

Optimization of Electric Arc Furnace Melting & Development of an EAF Reduced-Order Model with HPC

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Center for Innovation Through
Visualization and Simulation



Steel Manufacturing Simulation and
Visualization Consortium



CIVS (2009) & SMSVC (2016)

- CFD modeling at PNW **since 1994**, steel industry applications **since 1999**
- **Five HPC4EI projects since 2015:**
 - **LLNL:** Virtual Blast Furnace; Utilizing HPC to Model the E-Iron Nugget Process
 - **ANL:** Optimization of Reheat Furnace Efficiency, **ORNL:** ROMs for Refining Ladle; EAF

Center for Innovation through Visualization and Simulation (CIVS)

- Missions
 - Innovation (**\$53+ million** grants)
 - Application (**\$40+ million** savings from 5 out of 460+ projects)
 - Education (**2250+** research students)
- Strategies
 - **Integration** of technologies
 - **Application driven**
 - Partnerships (**190+** organizations)

➤ Focused Areas:

- **Smart Manufacturing:** Digital Twin, AI, Multi-physics Modeling, Simulation & Visualization
- **Energy**, productivity, quality
- **Workforce Development:** Virtual training simulators

Steel Manufacturing Simulation and Visualization Consortium (SMSVC)

Project Technical Committees (**200+** industry participants)

- Ironmaking
- Electric Arc Furnace
- Refining Ladle
- Continuous Casting
- Reheating Furnace
- Safety and Training

Approach

- Application-driven
- Industry-driven
- **Industry relevance**
- Step-by-step, section-by-section, simple to complex
- Partial or full integration
- Validation by all means
- Roadmapping



➤ EAF Process

- 70% of steel production in U.S.
- Growing demand: 50% steel production expected by 2050 worldwide

➤ Current Issues for Optimization

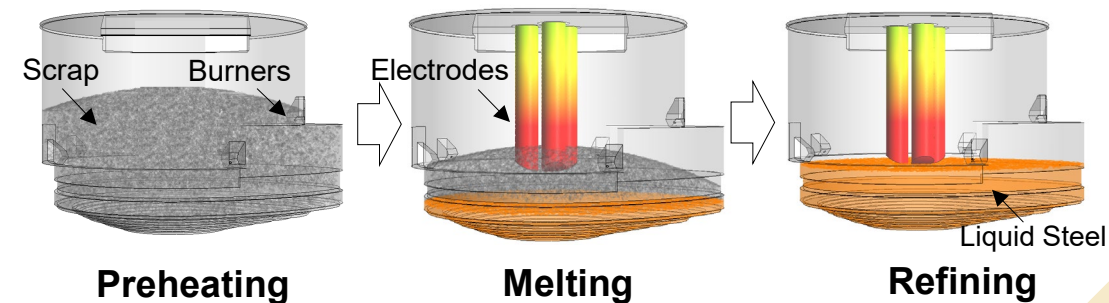
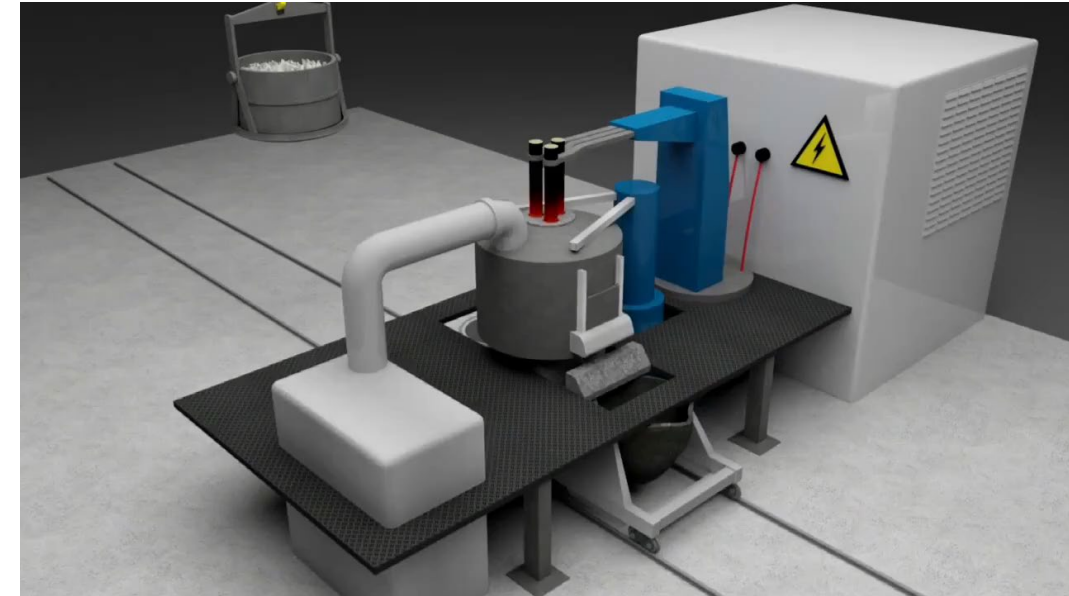
- Limited comprehensive multi-physics CFD modeling due to process complexity
- Limited plant data collection

➤ Objective

- To develop and implement a comprehensive EAF-CFD tool for
 - Design, trouble-shooting & optimization
 - Integrating with ML to build a digital twin

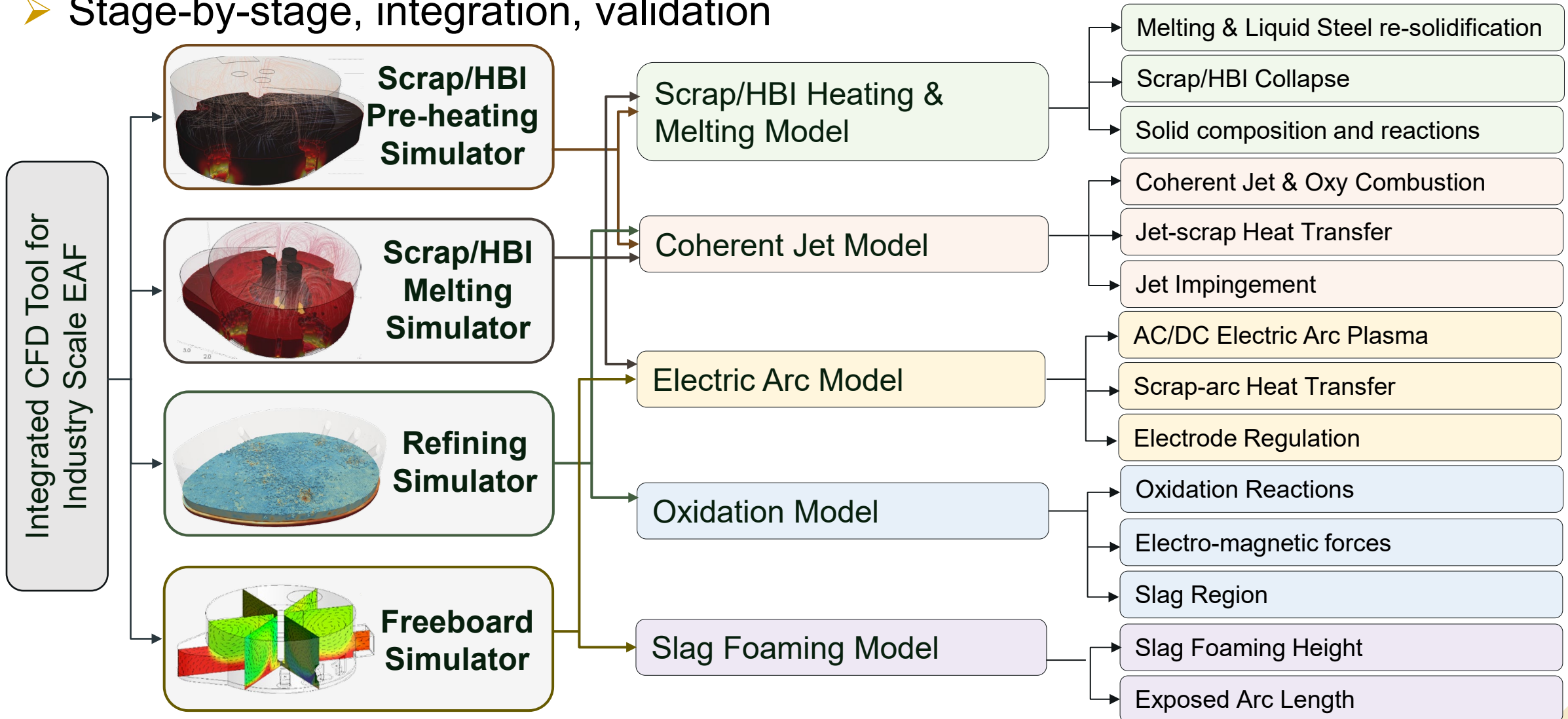
➤ Potential Impacts

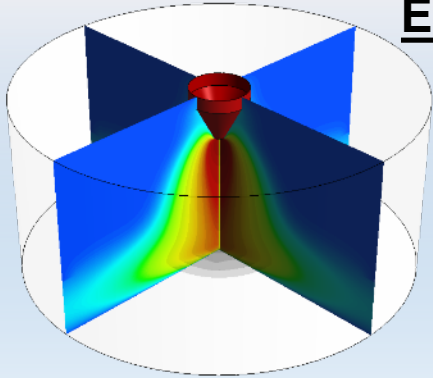
- Higher EAF productivity & energy efficiency
- Real-time process control for better quality



EAF-CFD Methodology

- Application-driven, Industrial relevance
- Stage-by-stage, integration, validation





Electric Arc Model (DC/AC)

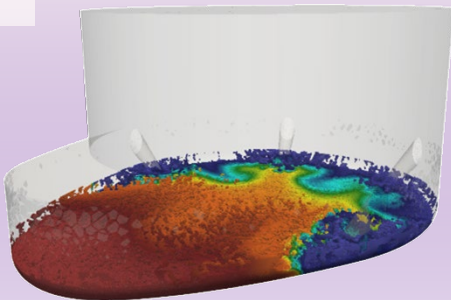
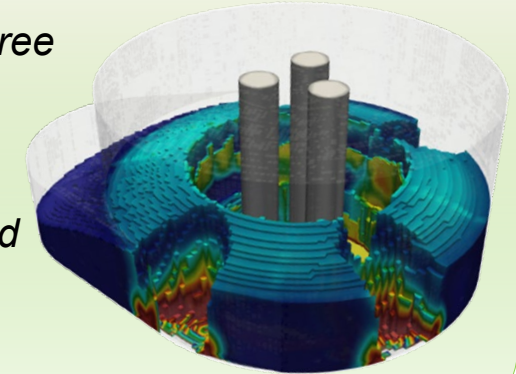
Uniqueness: Arc model, validated in various EAF, provides arc heating dissipation in the Melting Simulator

Application: Provided arc power-melting time relationship to industrial EAFs

Scrap Melting Simulator

Uniqueness: Integrating three models: Scrap heating & melting, DC/AC electric arc and Burner models

Application: First-of-its-kind tap-to-tap melting process simulation with excellent validation



Bath Refining Simulator

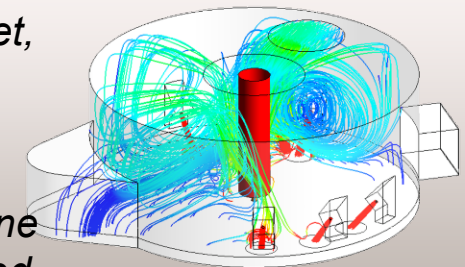
Uniqueness: Coupling three phases (steel, slag, gas) with refining reactions

Application: Simulated a Nucor EAF with excellent validation

Freeboard Simulator

Uniqueness: Integrating co-jet, arc and slag foaming models

Application: Resolved industrial EAF overheating panel issue and provided online calculator with scenarios based on slag composition



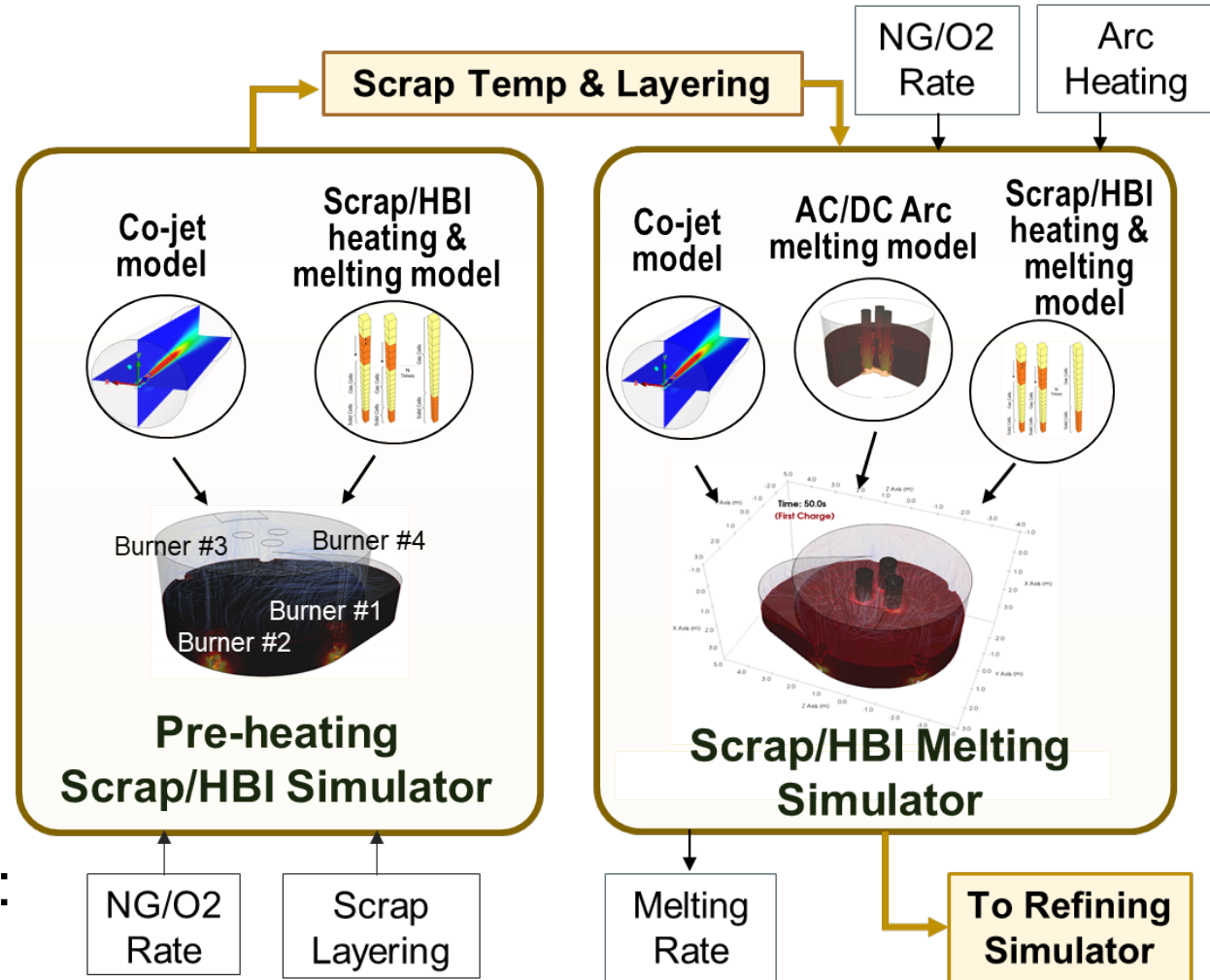
Challenges and Approach for Scrap Melting

Challenges

- Multi-physics: fluid flow, heat transfer, chemical reactions, electromagnetics
- Multi-phase: scrap material representation, gas, molten bath
- Heating sources: electric arc (AC/DC) and chemical heating
- Multiple time and length scales

Approach

- Integrating models designed specifically for EAF operations, co-jet, arc heating and scrap heating & melting models, into:
 - Pre-heating simulator
 - Scrap/HBI melting simulator



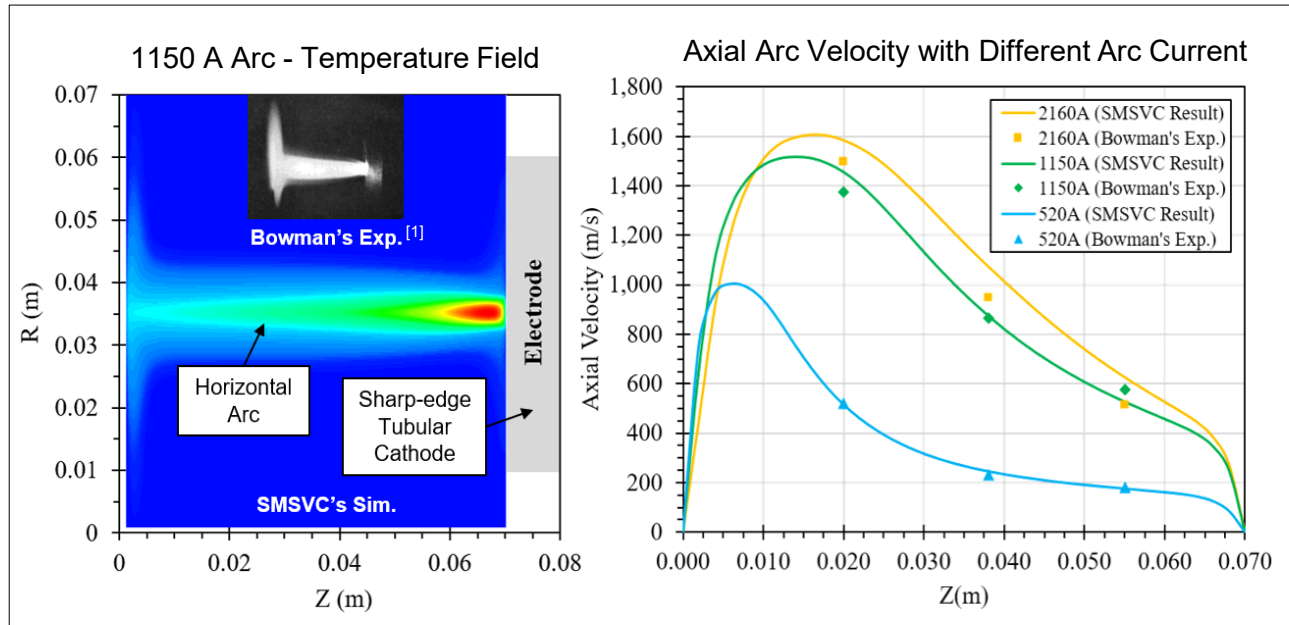
Electric Arc Model

➤ **Objective:** to predict **DC/AC** arc performance & heat dissipation

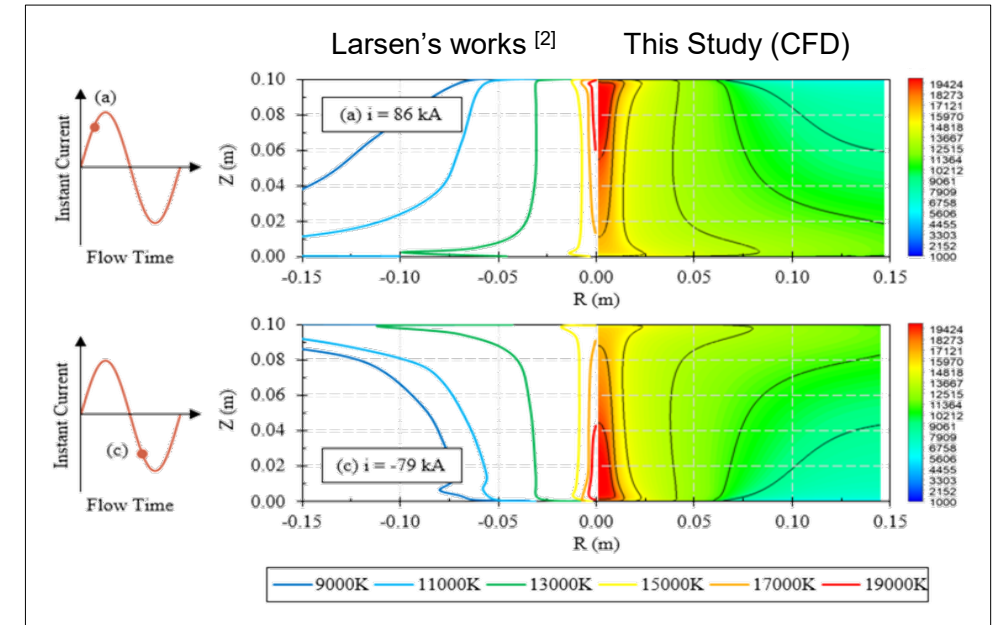
➤ **Methods:**

- Maxwell's equations → Lorentz force & plasma heating
- Navier-Stokes equations → arc plasma flow

Model validation:
~ 12.3%



Validation of **DC** Electric Arc Model



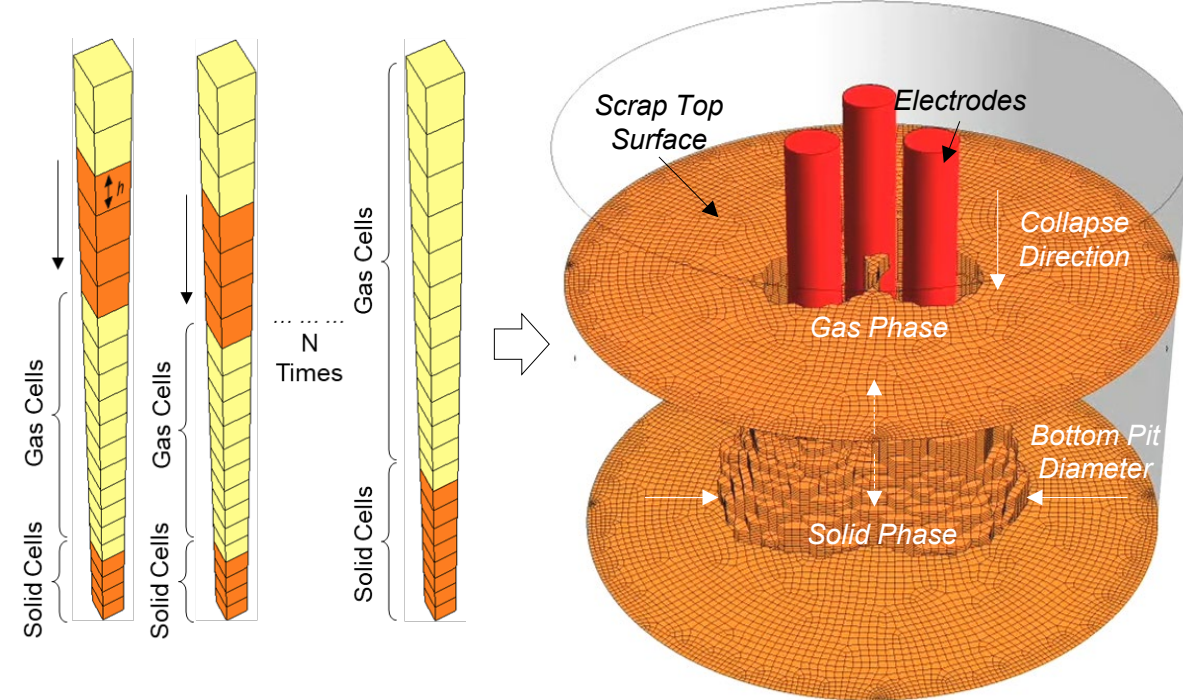
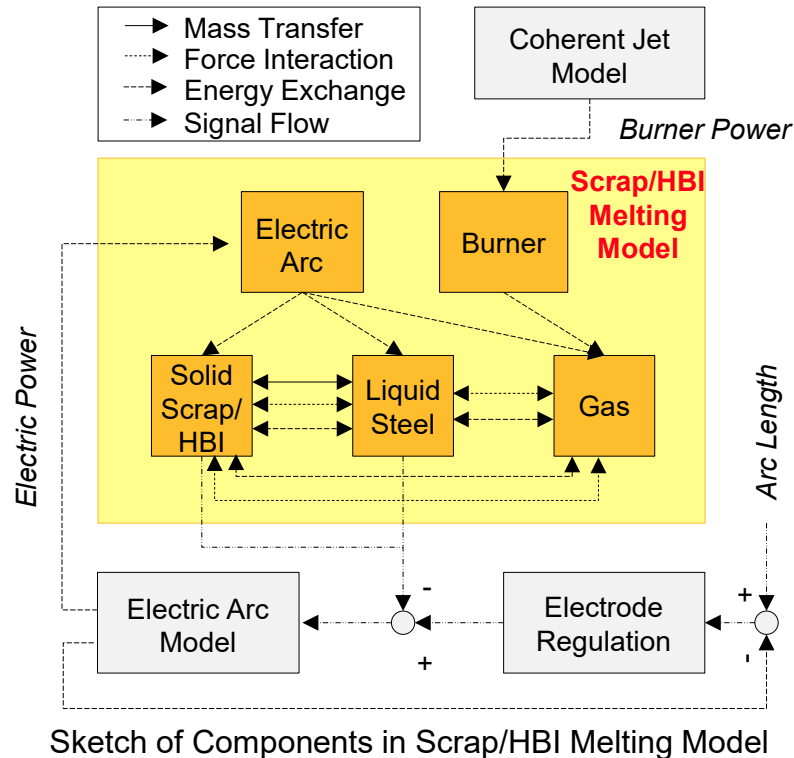
Validation of **AC** Electric Arc Model

[1] B. BOWMAN, "Measurements of plasma velocity distributions in free-burning DC arcs up to 2160A," Journal of Physics D: Applied Physics, Volume 5, 1972, pp 1422 - 1432.

[2] Larsen, H. L., G. Liping, and J. A. Bakken. "A numerical model for the AC arc in the silicon metal furnace." In Proc. INFACON, pp. 517-527. 1995.

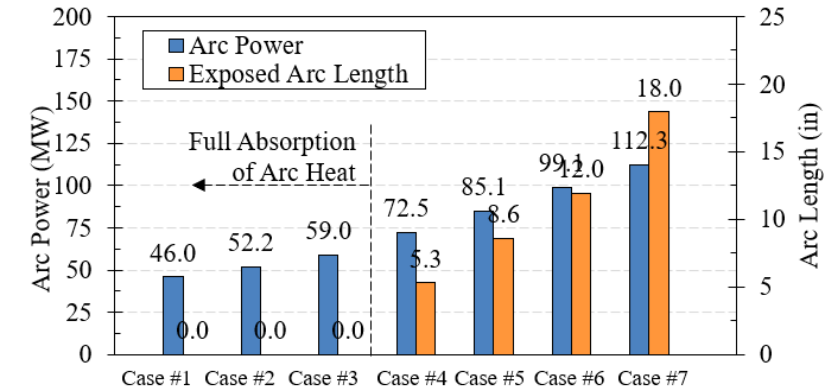
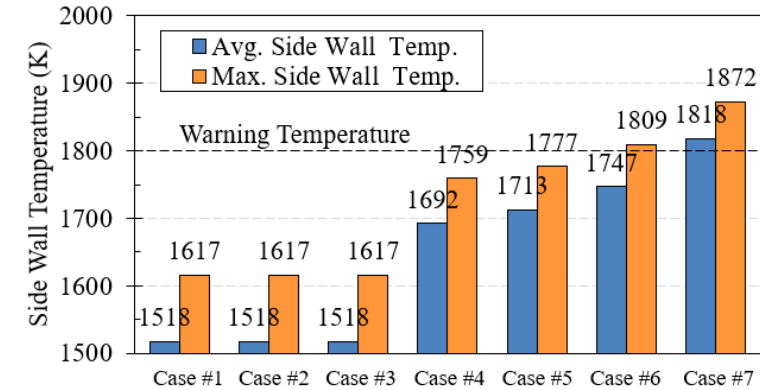
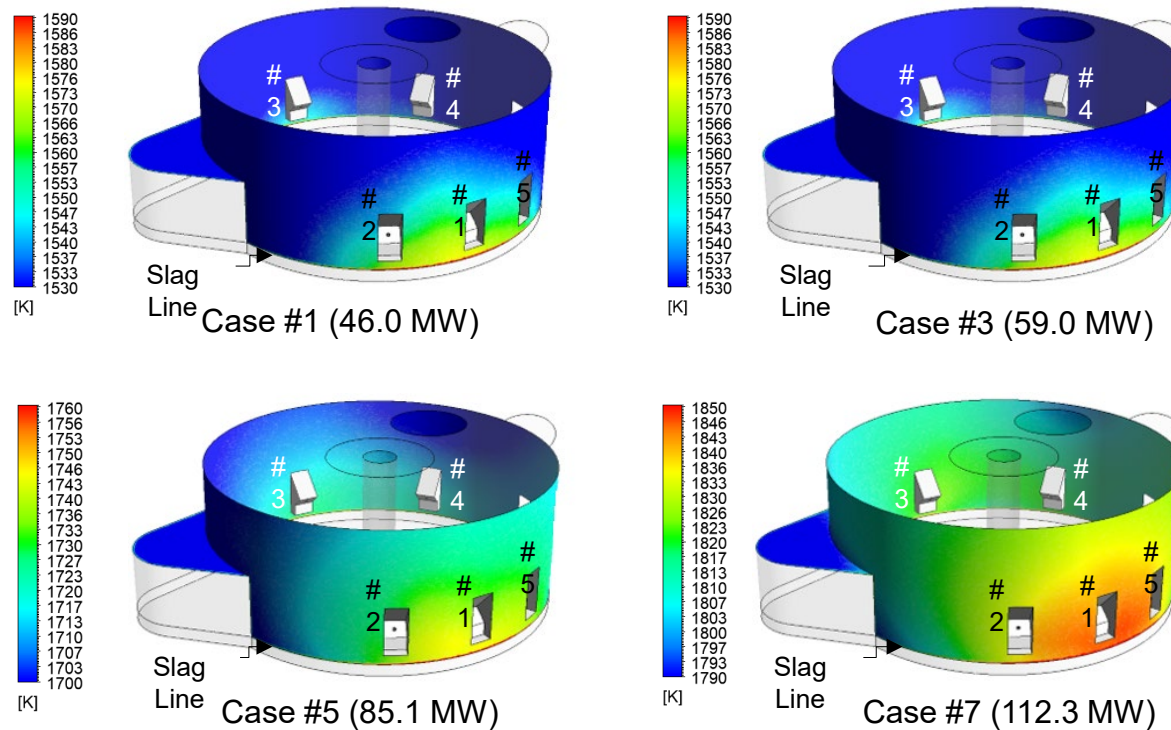
Scrap Heating & Melting Model

- **Objective:** to simulate dynamic scrap melting process
- **Methods:**
 - Dual-cell-based approach (scrap/HBI) + Eulerian approach (gas, liquid)
 - Stack approach for scrap/HBI collapse simulation
 - Exothermic carbon reactions in scrap/HBI
- **Unique features:** predict **dynamic scrap/HBI melting/re-solidification & collapse**



Example Application: Water Panel Overheating

- **Objective:** Address excessive side wall temperature issues for SSAB
- **Simulator:** Freeboard simulator (slag foaming + electric arc + coherent jet models)
- **Results:** ↑ arc power → arc exposure ↑ and potential of overheating occurrence ↑
 - Arc power < 59.0 MW → maximization of the arc heat absorption to slag/bath
 - Arc power > 85.1 MW → water panel overheating



Application: Scrap Melting in SSAB DC-EAF

➤ **Issues to be addressed:**

- Insufficient data showing melting performance collected during operation
- Limited optimization of layering and power parameters via trial and error

➤ **Objectives:**

- To provide a CFD database of industrial SSAB DC-EAF operations
- To develop AI/CFD – based reduced order models (ROM) for real-time prediction of melting profile, electrode position, and arc heating distribution

➤ **Industrial relevance:**

- Provide an AI tool for monitoring process operation
- Provide operators with real-time data for process optimization

➤ **Approach:**

- Conduct simulations using validated CFD model
- Using machine learning and CFD database to develop ROMs
- Investigate impacts of electrode power on melting performance using CFD results

CFD Simulation Conditions for SSAB Tap-to-Tap

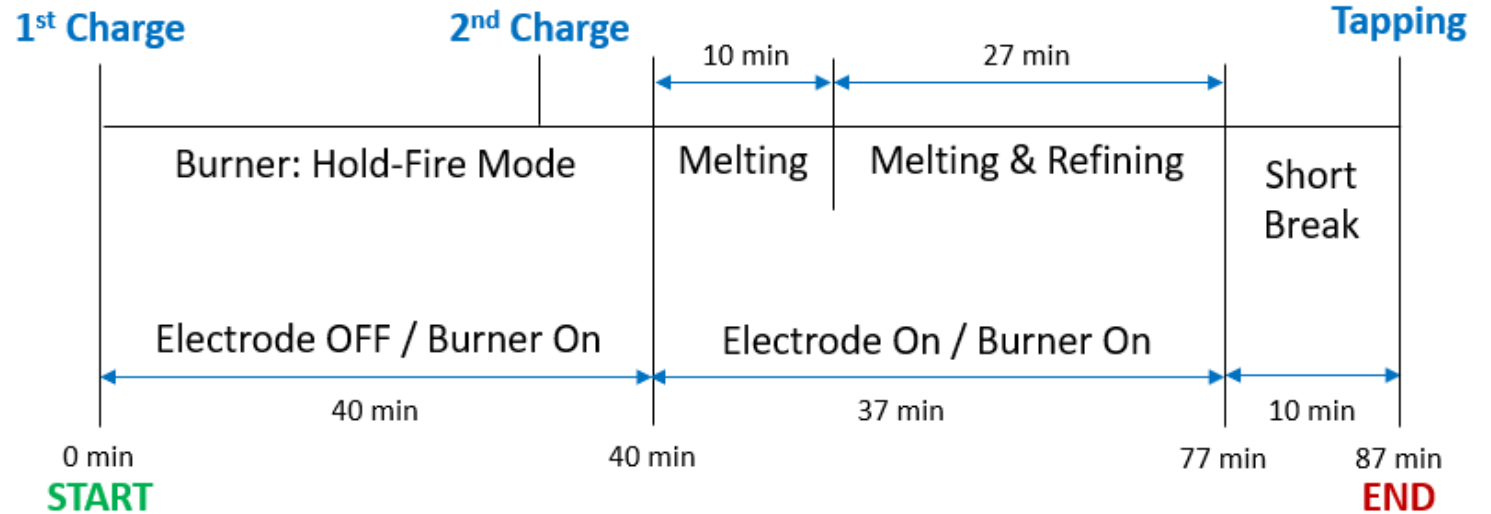
➤ Applied simulator:

- Pre-heating simulator
- Scrap melting simulator

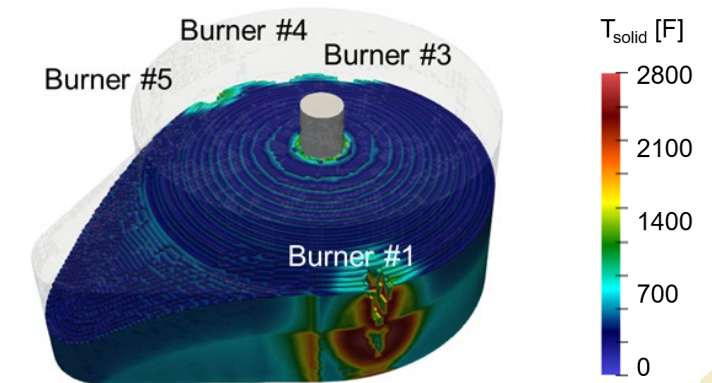
➤ Data provided include:

- Burner injection rates
- Charging recipe
- Electrode profiles

SSAB Tap-to-Tap Operation Timeline



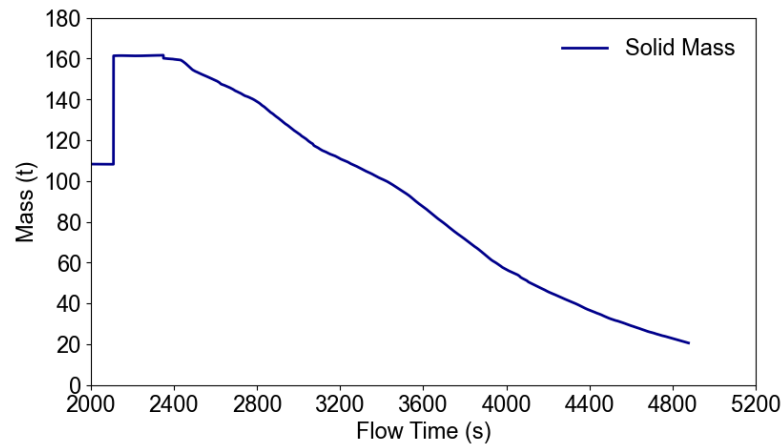
Burner Location



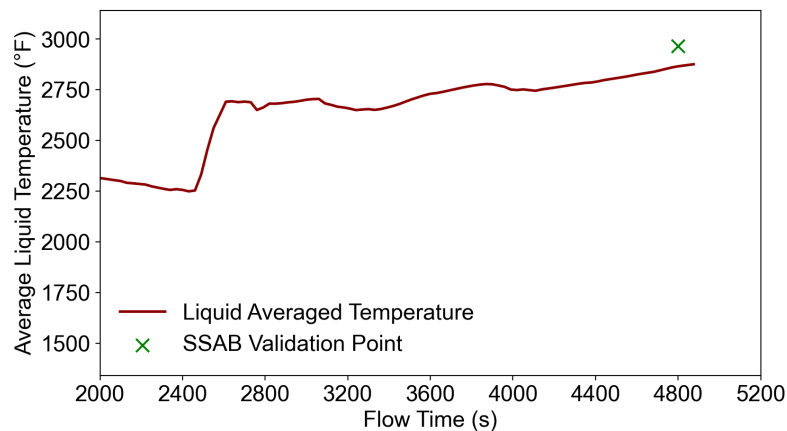
Operation Conditions			
Scrap Layering Condition	1st Bucket	8 Commodities	10.8 t
	2nd Bucket	1 Commodity	53.0 t
Burner Injection Parameter	Burner 1&3	Combustion + Lancing	
	Burner 4&5	Combustion	

CFD Validation: Good Agreement with Plant Data

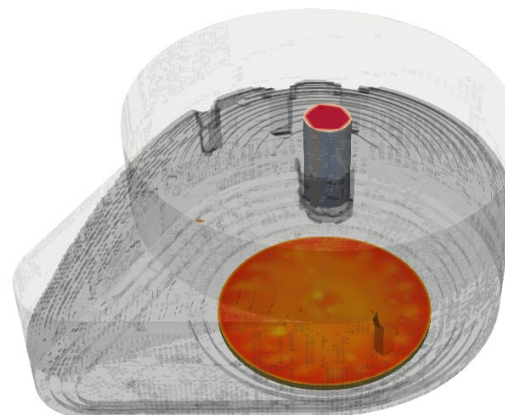
- Validation: compare CFD simulation results with plant actual data
 - Melting rate diff.~ **9.8%**, liquid temperature diff.~ **2.9%**
 - Modeled melting rate lower due to no arc shrouding for simulation stability



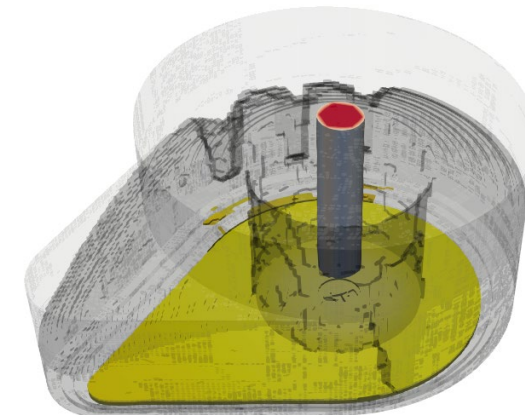
	SSAB	CFD	Difference
Melting Rate (kg/s)	65.3	59.1	-9.8%
Molten Steel Temperature (°F)	2963	2869	-3.2%



Time: 2390s



Time: 3070s



SSAB DC-EAF: Baseline Results

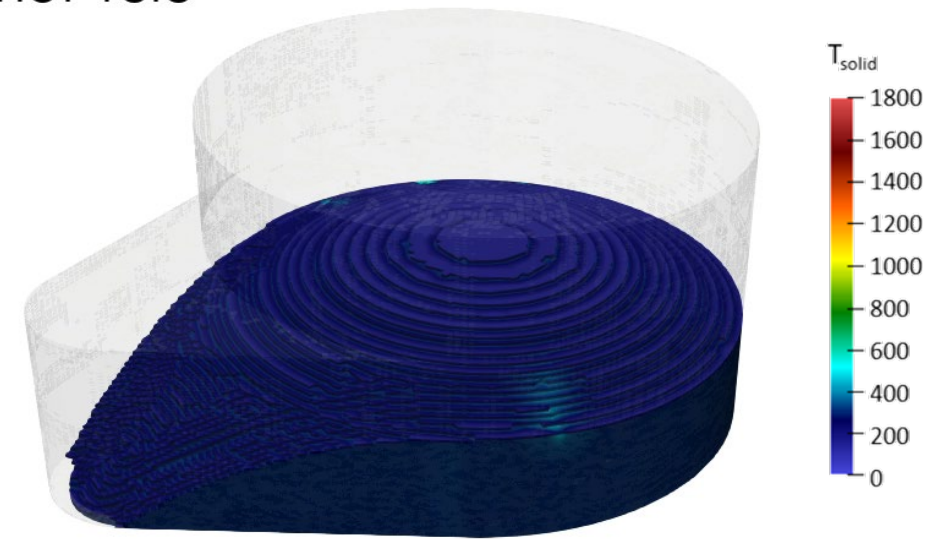
Hold-fire stage (40 min):

- High-temperature gas into freeboard after cavities formation
- Hold-fire stage increases volume fraction and scrap temperature of initial charge

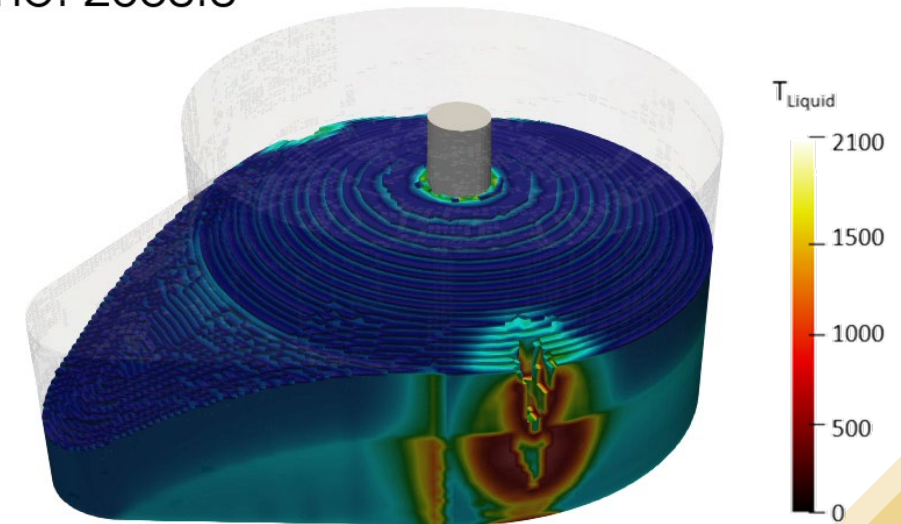
Melting stage (37 min):

- Bore-in: Re-solidification beneath the electrode
- Melting evolves from inside to outside & bottom to top

Time: 10.0



Time: 2360.0



Information per case		
Workstation (20c)	~2,000 hrs	40,000 CPU-hrs
Purdue Cluster (128c)	300 hrs	38,400 CPU-hrs
ORNL Cluster (128c)	200 hrs	25,600 CPU-hrs
Cases:		
• Parallel simulation of five scenarios at once		
• 1+ hr flowtime simulations for melting, heat transfer, combustion, & more		

CFD Results: The Impact of Power

15t of Scrap Melted

Case	100%	90%	80%
Operating Time(min)	3.8	3.9	4.1
Consumption(kwh/ton)	416.2	393.6	371.1

45t of Scrap Melted

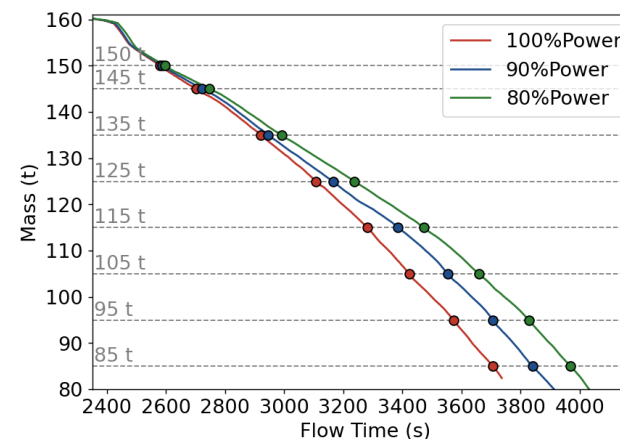
Case	100%	90%	80%
Operating Time(min)	12.6	13.6	14.8
Consumption(kwh/ton)	552.5	540.9	529.9

75t of Scrap Melted

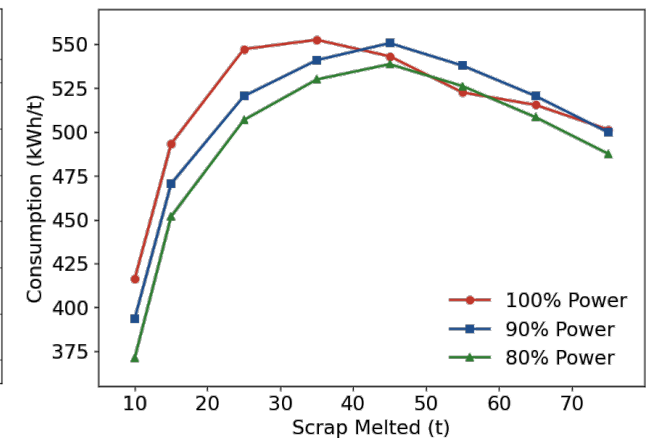
Case	100%	90%	80%
Operating Time(min)	22.6	24.8	27.0
Consumption(kwh/ton)	501.3	499.7	487.5

- Operating time shows a nearly linear increase with the amount of scrap melted
- After melting of 75 t scrap:
 - 80% power case → lowest specific energy consumption: 487.5 kwh/ton
 - 100% power case → fastest melting
 - time difference between cases ~2.2 mins

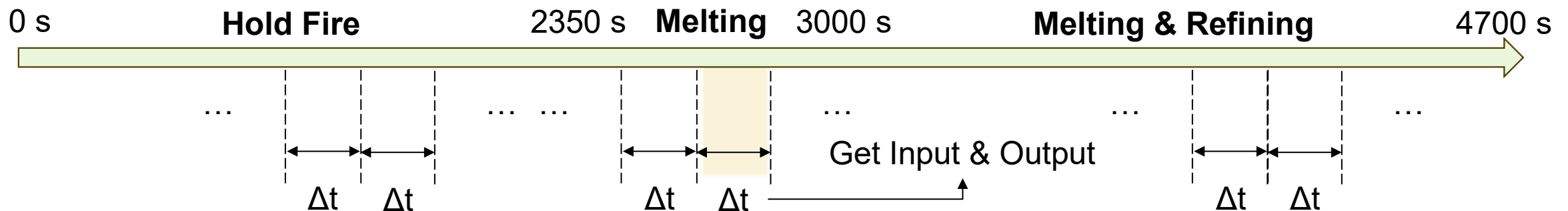
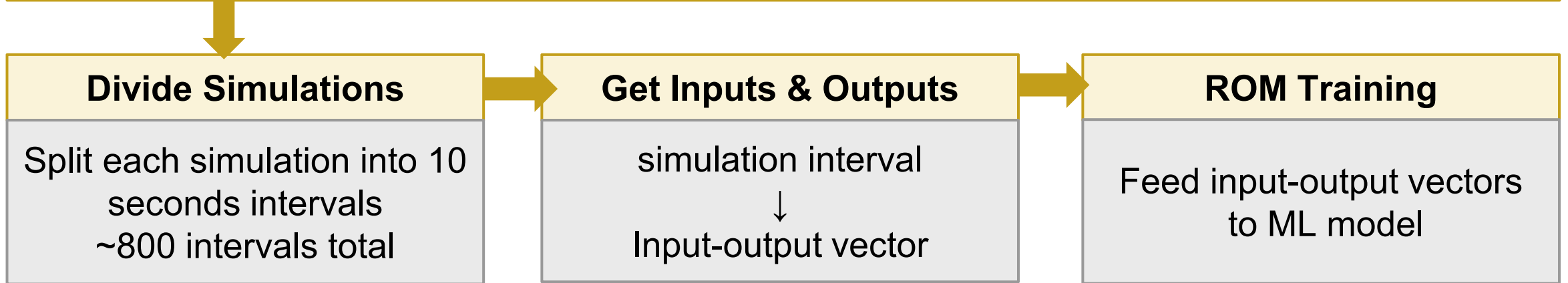
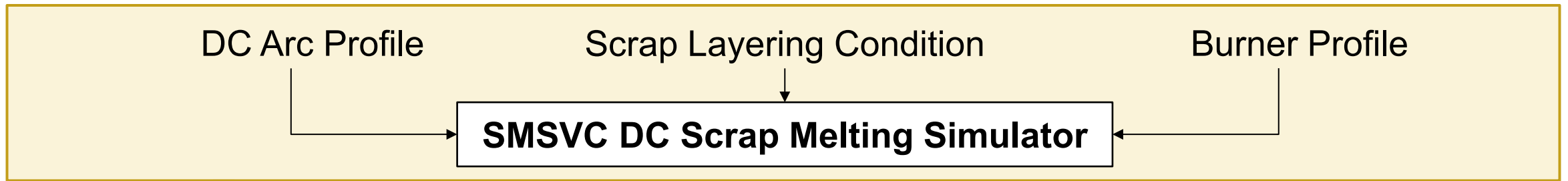
Scrap Melting Profile



Energy Consumption



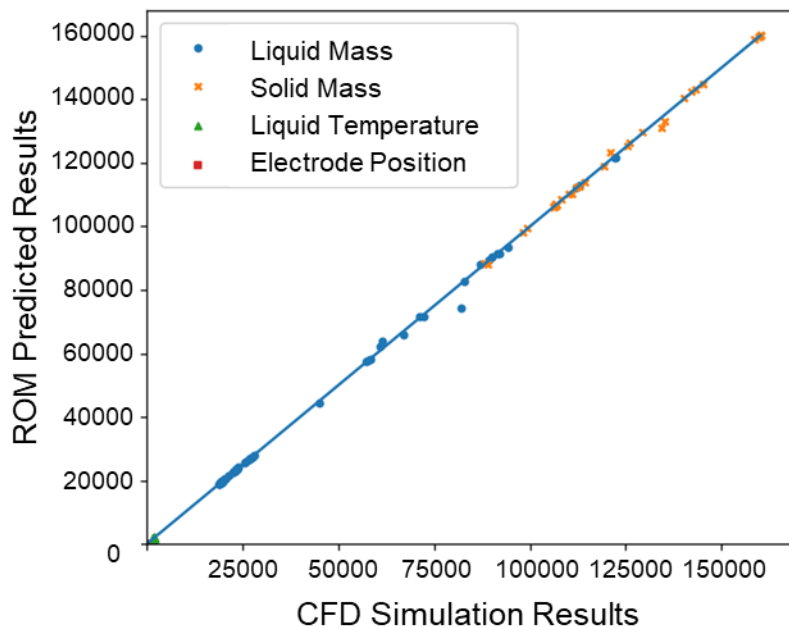
ROM Methodology: From CFD To ML



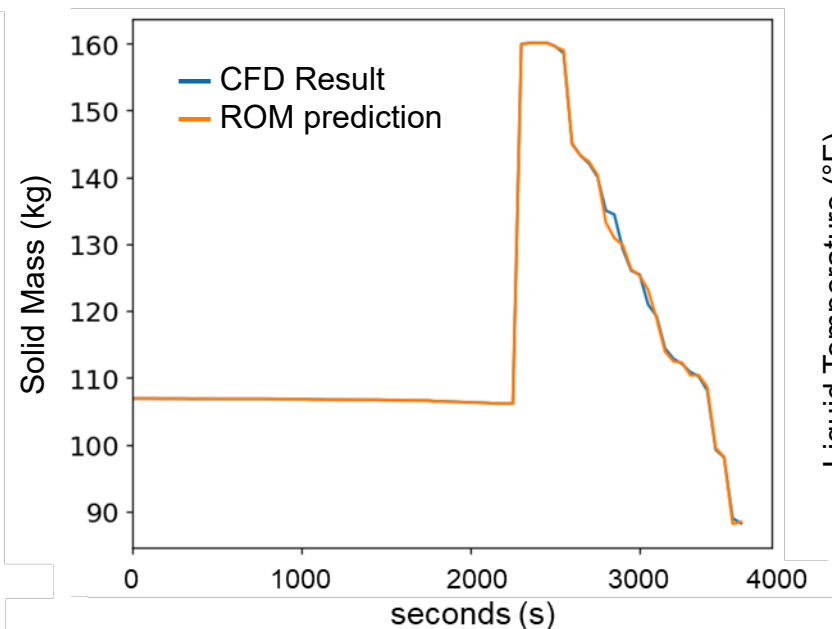
Reliable ROM Prediction for Baseline DC Case

- CFD and ROM predictions agree well using xgboost model
 - Training data: 80% Prediction: 20% (each case)
 - Predicted outputs: solid mass, liquid mass, liquid temperature and electrode position
 - Validation shows small difference between ROM and CFD results
- ROM significantly reduced computational time
 - CFD (3 weeks) vs. ROM (3 minutes)

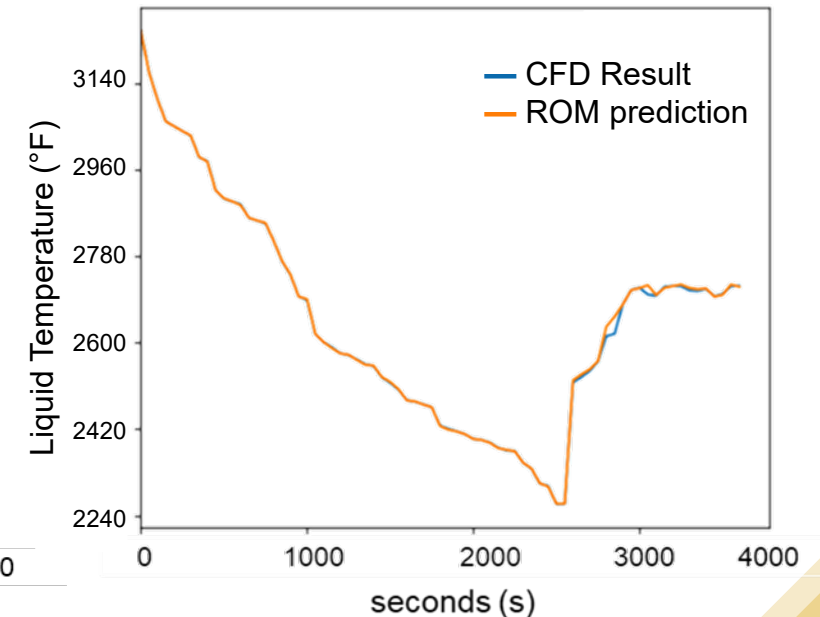
Validation: ROM Results vs. Simulation Data



Solid Mass: ROM vs. CFD

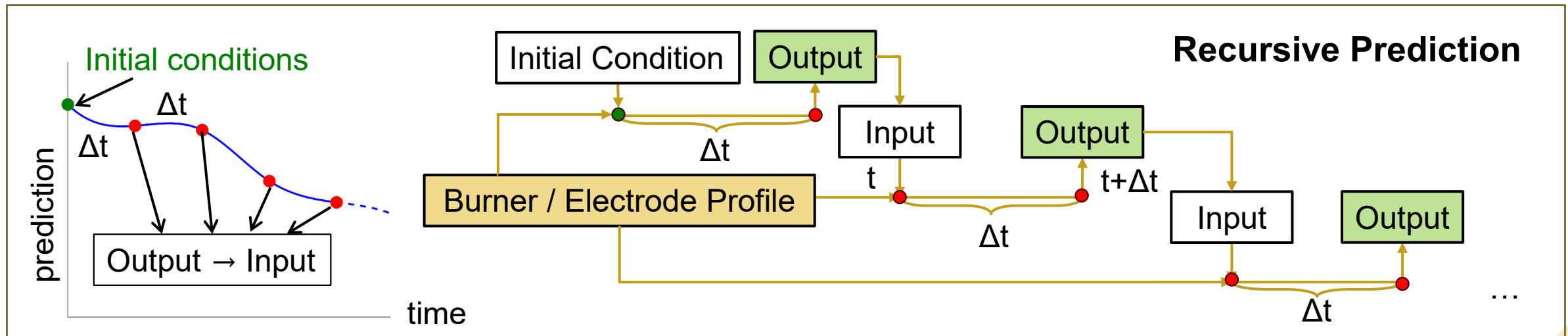
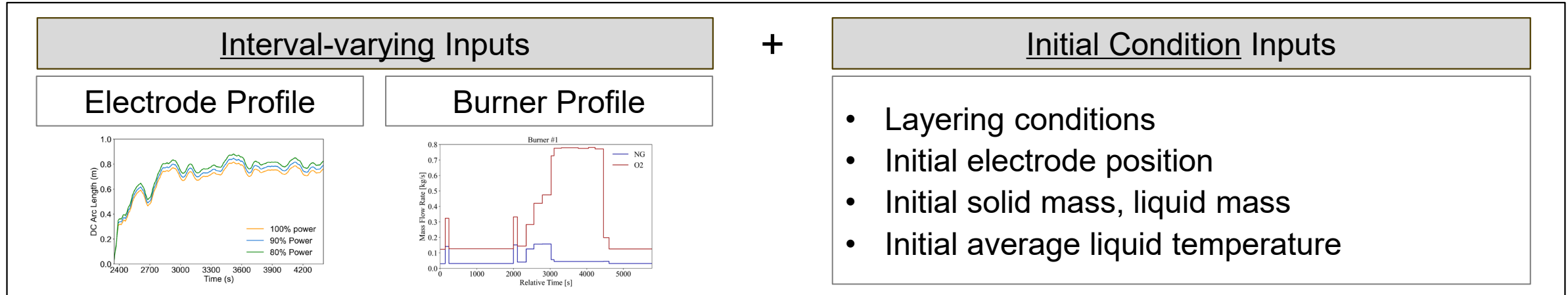


Liquid Temperature: ROM vs. CFD



Improved ROM: Recursive Prediction

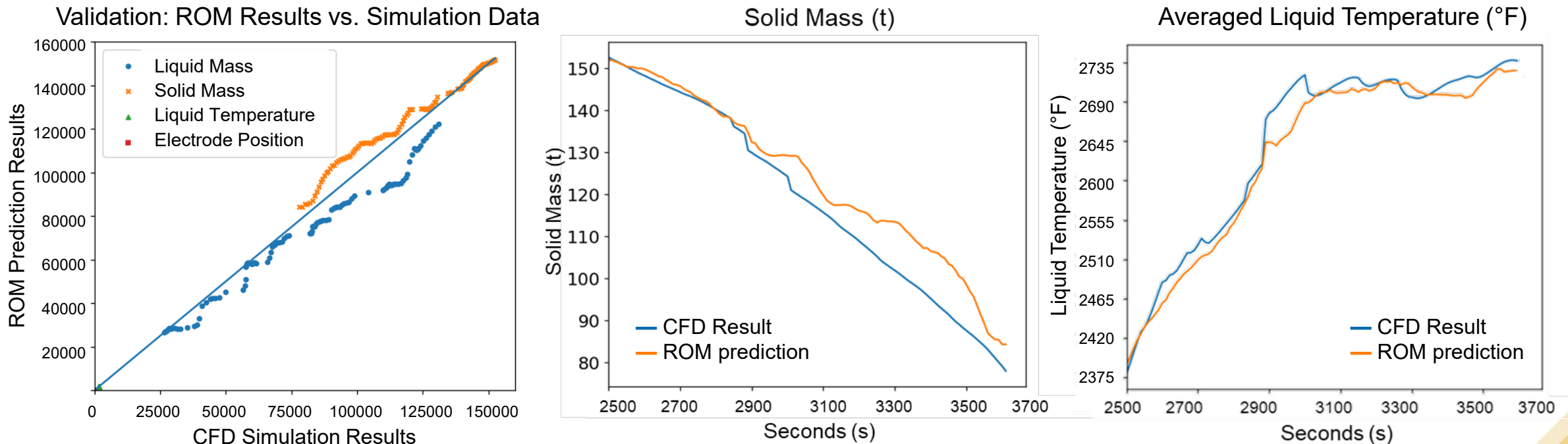
- **Objective:** To predict every tap-to-tap operation only with initial conditions, burner and electrode profiles with ML ROM trained by CFD database



Results of Recursive Approach

- Provide melting initial conditions + electrode/burner profiles (~2500s)
- Validation shows lower accuracy due to limited database
 - Add more CFD database to ROM training to improve the performance
 - Extending input/output variables can further enhance accuracy

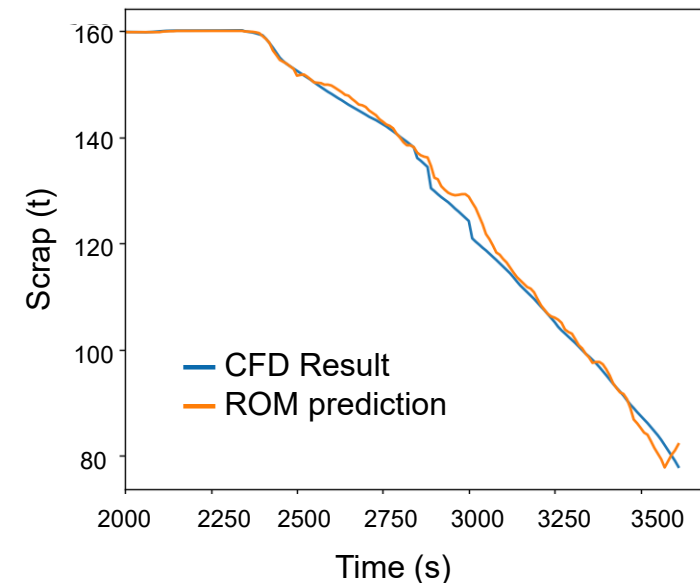
Results: ROM using recursive prediction (Start 2500s, T=1120s)



Conclusions & Summary

- Industrial DC-EAF operation conditions provided by SSAB
 - Good agreement between CFD results and plant data
 - Melting rate differs 9.8% and molten steel temperature differs 3.5%
- Impact of electrode power on melting performance determined
 - At 75 t of scrap melted, 10% less power extends melting time in ~2.2 min
 - At the same scrap amount, 80% power case has the lowest specific energy consumption: 487.5 kwh/ton
 - 100%-power operation: faster melting, slightly lower energy efficiency
- ML-based ROM developed based on CFD
 - Updated ROM → excellent prediction of heat
 - Recursive ROM → initial predictions align w/ trends
 - Next steps: ROM tuning w/ live data from industry
 - Proposed use of live electrode position to correct CFD-predicted values to aid ROM performance

Solid Mass (Plug Real Electrode Position each 200s)



Thank You

Acknowledgments

- Thanks to Sunday Abraham and Yufeng Wang in SSAB
- Thanks to SMSVC members
- Thanks to CIVS faculty, staff, and students
- Thanks to the HPC4EI program for supporting this project!

