — 20S/m — 47 S/m — 75S/m — 47
3-1 — 20S/m — 47 S/m — 75S/m — 47

The conductivities for the remaing regions are fixed in this version of the model:

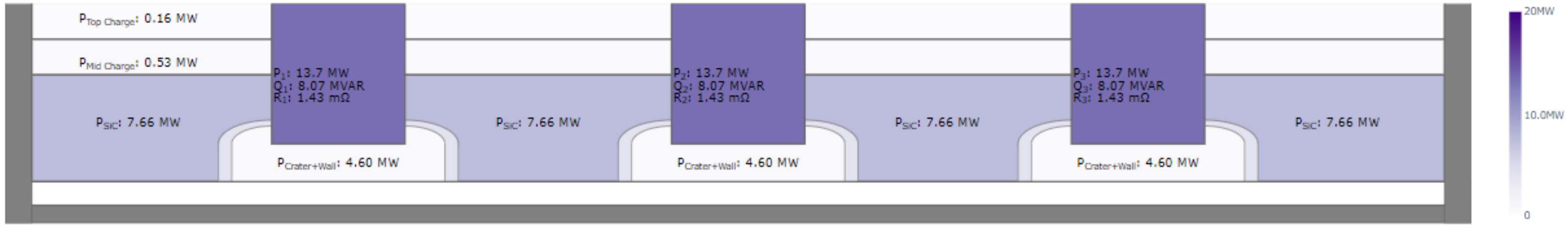
- Top charge : 1 S/m
- Mid charge : 3 S/m
- Arc : 7000 S/m
- Lining : 1e-06 S/m
- Steel : 3 MS/m
- Electrode : 80-100 kS/m

Reset Values to Default

Export Values to Excel

Output Data

Integral Circuit Model Bøckman



Total Active Power (P): 41.0 MW Total Reactive Power (Q) : 24.2 MW Total Resistance (R) : 4.23 mΩ

Total Values

Parameter	Integral	Circuit	Bøckman
Total Active Power [MW]	41.04	41.02	41.02
Total Reacting Power [MVAR]	24.20	24.70	25.47
Total Shell Power [MW]	0.32		
Roof Power [MW]	0.13		
Total Resistance [mΩ]	4.23	4.23	4.23
Total Reactance [mΩ]	2.34	2.34	2.34
Total Power in Crater+Walls [MW]	13.79		
Total Power in Top Charge [MW]	0.16		
Total Power in Mid Charge [MW]	0.53		
SiC Power El1-El2 [MW]	7.66		

Electrode 1

Parameter	Integral	Circuit	Bøckman
P(elec.) [MW]	13.68	13.67	13.67
Q(elec.) [MVAR]	8.07	-	-
R(elec.) [mΩ]	1.43	1.42	1.44
X(elec.) [mΩ]	0.78	0.78	0.77
V(elec.) [V]	159.05	158.79	160.75
P(shell) [MW]	0.11		-
P(Crater+Wall) [MW]	4.60		-

Electrode 2

Parameter	Integral	Circuit	Bøckman
P(elec.) [MW]	13.68	13.67	13.67
Q(elec.) [MVAR]	8.07	-	-
R(elec.) [mΩ]	1.43	1.42	1.44
X(elec.) [mΩ]	0.78	0.78	0.77
V(elec.) [V]	159.05	158.79	160.75
P(shell) [MW]	0.11		-
P(Crater+Wall) [MW]	4.60		-

Electrode 3

Parameter	Integral	Circuit	Bøckman
P(elec.) [MW]	13.68	13.67	13.67
Q(elec.) [MVAR]	8.07	-	-
R(elec.) [mΩ]	1.43	1.42	1.44
X(elec.) [mΩ]	0.78	0.78	0.77
V(elec.) [V]	159.05	158.79	160.75
P(shell) [MW]	0.11		-
P(Crater+Wall) [MW]	4.60		-

Thanks to COMSOL

- A sophisticated model of a submerged arc furnace was developed to simulate its electrical and electromagnetic conditions, providing insights into power distribution and field dynamics.
- The model was used to evaluate both novel and traditional measurement techniques.
- Highly parametrized versions of the model created data for training surrogate models, which enable rapid, computationally inexpensive predictions of furnace behavior.
- The work ultimately leads to improved operational control, enhanced measurement accuracy, and more efficient ferro-alloy production.

Thank you. Takk.

Merci. Gracias. Obrigado.

Manuel Sparta
masp@norceresearch.no

norceresearch.no

NORCE