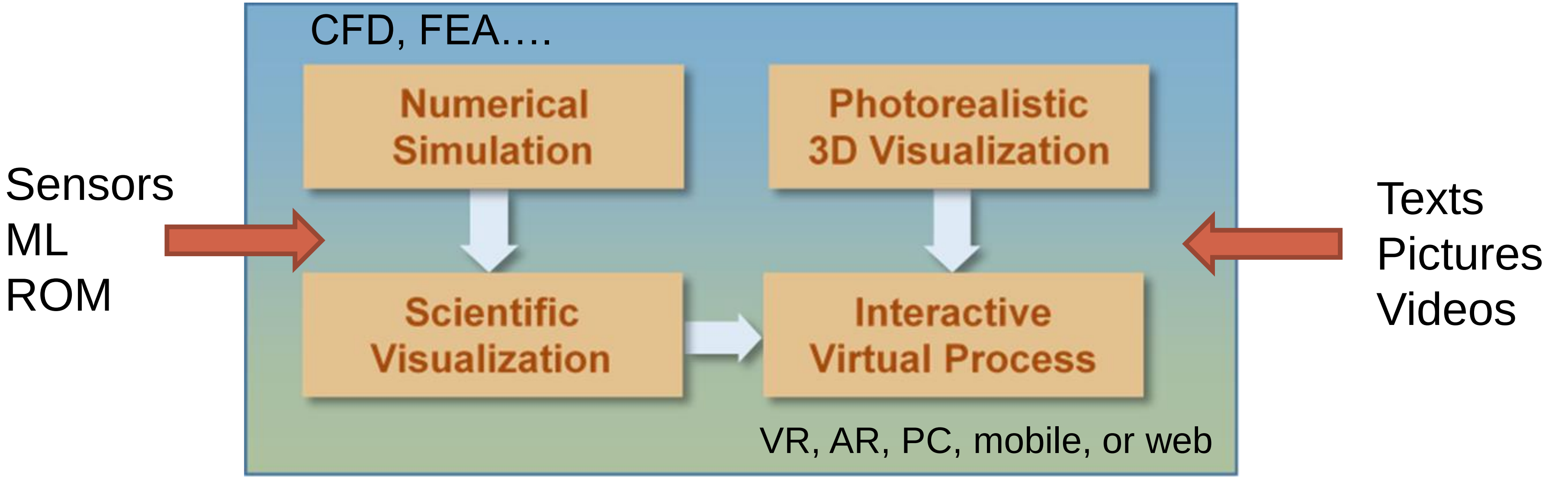
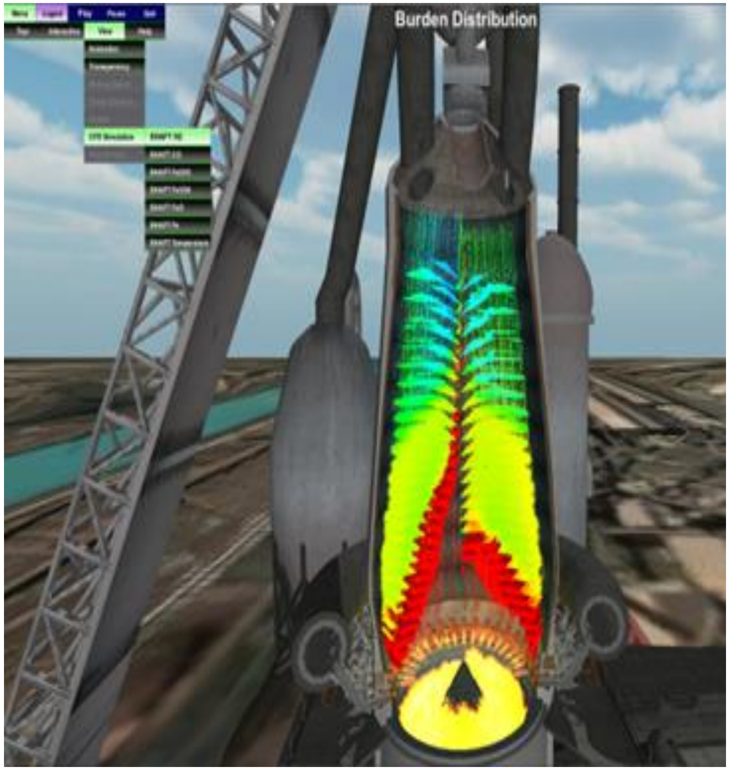
METHODOLOGY



- Section-by-section, Step-by-step, Integration
- Validation & verification
- 3-D interactive multiple platforms (immersive VR environment, AR, PC, mobile, or web versions)

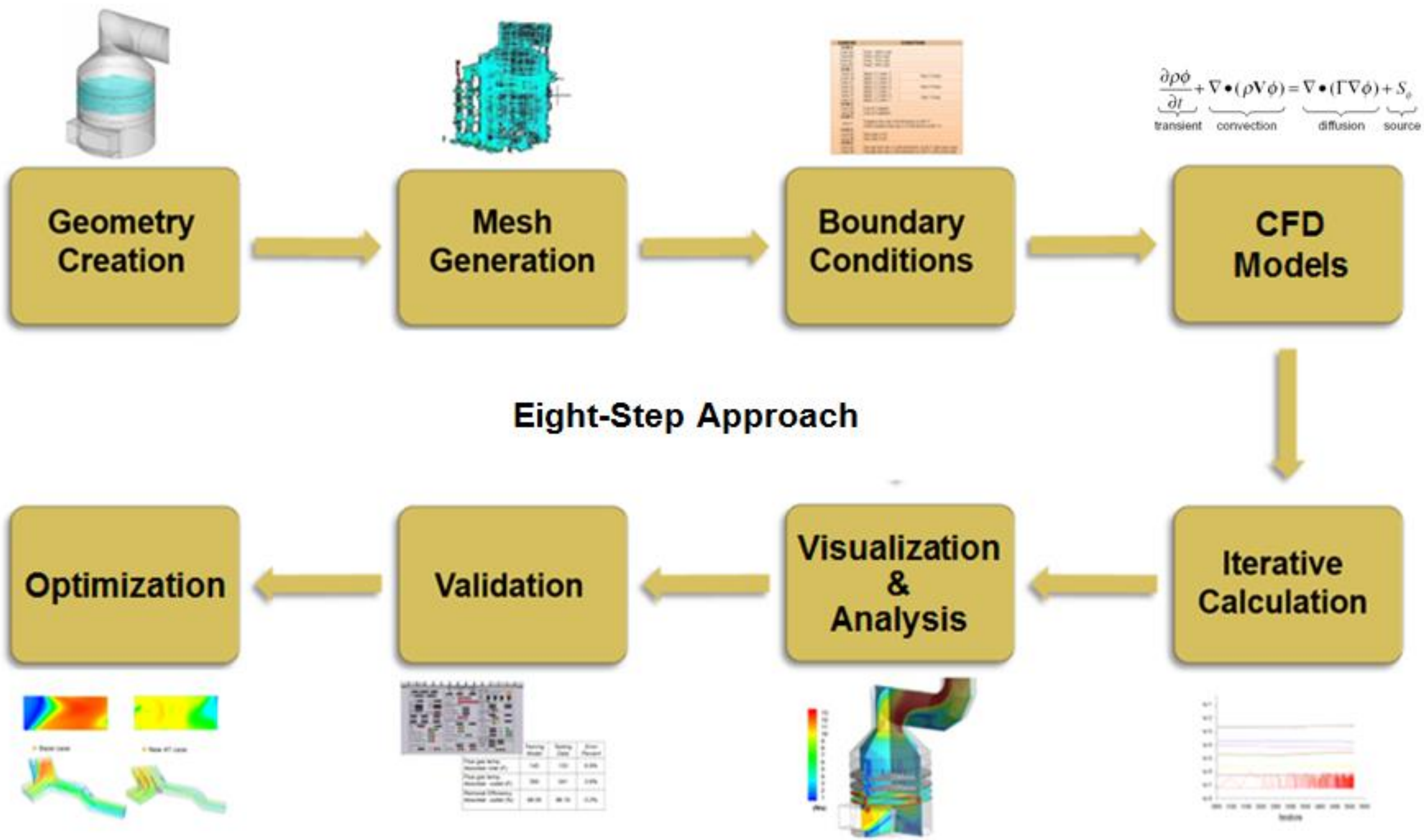
3D SIMULATION AND VISUALIZATION OF BLAST FURNACE

- **Issues:**
  - Furnace campaign life
  - Energy efficiency
  - Pollutant emissions
  - Furnace downtime
  - Training
- **Outcome (since 2002):**
  - Virtual blast furnaces
  - Copyrighted software packages
  - Multimillion dollars savings
  - Significant downtime reductions
  - Best Paper awards



Collaborators: *AISI, AIST, ArcelorMittal USA, ArcelorMittal Dofasco, AK Steel, Stelco, Tata Steel U.S. Steel, and Union Gas*

COMPUTATIONAL FLUID DYNAMICS (CFD)

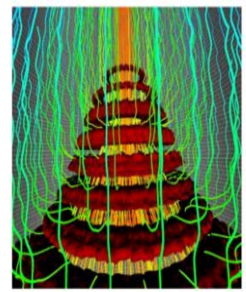


3-D BLAST FURNACE MODELS

Comprehensive 3-D Blast Furnace CFD Models

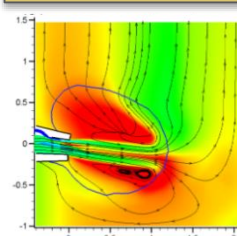
- 3D CFD software packages
- Graphic User Interfaces (GUI)
- VR visualization

Shaft



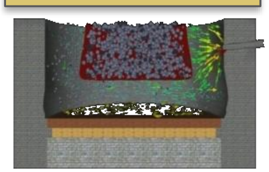
- Flux Reaction
- Cohesive Zone
- Coke Gasification
- Ore Reduction
- Interphase Heat Transfer

Raceway & Combustion



- Fuel Lance/s & Tuyere
- Raceway Size/Shape
- Combustion

Hearth

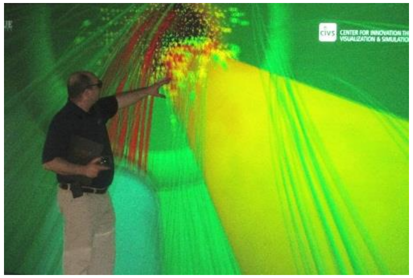


- Flow and Heat Flux
- Erosion
- Liquid Level

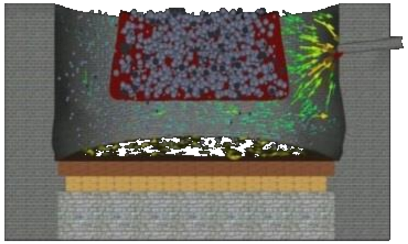
BLAST FURNACE CFD MODELS

- **Shaft Model:**
  - Burden distribution
  - Chemical reactions
  - Iterative method for cohesive zone shape and location
  - Iterative method for coke rate

- **PCI-Raceway Model :**
  - Multiphase reaction turbulent flow
  - Iterative method for raceway shape
  - Coal combustion (devolatilization, surface combustion)
  - Coke combustion (kinetic/diffusion model)
  - Gas combustion (eddy dissipation model)
  - P1 radiation model

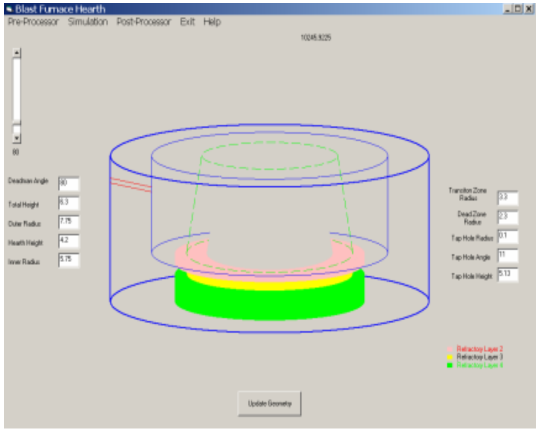


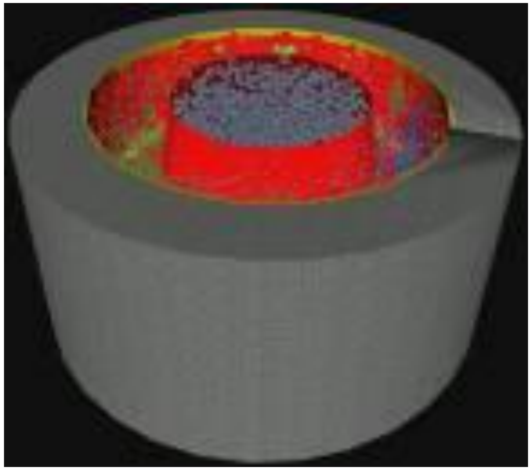
- **Hearth Model:**
  - Coupled CFD with inverse Heat Transfer for Skull/Erosion Profile
  - Conjugate heat transfer
  - Real geometry (skulls, refractories, ram, shell…)
  - Variable properties
  - Liquid Level



CFD HEARTH MODEL

- Features
  - GUI preprocessor
  - 3-D
  - Real geometry including deadman, blowing layer, skulls, refractories, ram, and shell
  - Velocity, pressure, species, hot metal and refectory temperatures
  - Inner profile
  - Liquid level and tapping
  - VR visualization





METHODOLOGY

3-D CFD model

Hot face temperature

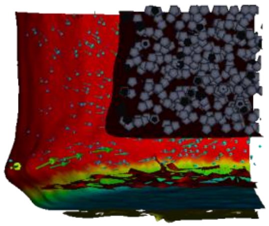
1-D heat transfer model

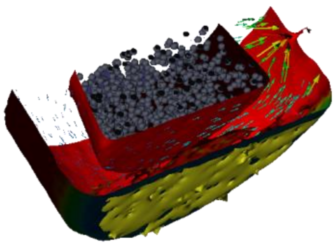
Inner profile

Predicted TC temperature

Inner profile

1-D fine tuning model

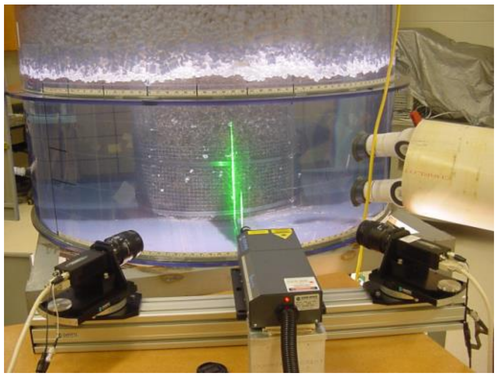


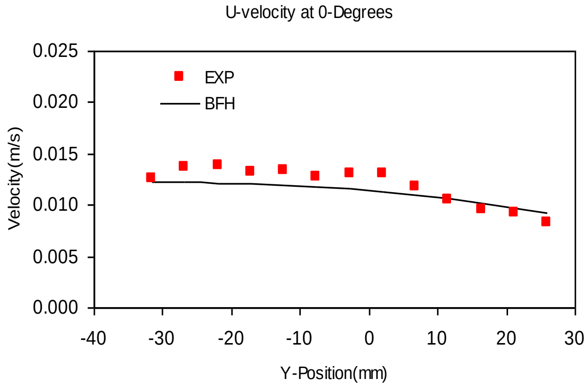


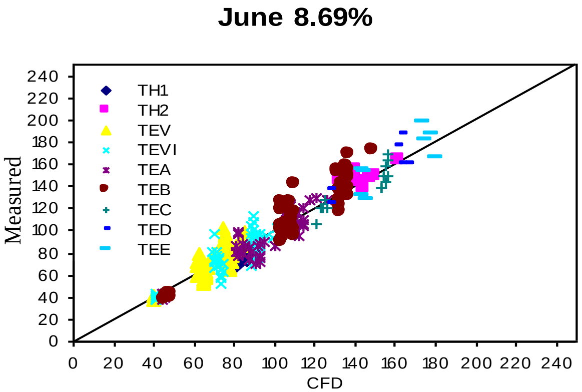
VALIDATIONS

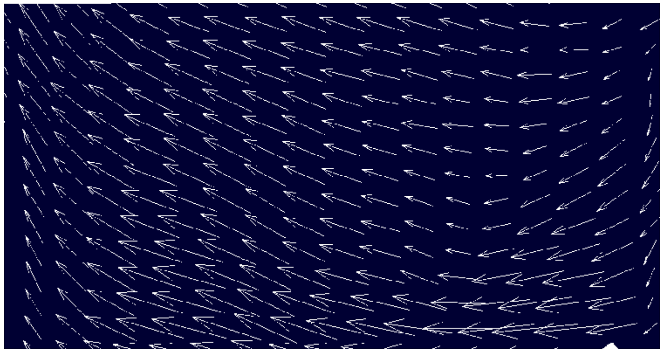
- CFD results were compared with the following measured data:
  - Velocity and streamlines 1/10th scale water model at PUC
  - Species distribution in a 1/50th scale warm water model at PUWL
  - Refractory temperatures of the Mittal No. 7 blast furnace (both old and new geometry)
  - Refractory temperatures of the US Steel No. 13 blast furnace

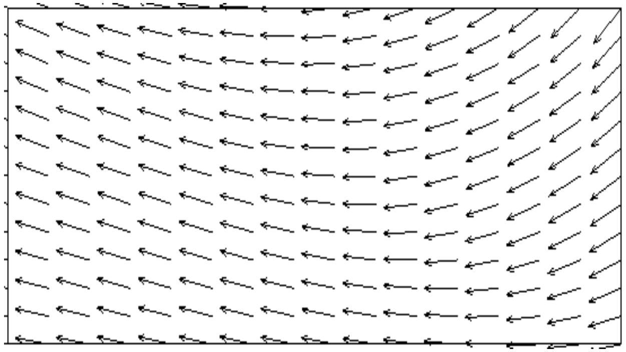
EXAMPLES OF VALIDATIONS





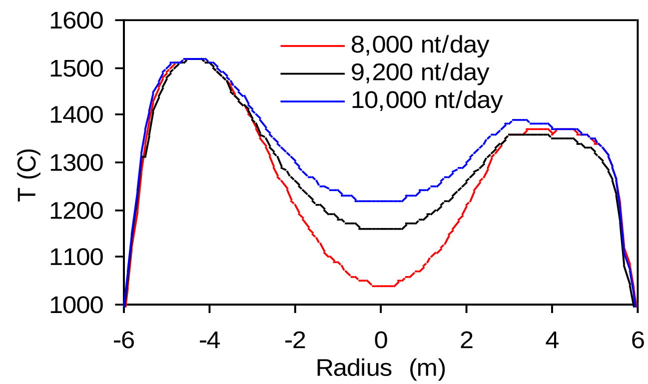


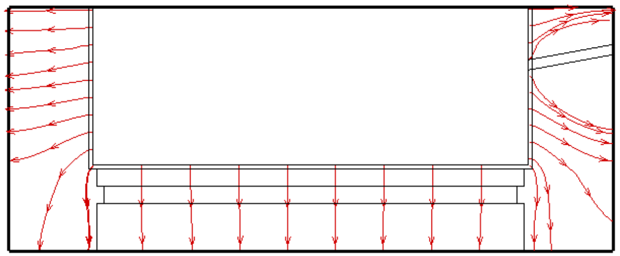


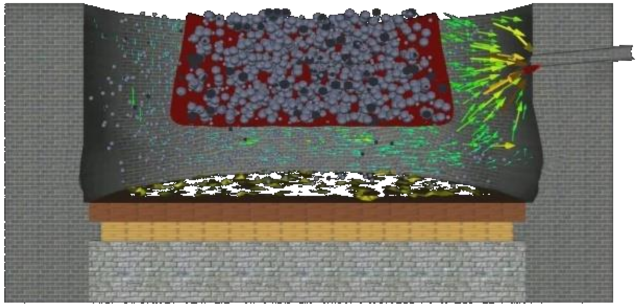


USE OF CFD HEARTH MODEL

- Visualize flow patterns
- Predict inner profiles
- Design monitoring systems for refractory temperatures
- Investigate the impacts of operating and geometrical conditions on the campaign life of hearth
- Troubleshooting
- Design new furnaces

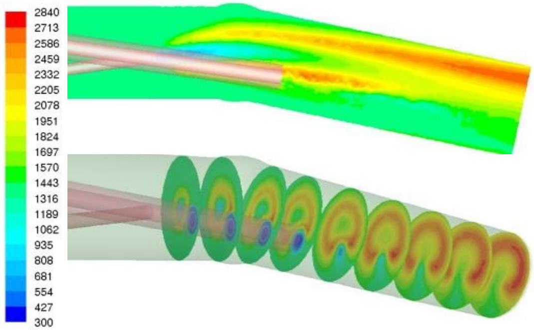


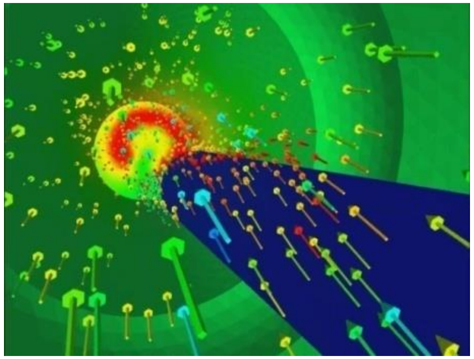




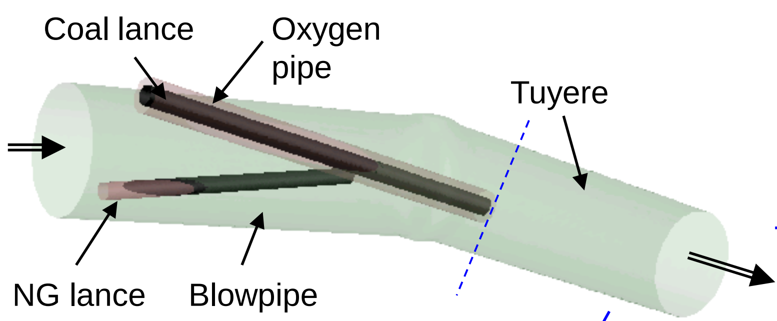
BF RACEWAY CFD MODEL

- **CFD Raceway Models:**
  - Lance
  - Raceway
  - Combustion
- **Recommendations :**
  - Strategies for high PCI & CH_4 rate
  - Guidance for lance design and protection
  - Solutions for troubleshooting
  - Evaluation of new alternative fuel injections

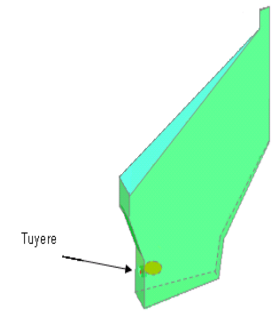




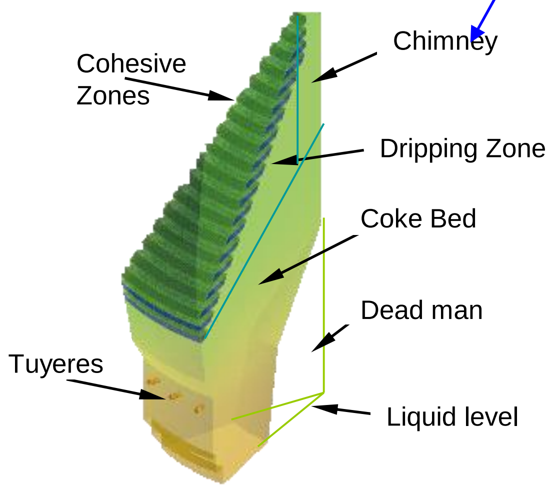
METHODOLOGY

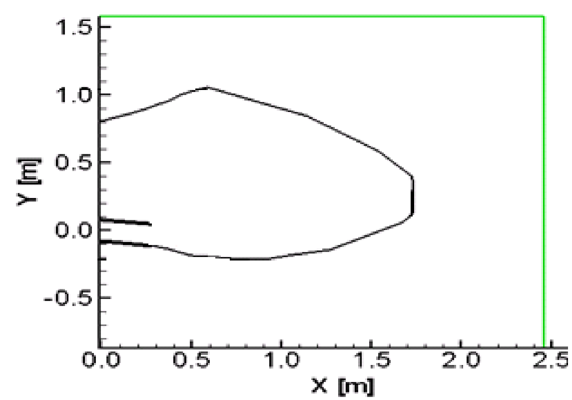


(a) Simulation of NG+Coal inside a tuyere



(c) Schematic of Raceway combustion

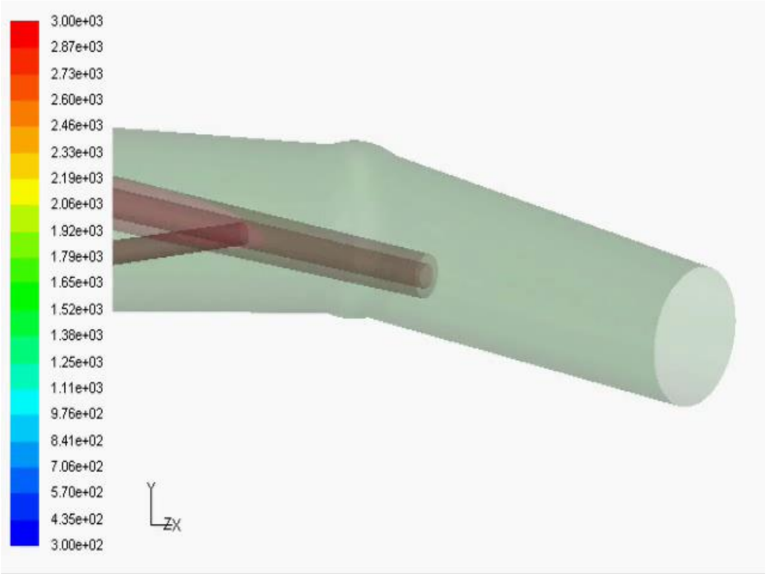




(b) Obtain the raceway shape and size

LANCE AND TUYERE

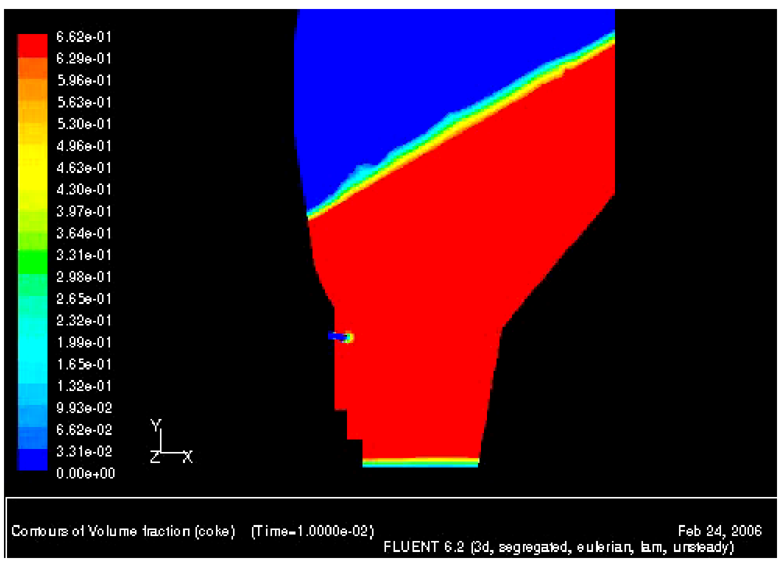
- Fluent is used
  - 3-dimensional, Turbulent
  - Heat transfer
  - Multiphase flow
  - Multispecies reactions
  - Coal combustion
  - Natural gas co-injection
  - Oxygen enrichment

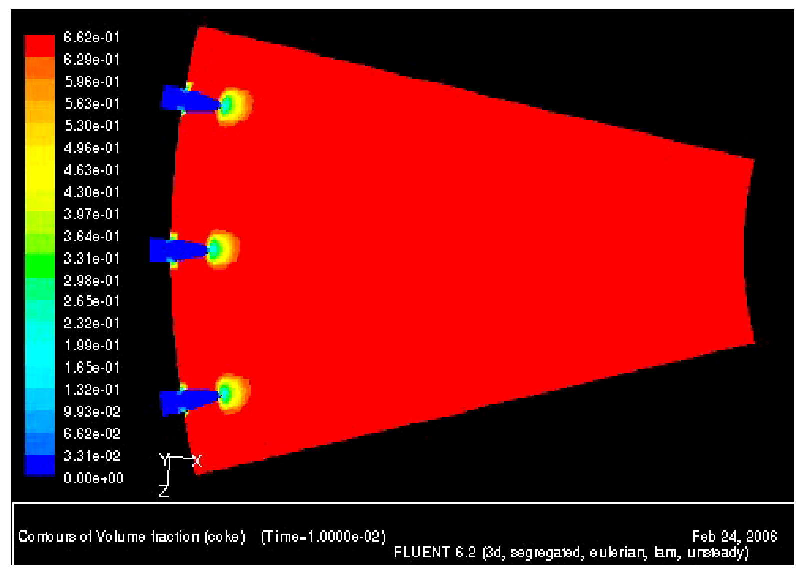


- Cases studied for
  - Coal devolatization in the lance; Effects of PCI rate, PCI carrier gas flow rate, Oxygen lance flow rate, and blast air temperature, etc; Lance arrangements; Maximize PCI rate; Lance failure; Tuyere failure, etc.

RACEWAY FORMATION KINETICS

- Fluent is used
  - 3-D transient gas-particle flow simulations
  - Eulerian approach
  - A multi-fluid granular model is used to describe the flow behavior of the fluid-solid mixture.



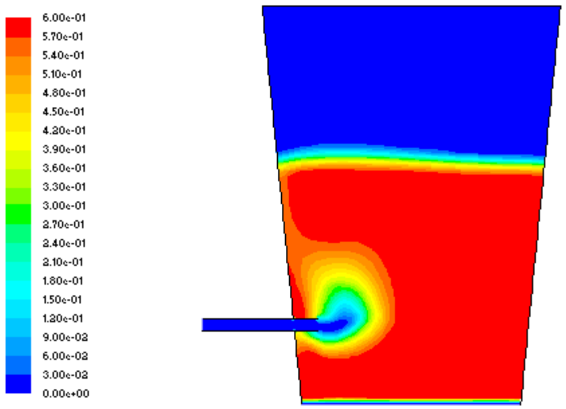


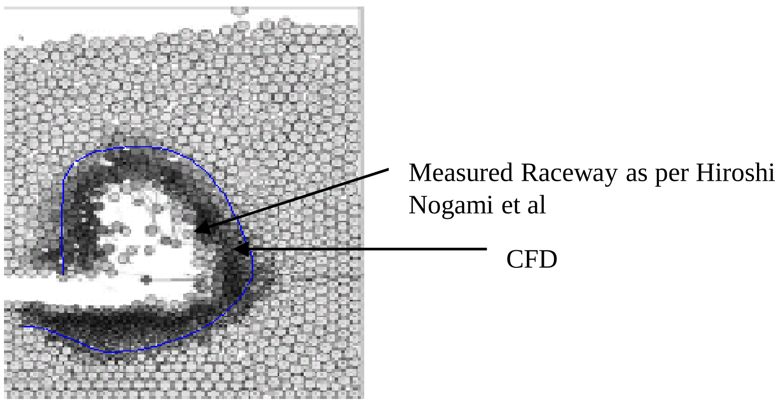
RACEWAY COMBUSTION

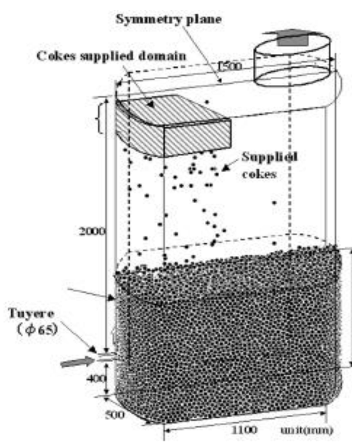
Main Features of In-House CFD Code

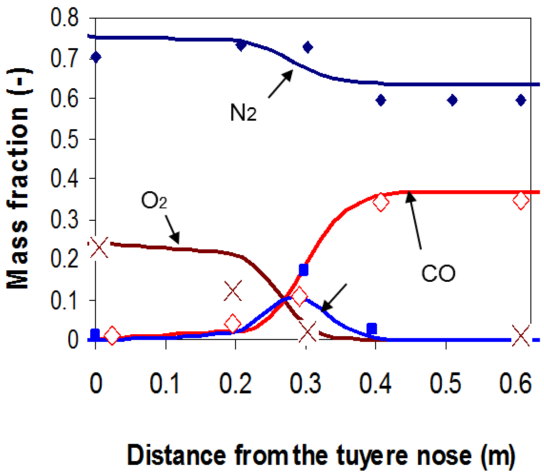
- 3-dimensional
- Turbulent
- Multiphase flow (gas, pulverized coal, and coke particles)
- Heat transfer
- Multispecies reactions
- Coke combustion
- Coal combustion (moisture evaporation, volatilization, Char combustion)
- Natural gas co-injection
- Coke combustion rate
- Natural gas combustion rate

VALIDATION



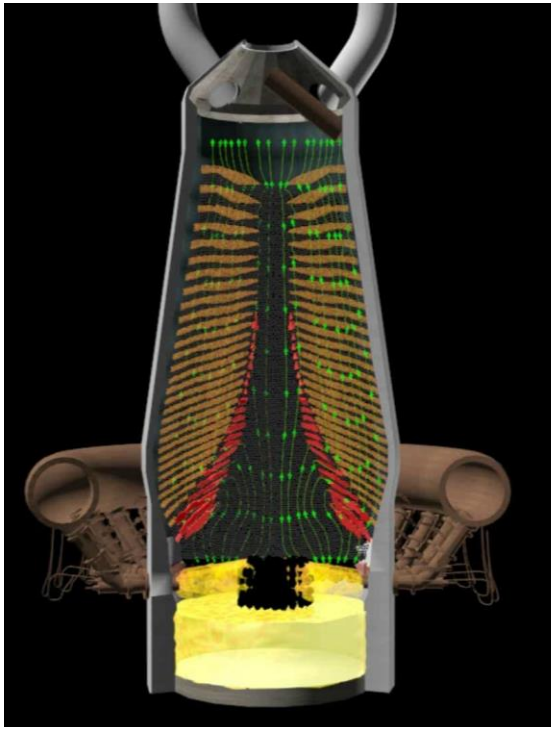




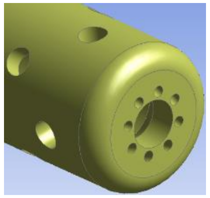


❖ "Raceway design for the Innovative Blast Furnace", Hiroshi Nogami, Hideyki Yamaoka, Kouji Takayani, ISIJ 2004.

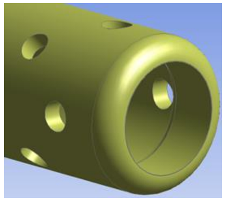
Example: High Rate Natural Gas Injection in Blast Furnace



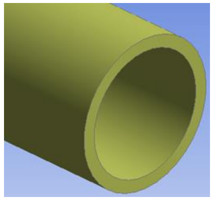
- **Issue:**
  - Unstable operation at both full and low production with high natural gas injection.
- **Outcomes:**
  - Established good practice of natural gas lance selection to better suit the furnace production rate.
  - Stable and controllable operation.
  - Eliminated production loss caused by high blast pressure at full production rate.



Fast Lance

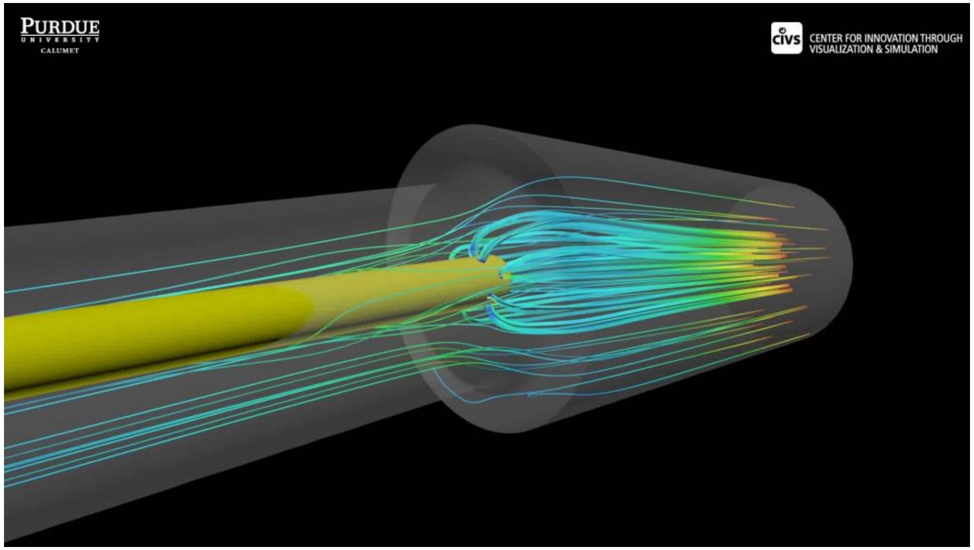


Bored Lance

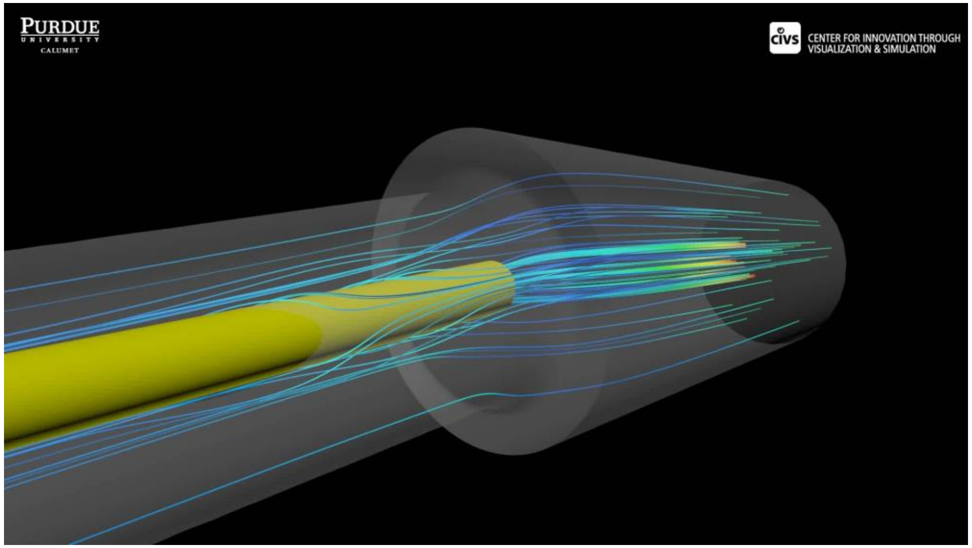


Straight Lance

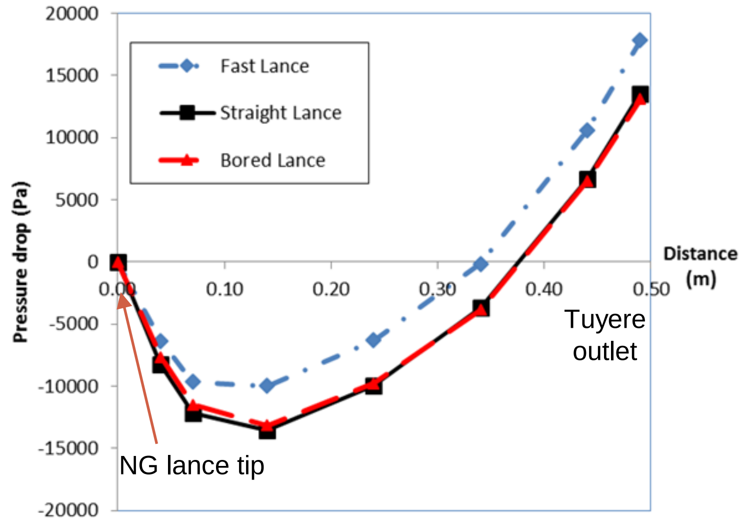
Collaborators: John D'Alessio, U.S. Steel Canada



Fast Lance



Straight Lance

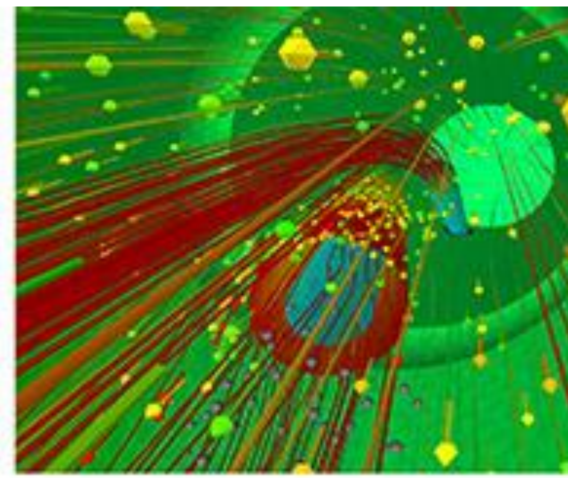


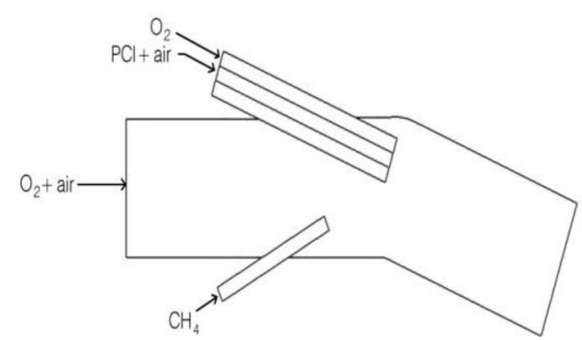
Pressure Drop Across Tuyere

	High Production	Low Production
Fast Lance	**Unsuitable** ▪ Pressure drop too high for stable operation ▪ Plant cannot supply enough wind to maintain high production	**Suitable** ▪ Increased combustion provides higher tuyere velocity ▪ Helps to avoid the practice of tuyere plugging
Straight or Bored Lance	**Suitable** ▪ Plant can supply enough wind due to the lower pressure drop	**Unsuitable** ▪ Tuyere velocity too low due to reduced combustion

Example: Troubleshooting Blast Furnace PCI Lance

- **Issues:**
  - Lance failures
  - Lance performance
- **Outcomes:**
  - Significant downtime avoidance by half due to fewer lance failures
  - A coke rate savings of 15 lbs./NT hot metal was realized
  - $8.5 million per year cost savings





Collaborator: John D'Alessio, U.S. Steel Canada

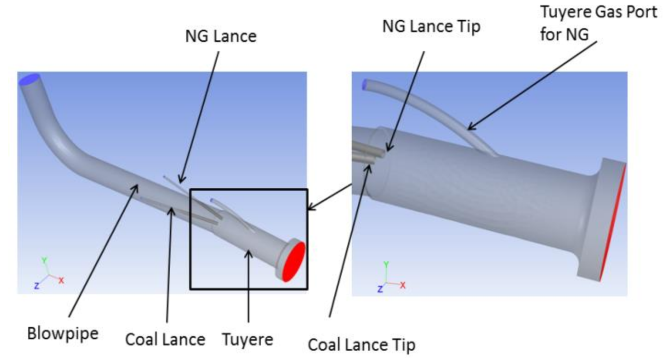
Example: ArcelorMittal Dofasco Case

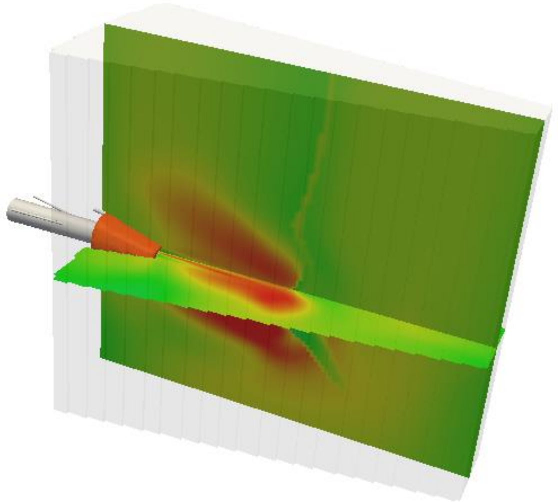
Objective:

- To increase coal combustion efficiency
- To optimize NG injection location and rate

Outcomes:

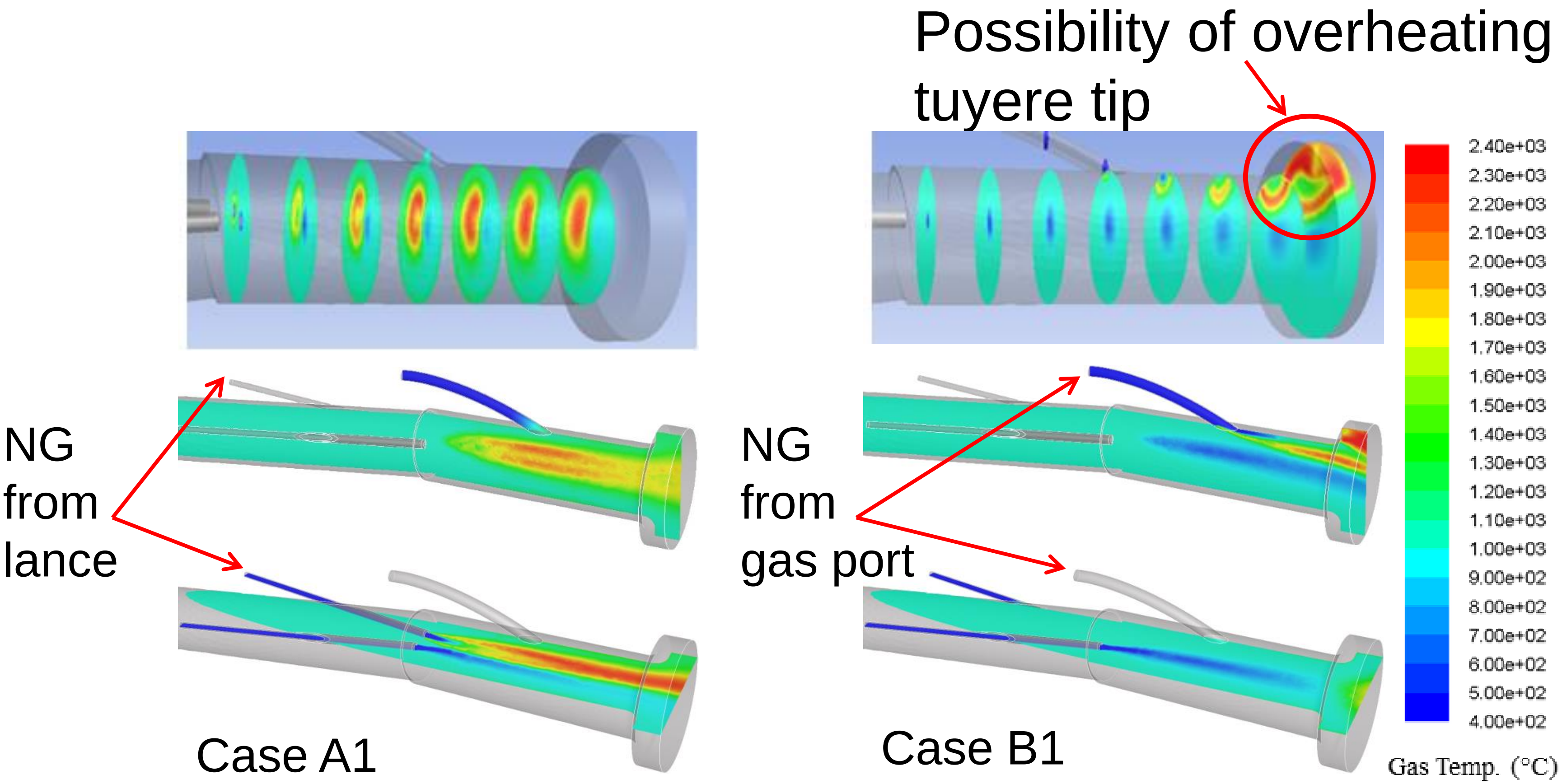
- Parametric effects on coal combustion efficiency with 11 cases
- Recommended NG injection configurations and injection rate





Collaborator: Dave Pomeroy, ArcelorMittal Dofasco

Effects of NG Injection Location on Gas Temperature



Effects of NG Injection Location and Rate on Coal Burnout

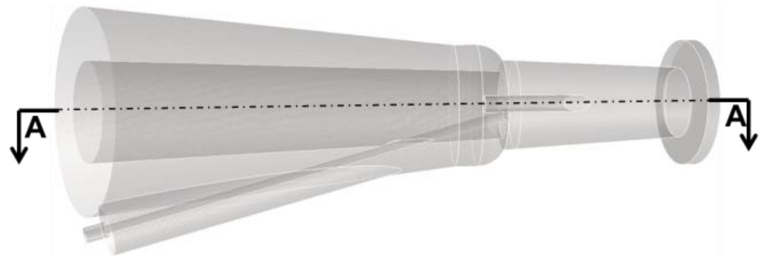
Case	**NG from Lance**	**NG from Gas Port**	**Coal Combustion Efficiency**
A1	R_{NG}	0	**80.5%**
A2	$1.5 \times R_{NG}$	0	**85.0%**
A3	$2.0 \times R_{NG}$	0	**90.1%**
B1	0	R_{NG}	**78.9%**
B2	0	$1.5 \times R_{NG}$	**78.6%**
B3	0	$2.0 \times R_{NG}$	**79.8%**
Note: Coal Combustion Efficiency is the total coal burnout percentage in raceway			

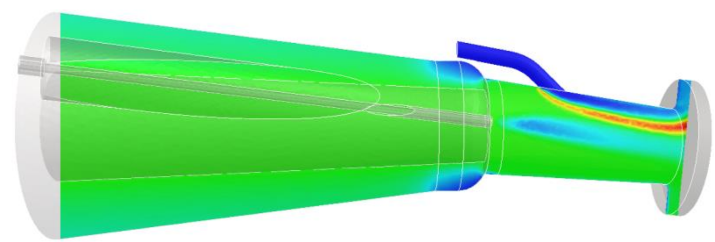
- The coal combustion efficiency increases **when the NG is injected from the lance**
- As rate of NG from lance increase, the total coal burnout increases

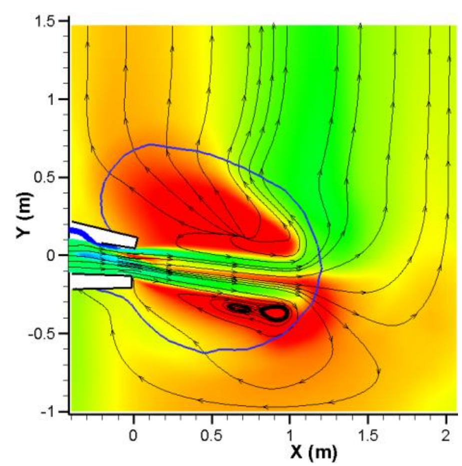
Example: Co-Injection of NG and PCI

- **Issue:**
  - Need efficient replacement rate of coke by PC and NG
  - Improve combustion efficiency of injected fuels

- **Outcome:**
  - Identified improvements in combustion efficiency
  - Possible enhancement of production by 2.5% if implemented



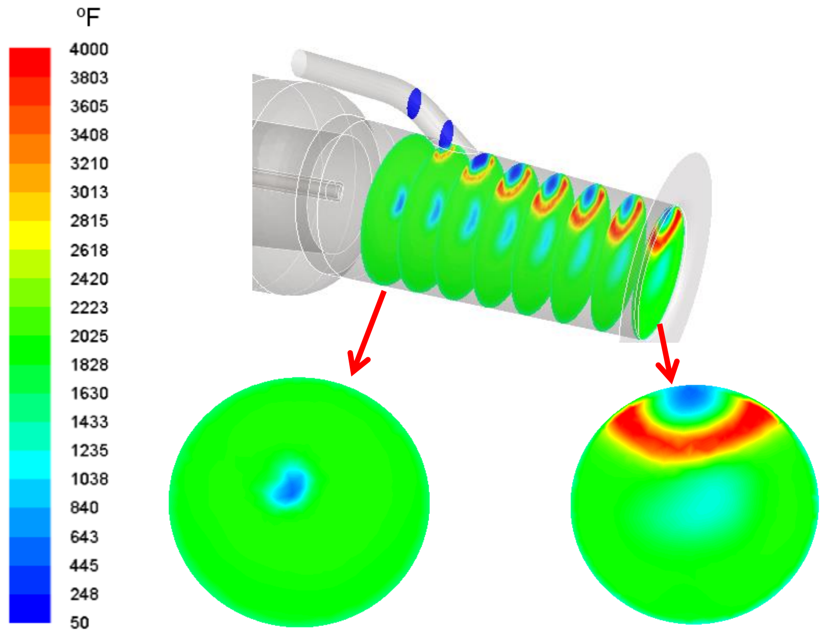




Collaborators: Stuart Street, AK STEEL
(Former SEVERSTAL, Dearborn)

Results & Discussion

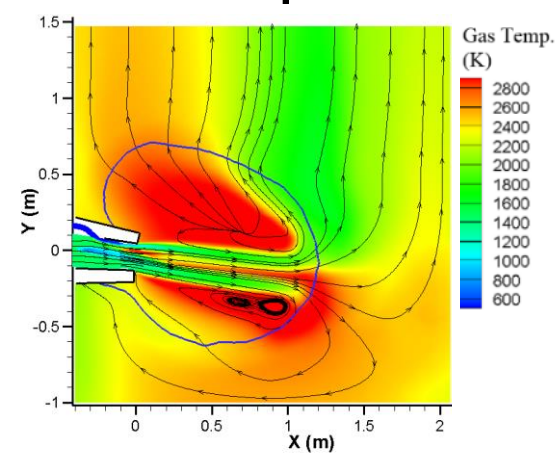
- Unexpected explanation for industrial failures
  - NG combustion in tuyere near upper wall
  - High thermal stress and wear



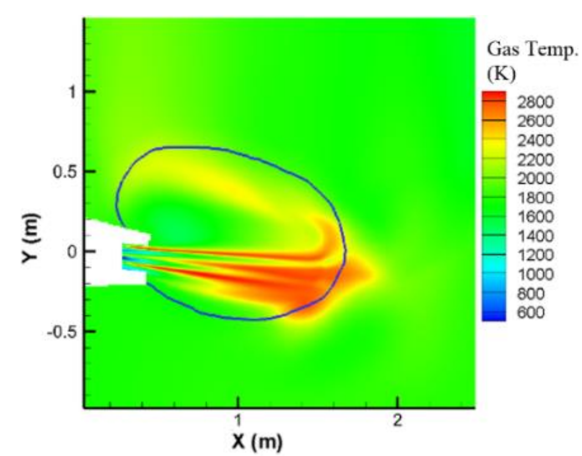
Example: Testing Unplanned Loss of PCI

- **Issue:**
  - Co-injection blast furnace loses PCI capability for one of a number of reasons
  - To maintain production, pure NG operation is required
- **Outcome:**
  - Examined the impacts of a switch to pure NGI
  - Potential avenues for higher NGI rates highlighted (preheating)

Standard Operation



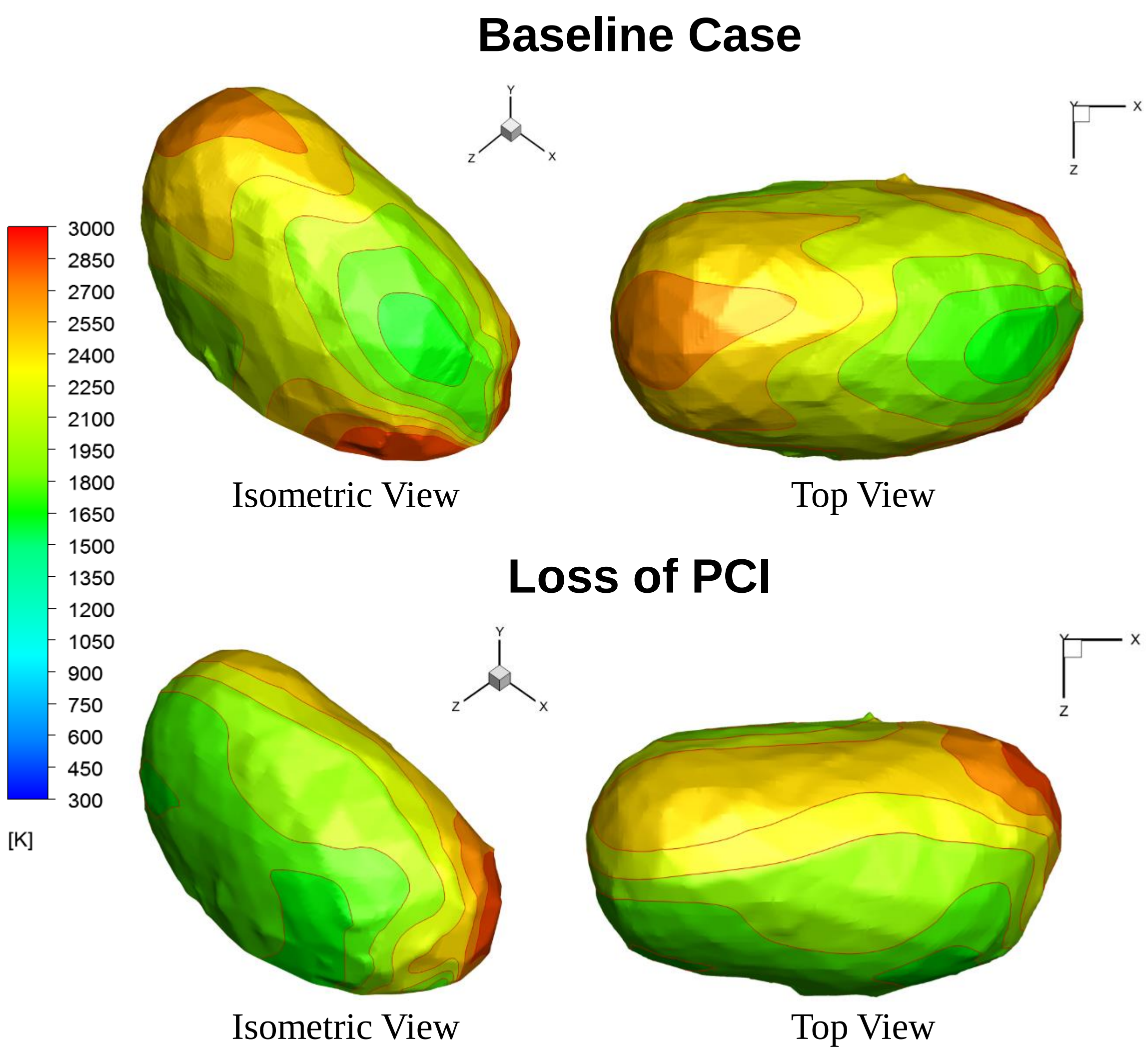
Loss of PCI



Collaborators: Stuart Street, AK STEEL
(Former SEVERSTAL, Dearborn)

Results & Discussion

- Resulting RAFT is **11%** lower than baseline, at **1,994 K**
  - Temperature drop due to abundance of H_2O and CO_2
- Raceway gas temperature distribution is also dramatically different
- Highest temperatures correspond to locations of NG combustion
- Little recirculation of combustion products within raceway

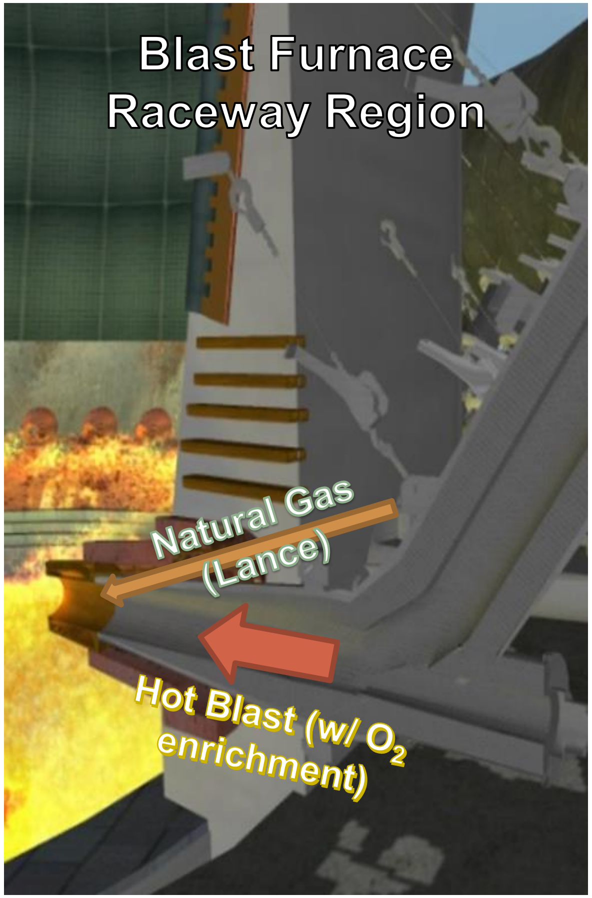


Impacts of PCI Loss and Pure NGI

- Nearly all injected fuel is consumed within raceway
- While CH_4 combustion provides heat, byproducts of CH_4 combustion result in endothermic reactions
- These results shine light on the quenching effect observed in industrial furnaces at high NG rates
- Limiting factors for furnace stability include condensation in BF (impacted by O_2 in blast) and RAFT for furnace heat
- O_2 can increase heat, but drops top temp. Max NGI rate is typically near 150 kg/mthm
- Potential to address this problem by pre-heating injected natural gas to maintain RAFT without impacting top temperature

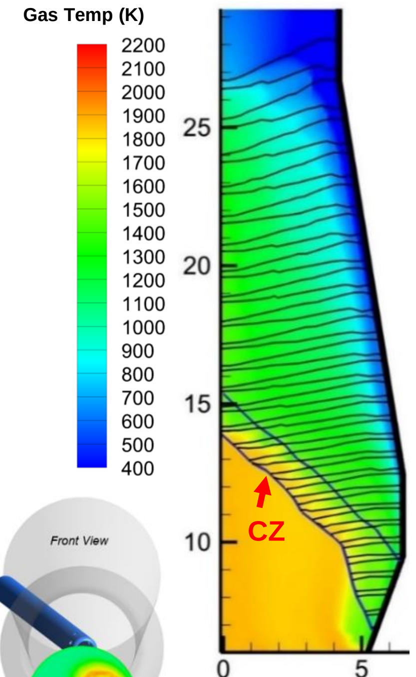
Example: Preheating Natural Gas

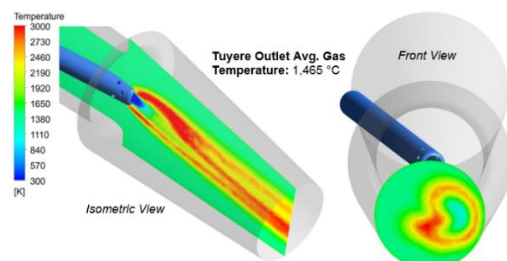
- **Issues:**
  - High NG injection to replace coke is desired to improve energy efficiency and emissions
  - Furnace unstable at high NG rates due to quenching effects on raceway flame T
- **Potential Solution:**
  - Preheating NG may:
    - ✓ Increase sensible heat input
    - ✓ Increase NG injection velocity (enhanced mixing/combustion)
    - ✓ Counter reduction in raceway flame temperature
- **Research:**
  - Use CFD to determine effects of NG preheating on coke rate and energy efficiency



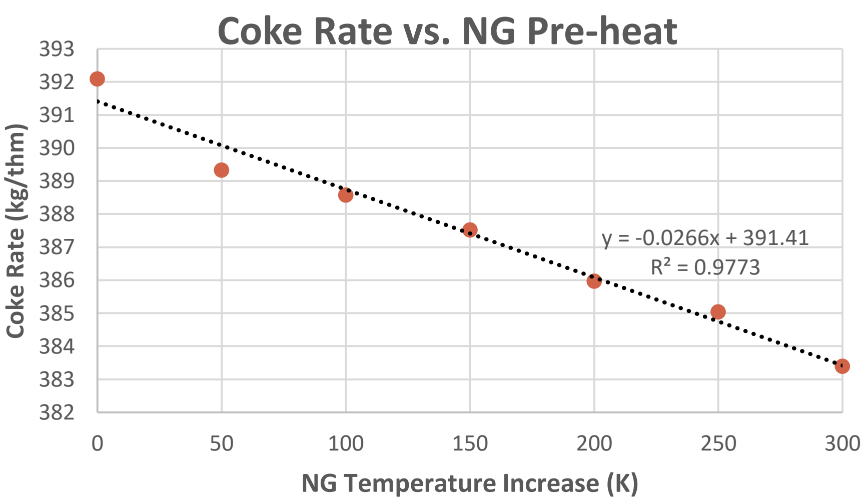
Effects of Pre-heated NG

- Blast furnace coke rate decreases as natural gas temperature is increased
- Preheating natural gas from 300 K to 600K can provide a drop of **8.7 kg/thm in furnace coke consumption (2.3%)**
- Assuming a coke price of $275/ton, for a BF operating at 6,500 thm/day, **~$5.88M will be saved annually**





Baseline Case



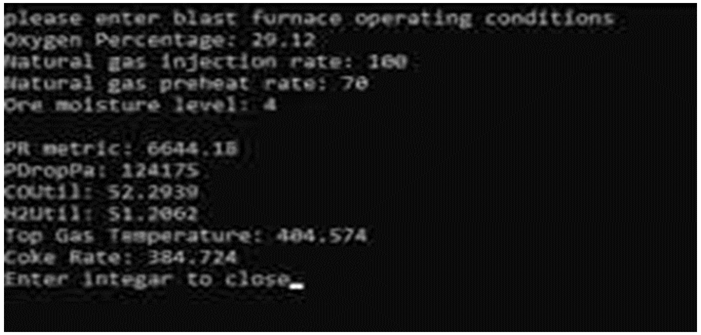
NG T	Coke Rate (kg/thm)	Coke Rate Δ	% change
300 K (base)	392.1	0 kg/thm	0%
350 K	389.3	- 2.8 kg/thm	0.7%
400 K	388.6	- 3.5 kg/thm	0.9%
450 K	387.5	- 4.6 kg/thm	1.2%
500 K	386.0	- 6.1 k/thm	1.6%
550 K	385.0	- 7.1 kg/thm	1.8%
600 K	383.4	- 8.7 kg/thm	2.3 %

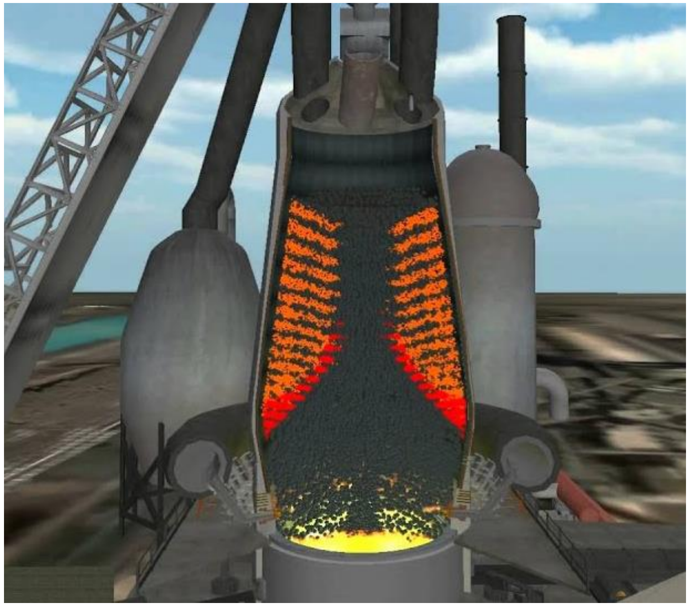
Example: HPC4Mfg

- Sponsors: DOE/AMO, LLNL
- Goals:
  - Significantly reduce computational time
  - Improve resolutions
  - Develop integrated blast furnace simulators for process control, optimization, design, troubleshooting, and workforce training
- Results:
  - Total of **~1000** cases run to analyze various operating conditions
  - Significant reduction in amount of time required to run large scale studies using capabilities of HPC
    - Time to run on HPC: **144 hours (1 week)**
    - Time to run on PC: **6,048 hours (9 months)**

BF 'Simulator' – Data Analytics

- New methodology for CFD data analytics
- Using CFD results from HPC parametric studies, develop interactive application to predict BF operation outputs
  - Functions at any data point inside data range
  - Will extrapolate for points outside range
- Predict TGF, FTA, coke rate, gas utilization, and shaft ΔP based on input conditions
  - Accuracy matching CFD models (in ideal operation) w/o needing a new run for each condition
- **Future Goals:**
  - Accessible from SMSVC website
  - Ability to import result sets from **any BF**
  - Addt'l variables could easily be added to expand the .CSV database





BF ‘Simulator’ – Data Analytics

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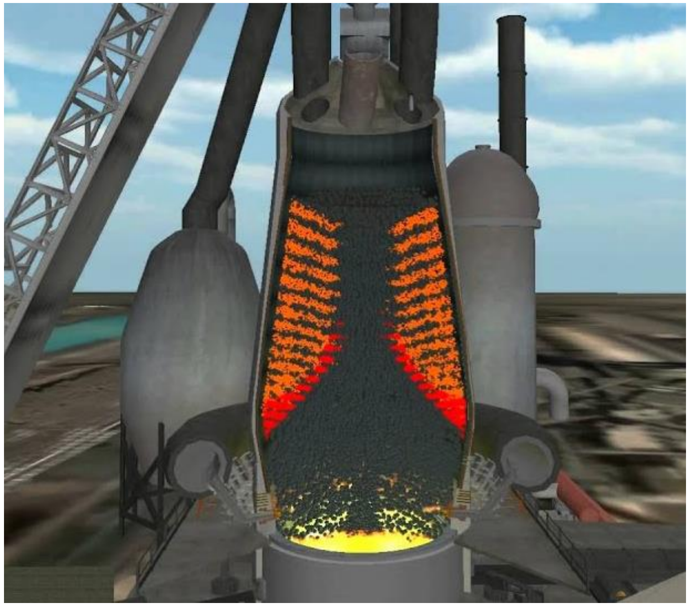
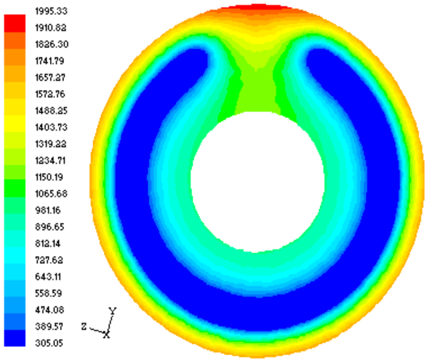
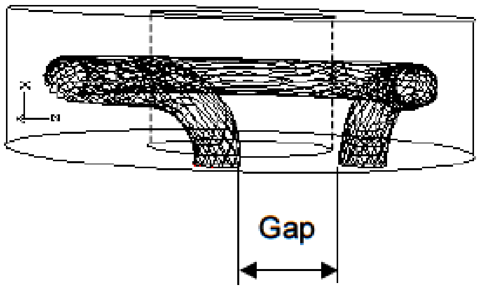


Example: Blast Furnace Tuyere Nose



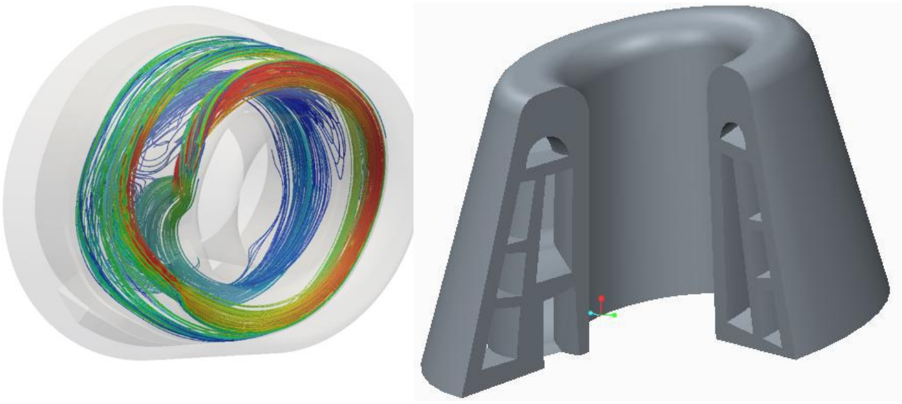
- **Issues:**
  - Tuyere failures
  - Downtime and maintenance cost
- **Outcomes:**
  - Identified insufficient cooling in between the nose inlet and the outlet pipe causing tuyere failures
  - 2005 AISI Institute Medal Award

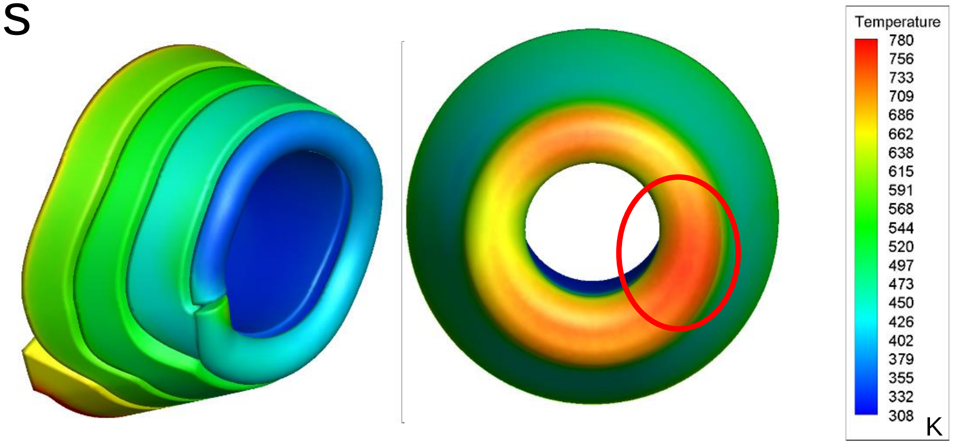


Collaborator: Yongfu Zhao, U.S. Steel Research

Example: Tuyere Failure Analysis

- **Issue:**
  - Unknown reason of tuyere failure
- **Outcomes:**
  - Identified the cause of failures
    - Thickness at the tuyere tip is significant (The thicker, the higher the temperature at the tip surface.)
    - Water temperature and velocity are not critical



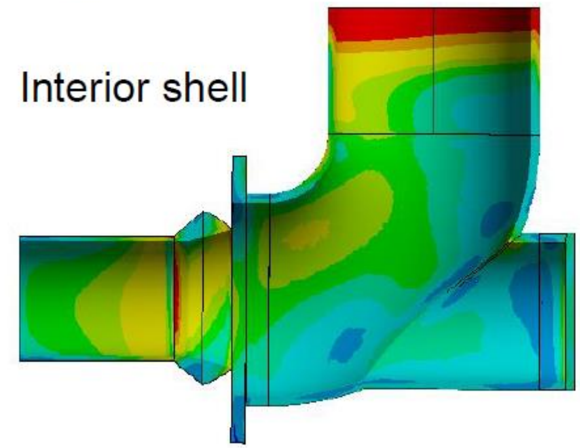


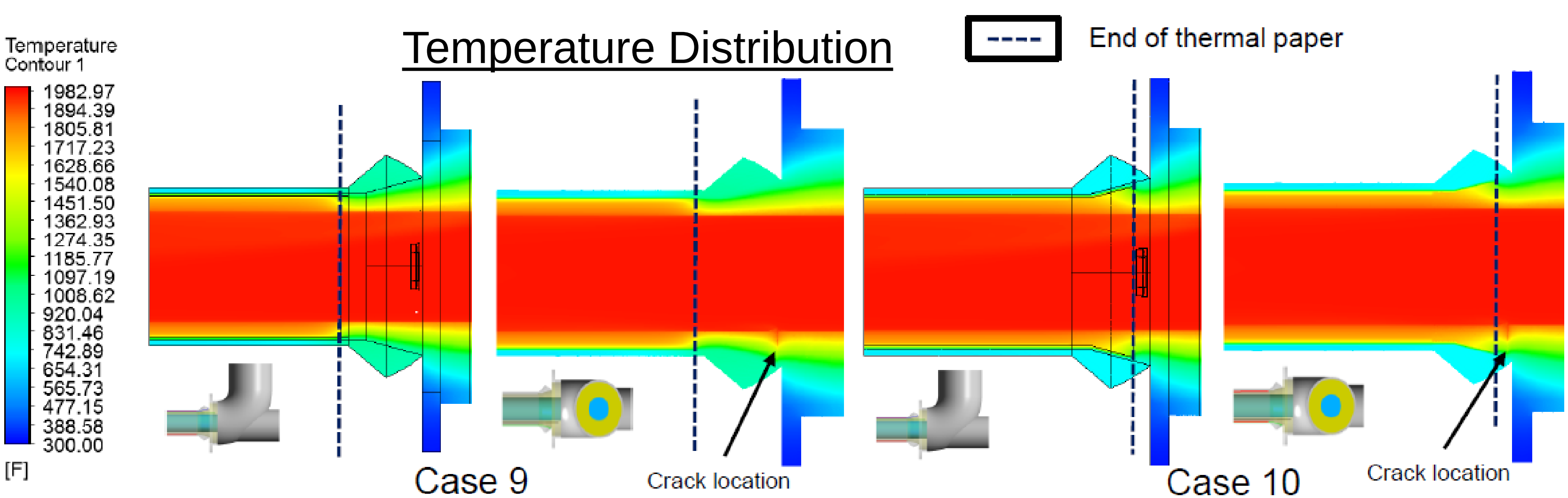
Collaborator: Sergey Trenkinshu, ArcelorMittal

Example: IH4 Blowpipe Redesign

Collaborator: Dale Goodloe, ArcelorMittal

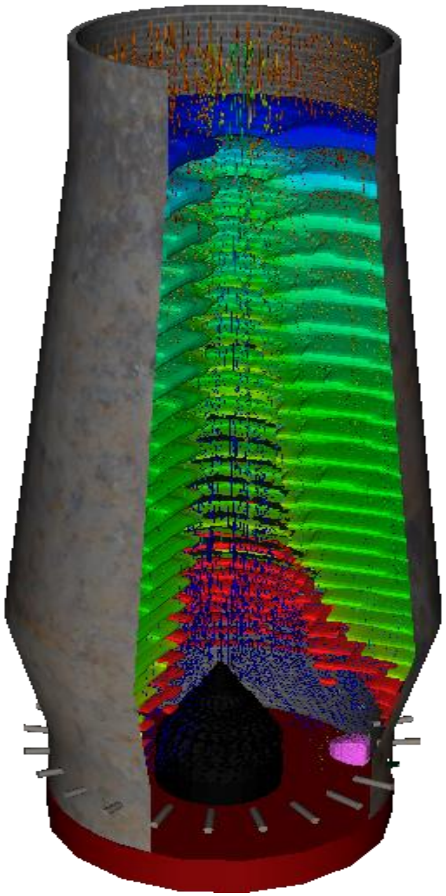
- **Issue:**
  - Blowpipes having short life expectancy
  - Refractory cracking, shell hot spots
- **Outcomes:**
  - Length of thermal paper extended, reducing thermal stress
  - Refractory changed to wall-cast, nearly doubling current strength





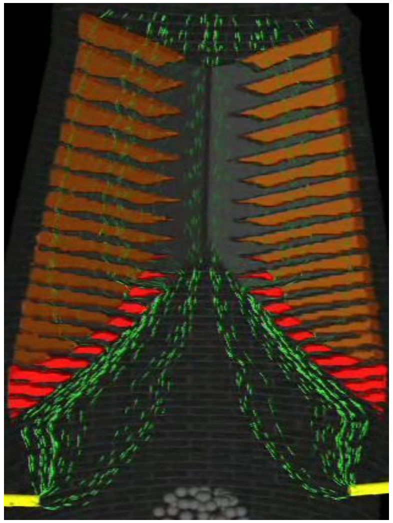
CFD SHAFT MODEL

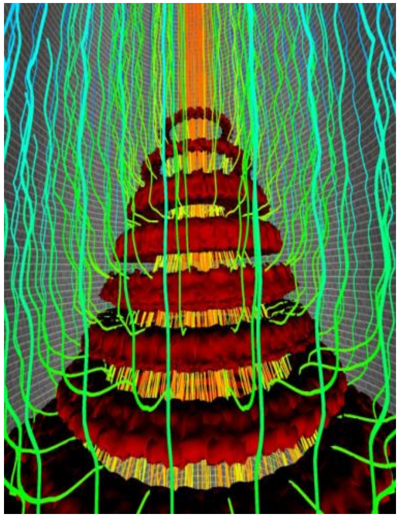
- **Features of CFD Shaft Model**
  - GUI preprocessor
  - 3-D
  - Burden distribution
    - Falling curve
    - Stock line profile
    - Burden descending
    - Mix layer
  - Velocity, pressure, species, gas and burden temperature
  - Chemical Reaction (Total 9 reactions considered)
    - Shrinkage un-reacted core model
    - Grain model



CFD SHAFT MODEL

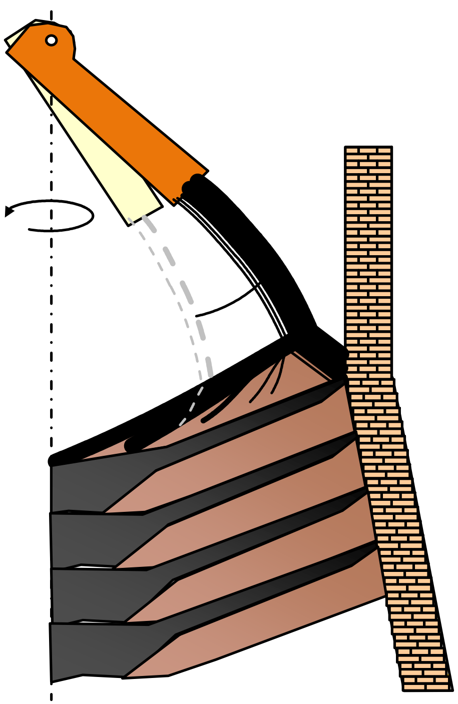
- **Features of CFD Shaft Model**
  - Cohesive zone shape and location
    - Uniform liquidus temperature
    - Non-uniform liquidus temperature (as a function of burden composition)
  - Reduction degree, Coke rate
  - CO and H_2 Gas utilization
  - Coal ash distribution in shaft
  - VR visualization

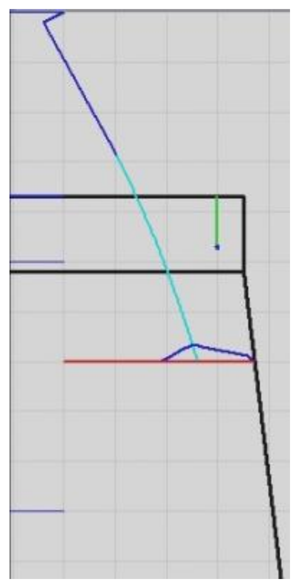




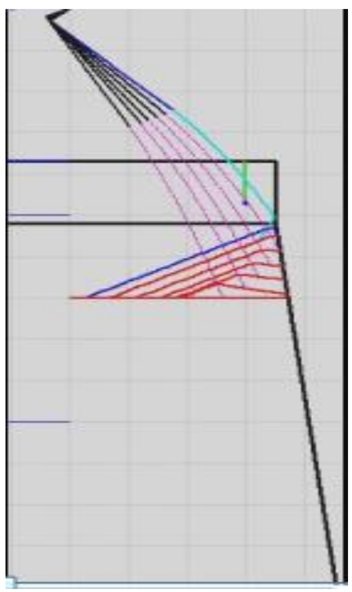
BURDEN DISTRIBUTION MODEL

- Predict burden distribution from a given charging matrix

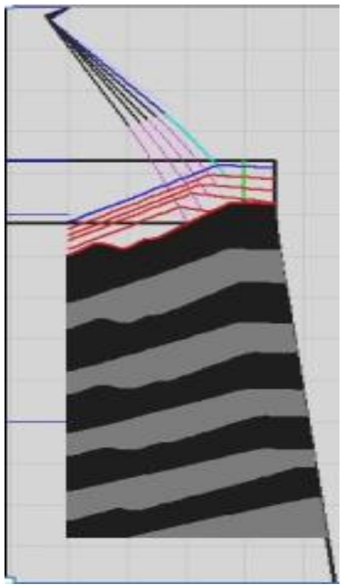




- Falling Curve



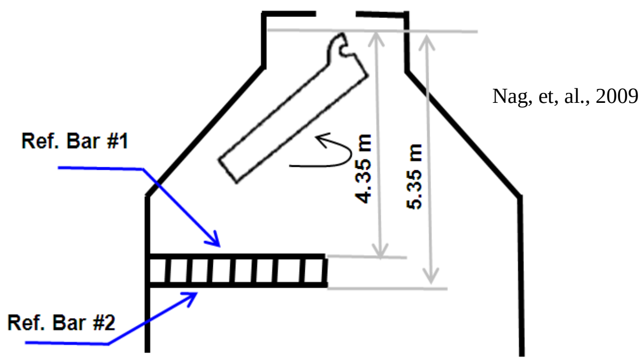
- Stock Profile Formation

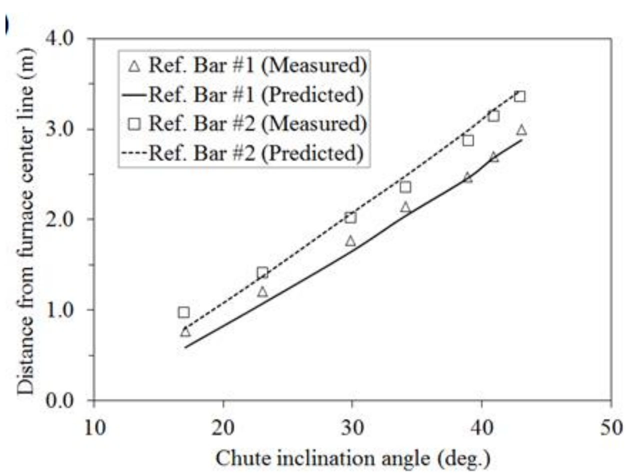


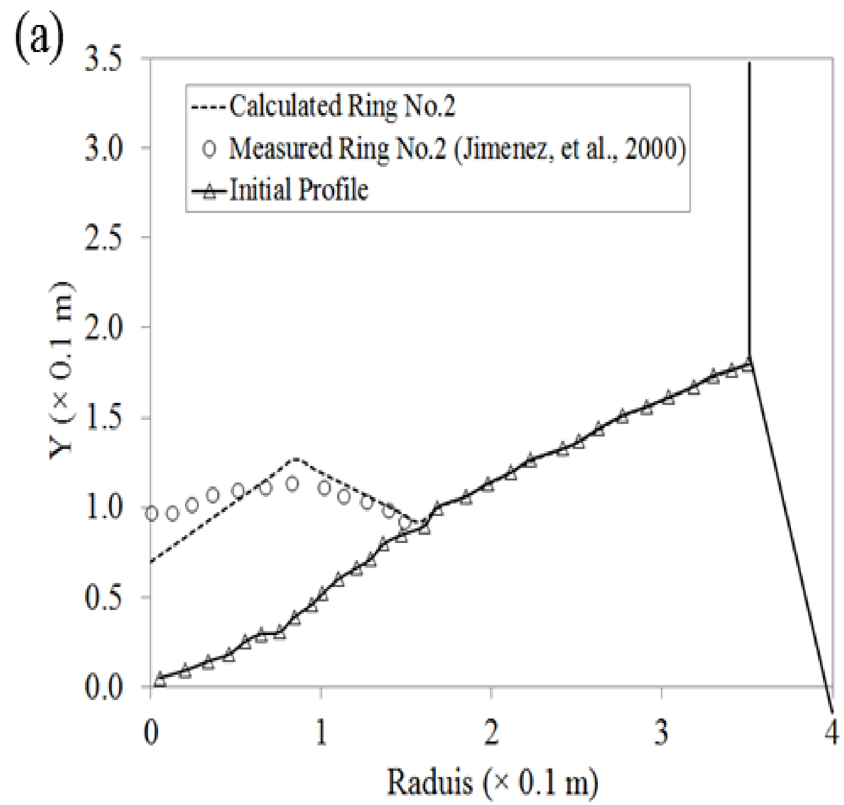
- Burden Descending

VALIDATION

- Measurement of the impact location for different chute angle
- Measurement of first layer profile







CHEMICAL REACTIONS

- Indirection reduction by carbon monoxide :
  - $3Fe_2O_3\ (s) + CO\ (g) \rightarrow 2Fe_3O_4\ (s) + CO_2\ (g)$
  - $Fe_3O_4\ (s) + CO\ (g) \rightarrow 3FeO\ (s) + CO_2\ (g)$
  - $FeO\ (s) + CO\ (g) \rightarrow Fe\ (s) + CO_2\ (g)$
- Indirection reduction by hydrogen:
  - $3Fe_2O_3\ (s) + H_2\ (g) \rightarrow 2Fe_3O_4\ (s) + H_2O\ (g)$
  - $Fe_3O_4\ (s) + H_2\ (g) \rightarrow 3FeO(s) + H_2O\ (g)$
  - $FeO\ (s) + H_2\ (g) \rightarrow Fe\ (s) + H_2O\ (g)$

Gas Solid Reaction Model
- Un-reacted Core Model
- Grain Model
- Kinetic Model

- Decomposition of flux:
  - $MeCO_3\ (s) \rightarrow MeO\ (s) + CO_2\ (g)$, Me=Ca, Mg

Un-reacted Core Model

- Coke gasification:
  - $C(s) + CO_2\ (g) \rightarrow 2CO\ (g)$
  - $C(s) + H_2O\ (g) \rightarrow CO\ (g) + H_2\ (g)$

Kinetic Diffusion Model

- Water gas shift reaction:
  - $CO(g) + H_2O\ (g) \leftrightarrow CO_2\ (g) + H_2\ (g)$

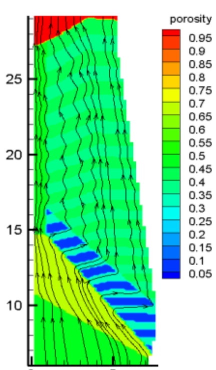
Assume Equilibrium When T>900 ºC

- Direct Reduction:
  - $FeO\ (l) + C\ (s) \rightarrow Fe\ (l) + CO\ (g)$

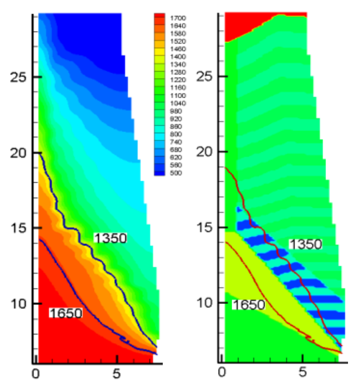
Kinetic Model

COHESIVE ZONE ESTIMATION

- Iterative Methodology
  - Step 1: Assume a cohesive zone (CZ) to initialize the burden structure for CFD simulation.
  - Step 2: Obtain the burden temperature distribution using the converged CFD results.
  - Step 3: Determine the new CZ using isothermal lines from CFD results with the softening temperature of iron ore (upper boundary) and the liquidus temperature (lower boundary) .
  - Step 4: Feed back the updated CZ to update the burden structure and conduct simulation.
  - Step 5: Repeat the Step 2-4 until the shape of cohesive zone converge

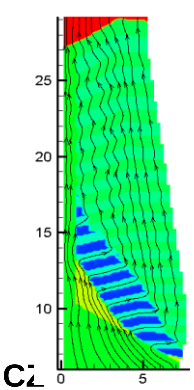


- Initialization CZ for 1st iteration

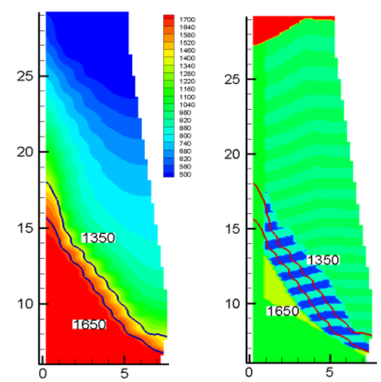


Solid temperature (K)

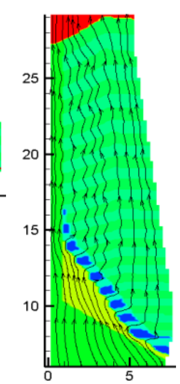
- Burden temperature contours for updating CZ



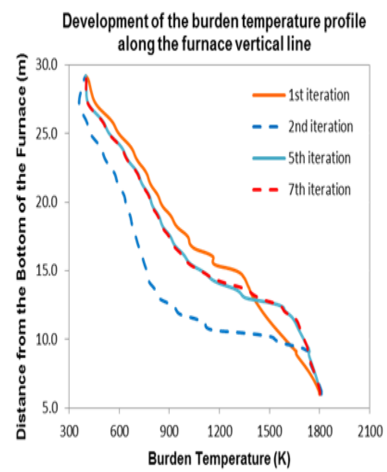
- CZ for 2nd iteration



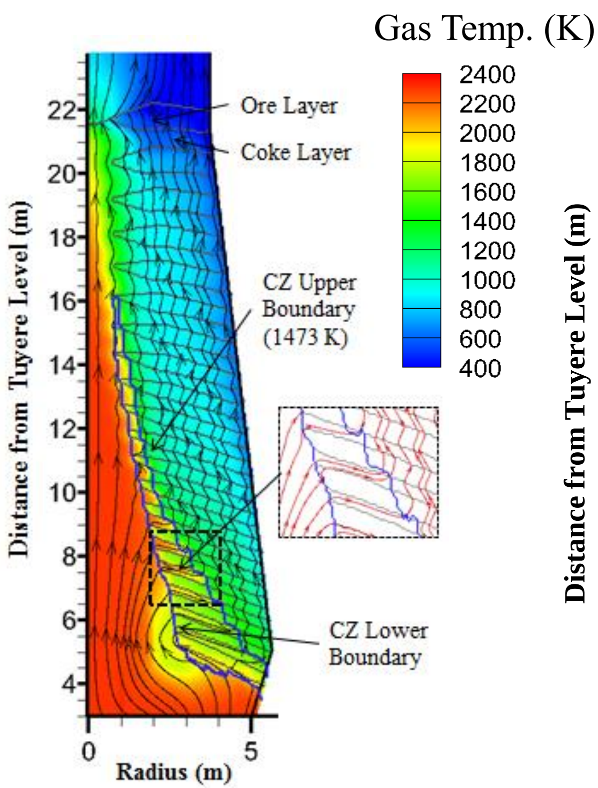
- Updating CZ

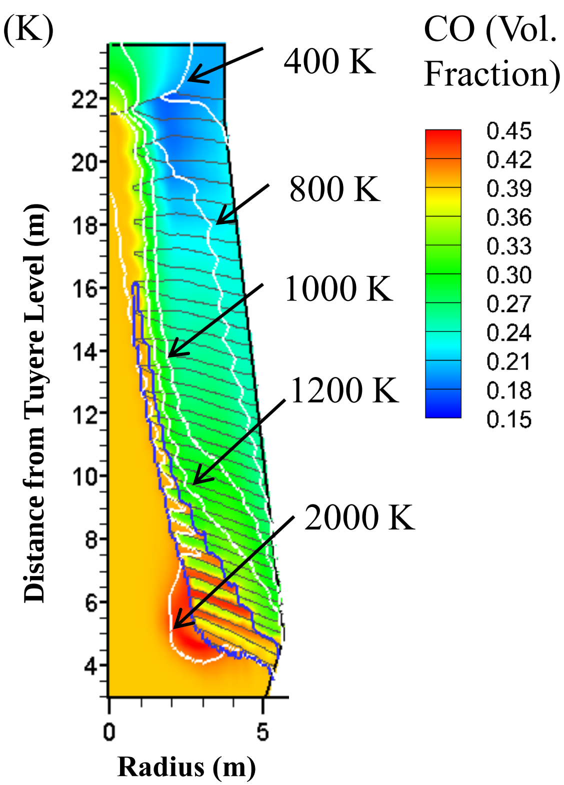


- CZ for 3rd iteration



VALIDATION



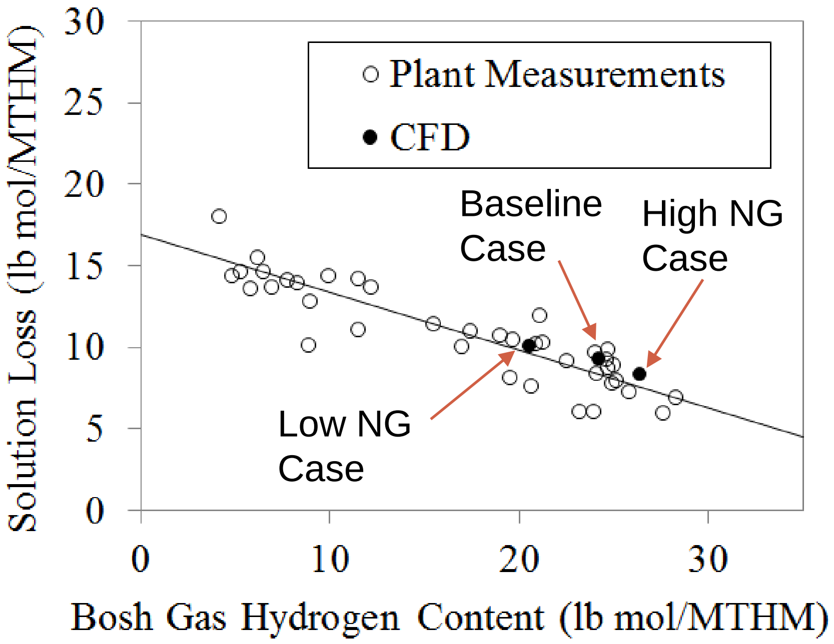


	Measured	CFD	Error ,%
Top Gas CO_2 %	22.18	22.46	1.26
Top Gas CO %	23.88	24.23	1.47
Top Gas H_2 %	6.33	6.50	2.69
Top Gas N_2 %	47.62	46.81	-1.70
CO Gas Utilization	48.15	48.11	-0.08
Pressure Drop (kPa)	163	176	7.63
Coke Rate (kg/MTHM)	412	408	-0.97

We appreciate USS for provide the measurements data for our validation.

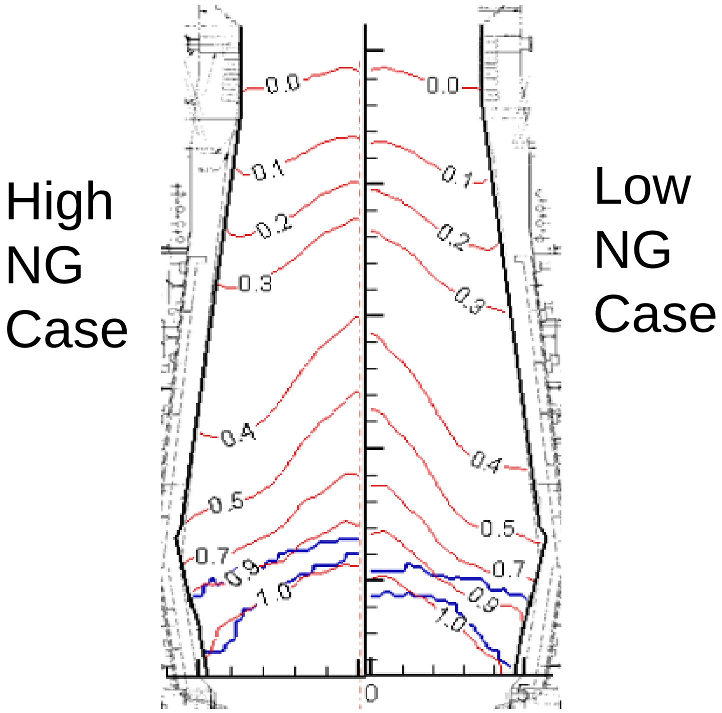
EFFECT OF NATURAL GAS RATE

- Solution loss



*Plant measurements are from literature: J.C. Agarwal et al , 1992 Ironmaking Conf. Proc.

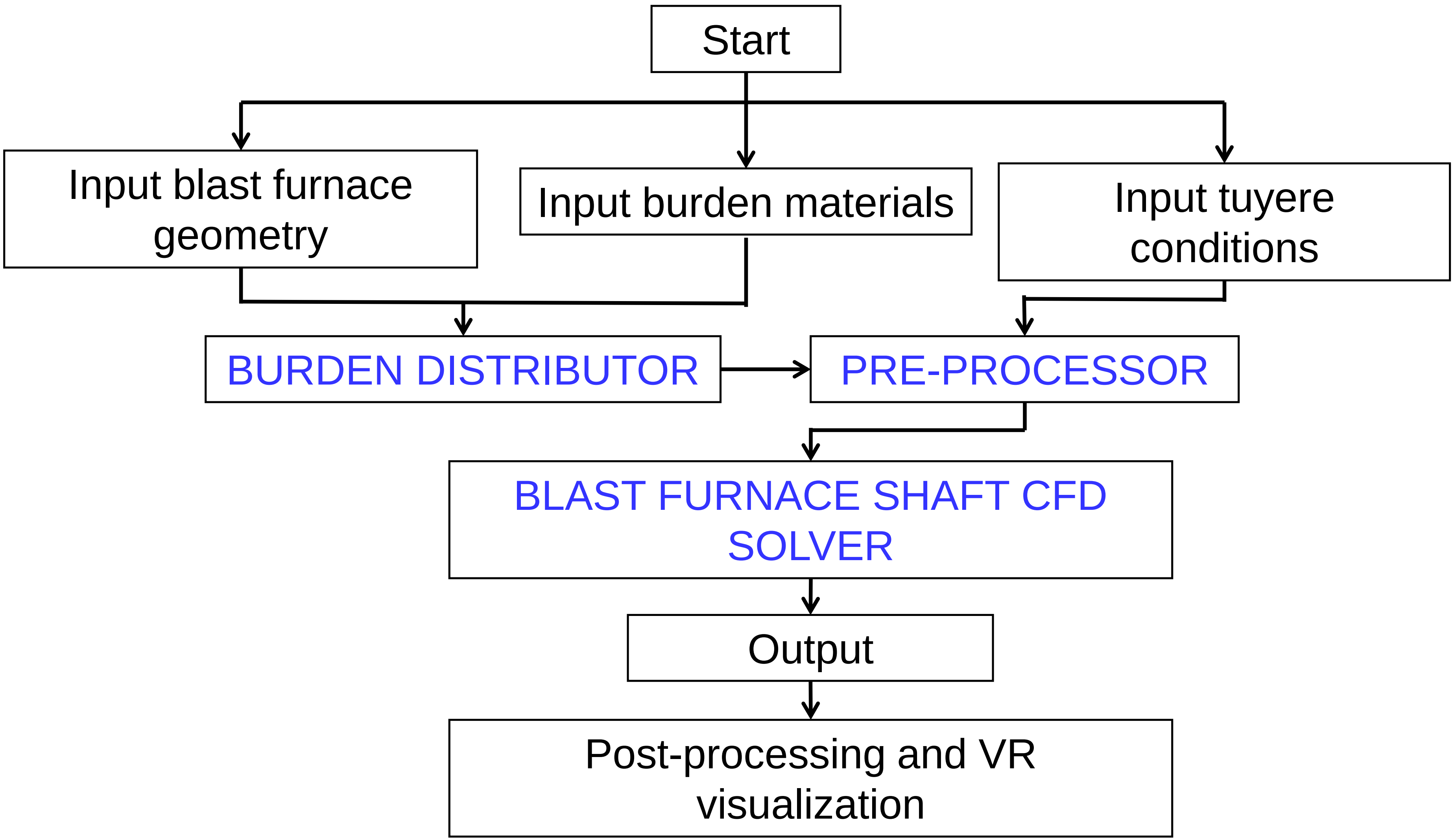
- Reduction degree



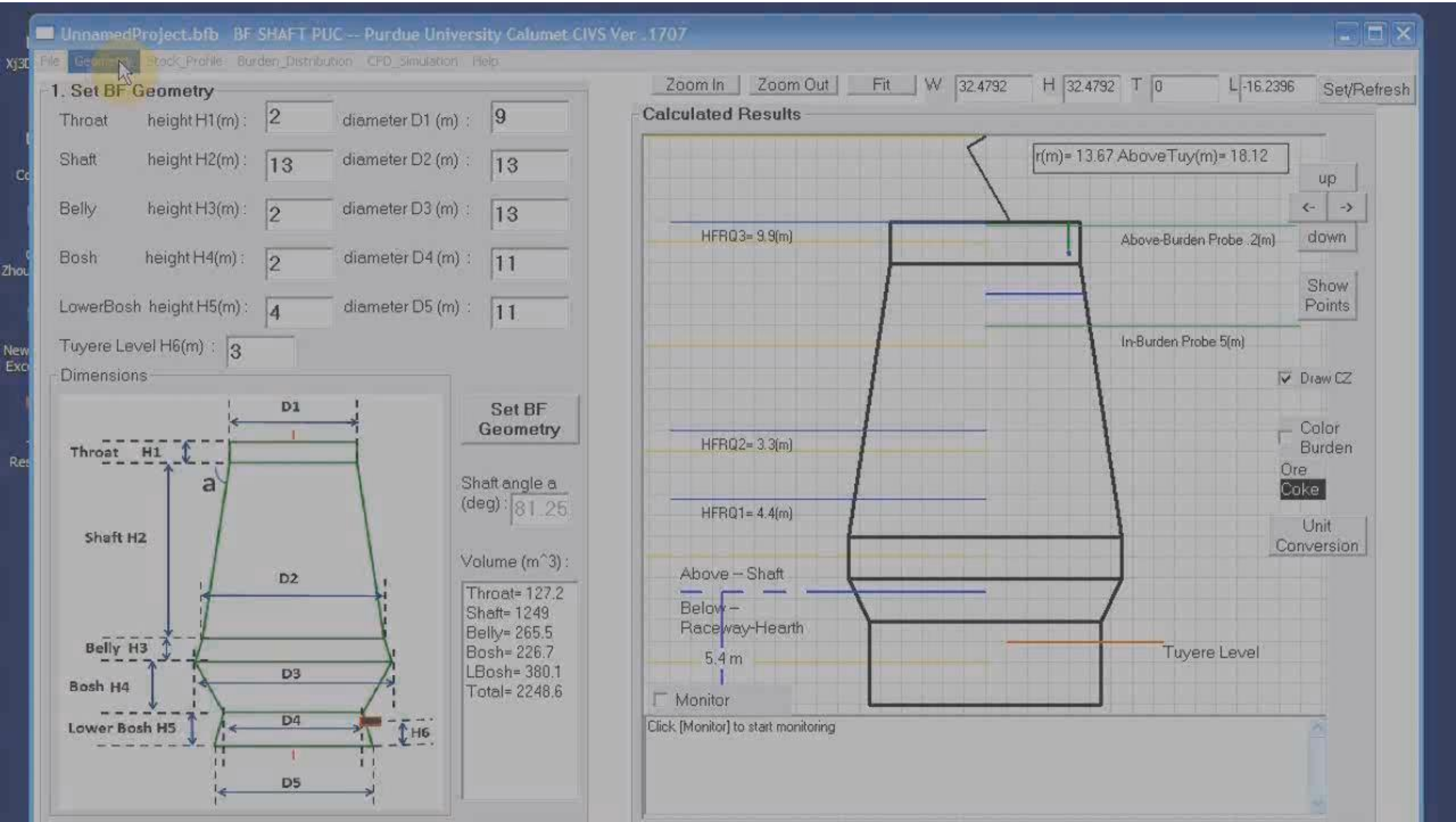
Case	Coke Rate
High NG Case	411 kg/MTHM
Low NG Case	423 kg/MTHM

- NG rate ↑ → solution loss ↓ coke rate ↓

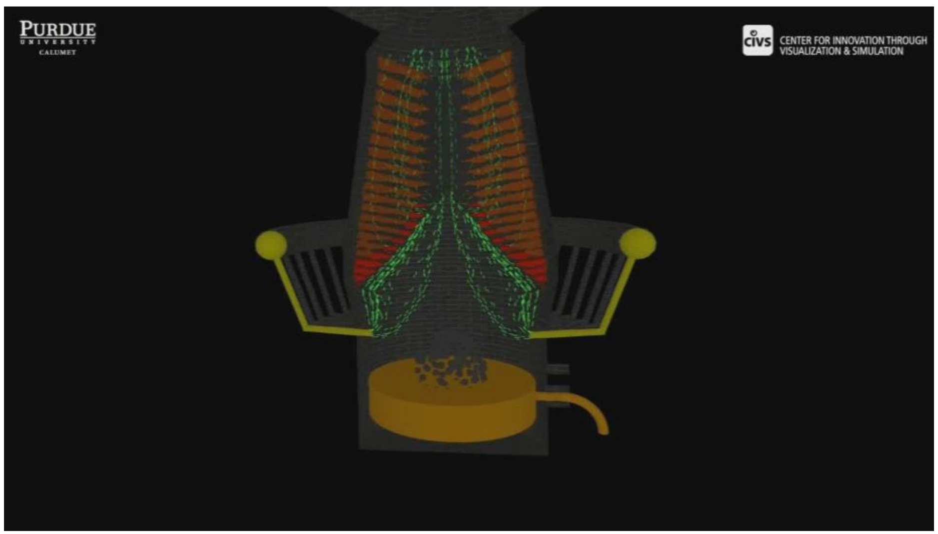
BLAST FURNACE SHAFT SIMULATOR (BFSS)

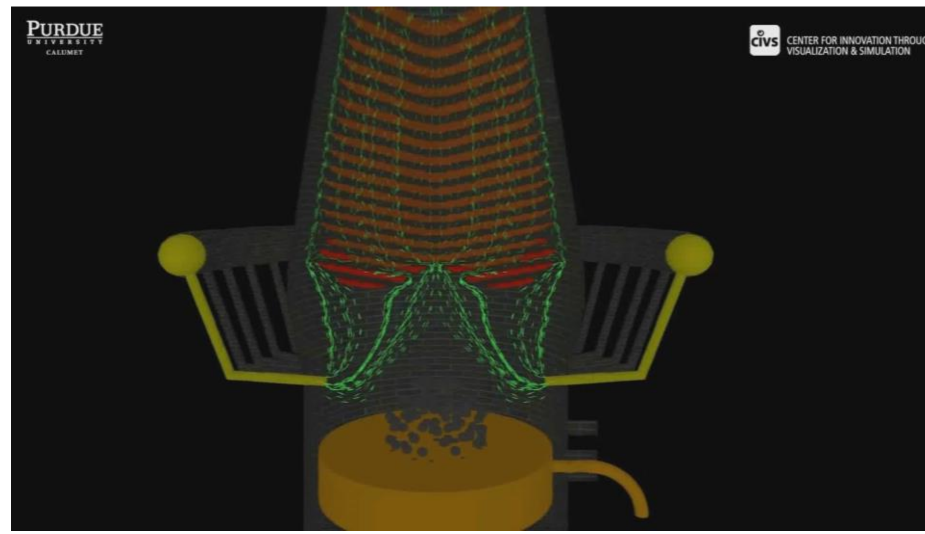


BLAST FURNACE SHAFT SIMULATOR



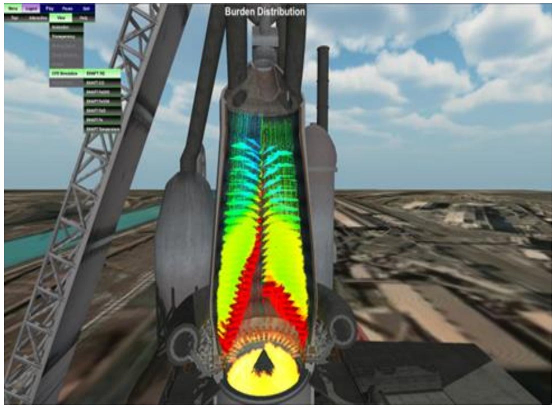
EFFECT OF BURDEN DISTRIBUTION





VIRTUAL BLAST FURNACE

- Multiple versions of training package
  - PC, Web, Mobile
  - 3D TV
  - 3D Immersive Virtual Reality (VR)
  - Augmented Reality (AR)
- Taught in industrial training and short courses world wide
- Used for problem solving for design, troubleshooting and optimization with multimillion savings and cost avoidance



U.S. Steel Blast Furnace Ironmaking Academy

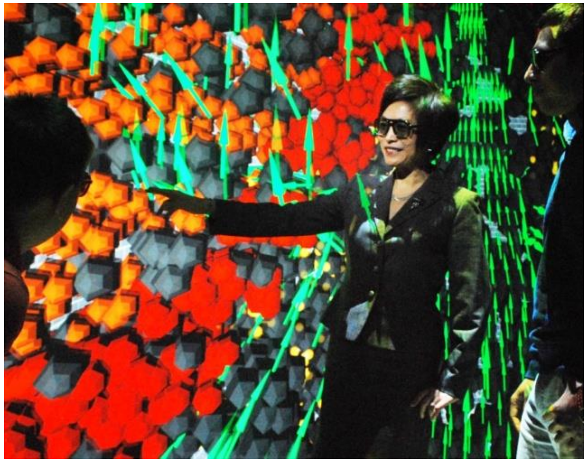
Total 20 Participants

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The VBF simulator was **beneficial** as a visual learning aid in this training course.	95%	5%	0%	0%	0%
The VBF simulator enables me to **better visualize** the blast furnace and its equipment in a way that is difficult for me to do with presentation slides or text alone.	85%	15%	0%	0%	0%
Training courses on **other process** (i.e., cokemaking, steelmaking, etc.) should develop similar simulations in the futures as a learning aid.	80%	20%	0%	0%	0%

"excellent training tool; great problem-solving capabilities"; "This interactive model helped me visualize the material flowing through the process. It was very helpful in understanding the flow"

SUMMARY

- Comprehensive CFD modeling and visualization provide important tools for blast furnace process/product design, optimization and troubleshooting to address issues on energy, environment, productivity, quality, and training
- The integration of CFD simulation and VR visualization provides innovative ways to create virtual worlds of real problems for cost-effective solutions



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- U.S. Dept. of Energy Advanced Manufacturing Office
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- Indiana 21st Century Research and Technology Fund
- Association of Iron and Steel Technology
- American Iron and Steel Institute
- Additional thanks to:
  - Steel Manufacturing Simulation and Visualization Consortium members
  - All industrial collaborators
  - CIVS staff & students

centers.pnw.edu/civs
www.steelconsortium.org