Case Studies of Optimizing and Troubleshooting FCC Reactors and Regenerators

Today's Presenter:

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Prop.
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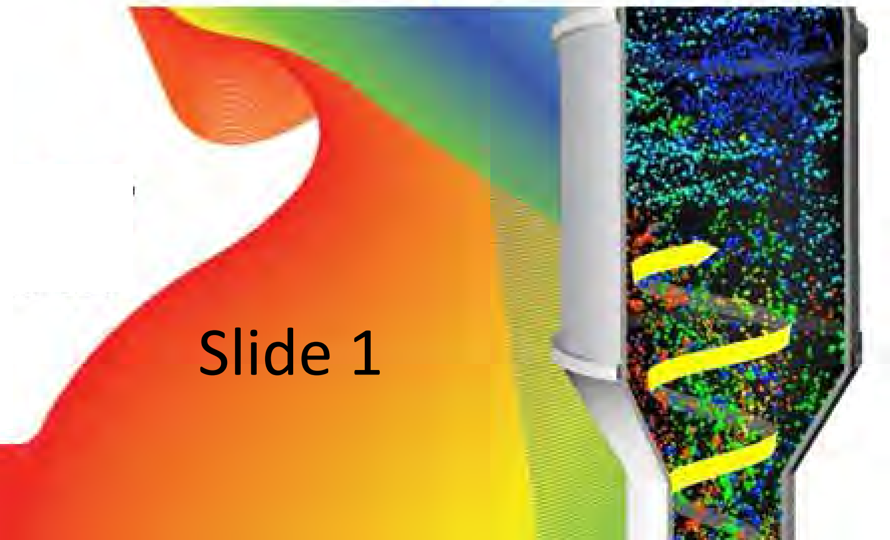

Outline

- Typical Industry Challenges for FCC Unit Design and Operations
- What is Lacking: A View Inside Your Fluidized System – Reactor or Regenerator
- Case Study 1: Afterburn Root Cause Analysis for a Commercial FCC Regenerator
- Case Study 2: Erosion Evaluation for a Commercial FCC Reactor Cyclone System at Marathon Petroleum's Catlettsburg Refinery
- Barracuda VR: Bringing Value Across Multiple Segments
- Summary / Q&A

Typical Industry Challenges

"Reliability is the #1 Issue in Refining" – Anonymous Oil Major Executive

- Need to **maximize yield** & performance of FCCU's while **minimizing CAPEX and risk**.
- Challenge to increase throughput, yields, and selectivity while maintaining or **improving on-stream reliability** and while extending operating cycles between refits.
- Desires to take advantage of short-term swings in commodity prices by allowing a **wider selection of feedstocks** (e.g., heavier oils, shale gas, etc.)
- Even for units operating well, the business and **regulatory environment is constantly changing** and putting new pressures on refiners and other operators (e.g., MACT, BACT). Units **not** operating well have a limited time to address the issues.
- Both **new equipment and revamps are expensive and risky**, yet design and operational decisions must often be made **without a full understanding** of root causes and effective solutions.

What is Lacking: A View Inside Your Fluidized System

Stop guessing! Take a look inside your unit to learn how it operates.

- Fluidization quality and mode (spouted-bed, bubbling bed, turbulent bed)
- Gas and particle residence time distributions
- Bed entrainment rate by particle size
- 3-D mixing profiles
- Temperature profiles (hot or cold spots)
- Solids flux, circulation rates, choked flows
- Erosion locations and severity
- Cyclone loadings, dipleg plugging
- Product generation rates and the limiters
- Oxygen usage
- Causes of excess emissions (e.g., NOx or SOx)
- View at normal operating point, start-up, turndown, or upset operating conditions

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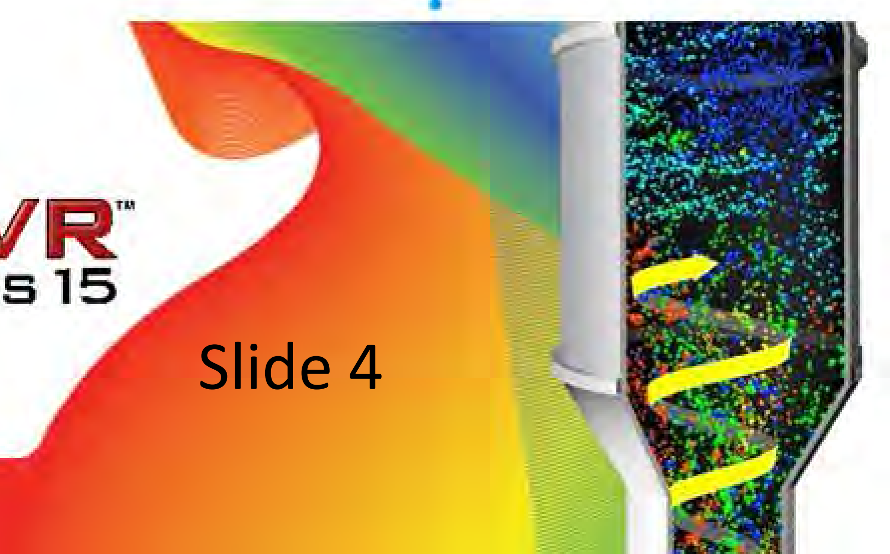
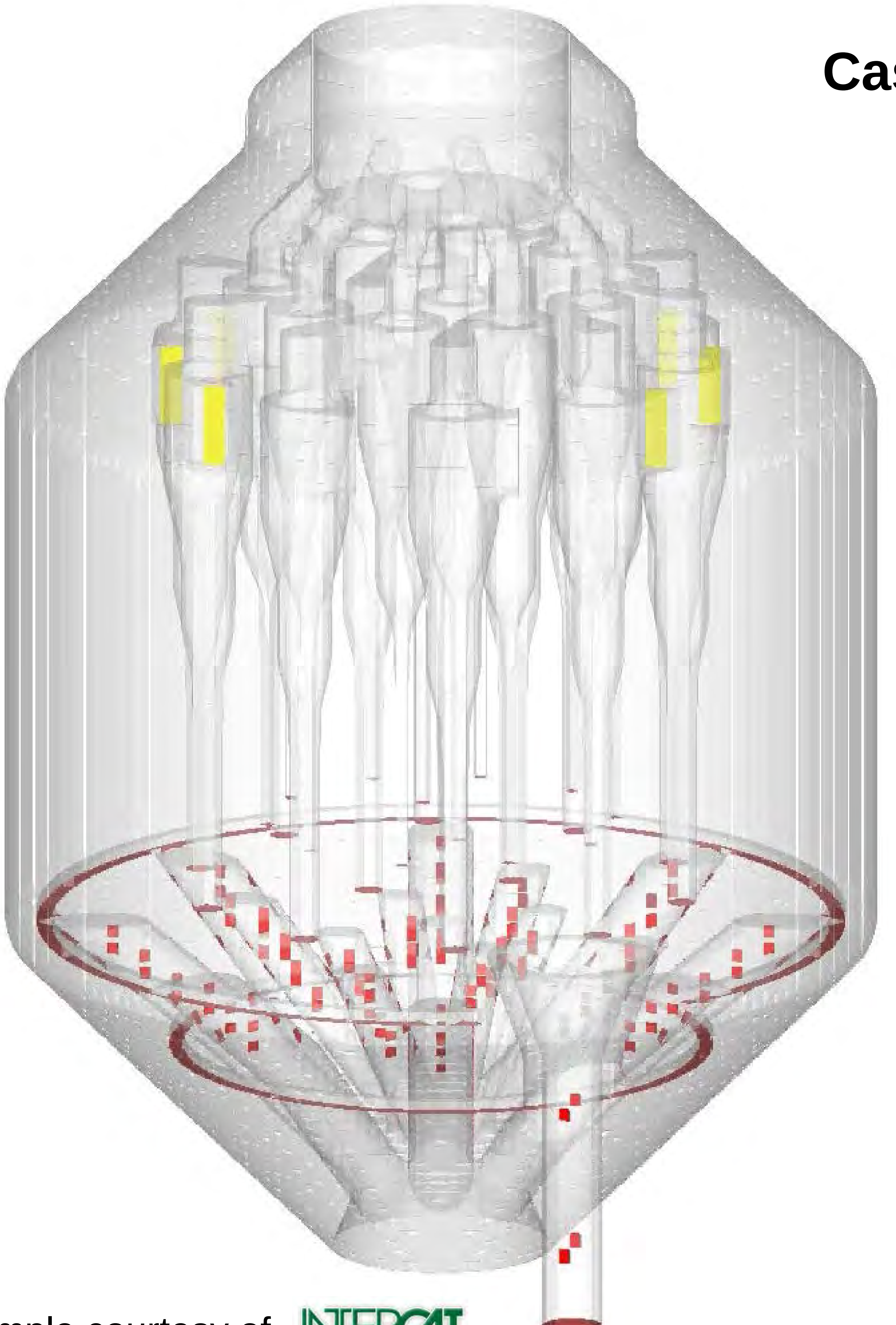


The Value of A View Inside Your FCCU Reactor or Regenerator

Optimal Design & Operation + Greater Reliability = Higher Profits

- **Reduce risks of any changes** planned for reliability improvement, uprates for throughput or yield, or feedstock/catalyst changes.
  - Mitigate erosion to increase life and reliability
  - Reduce catalyst carryover
  - Minimize catalyst losses & makeup cat requirements
  - Meet emissions requirements cost effectively
- Troubleshoot equipment and minimize downtime

➡ **More reliable and profitable FCC units.**

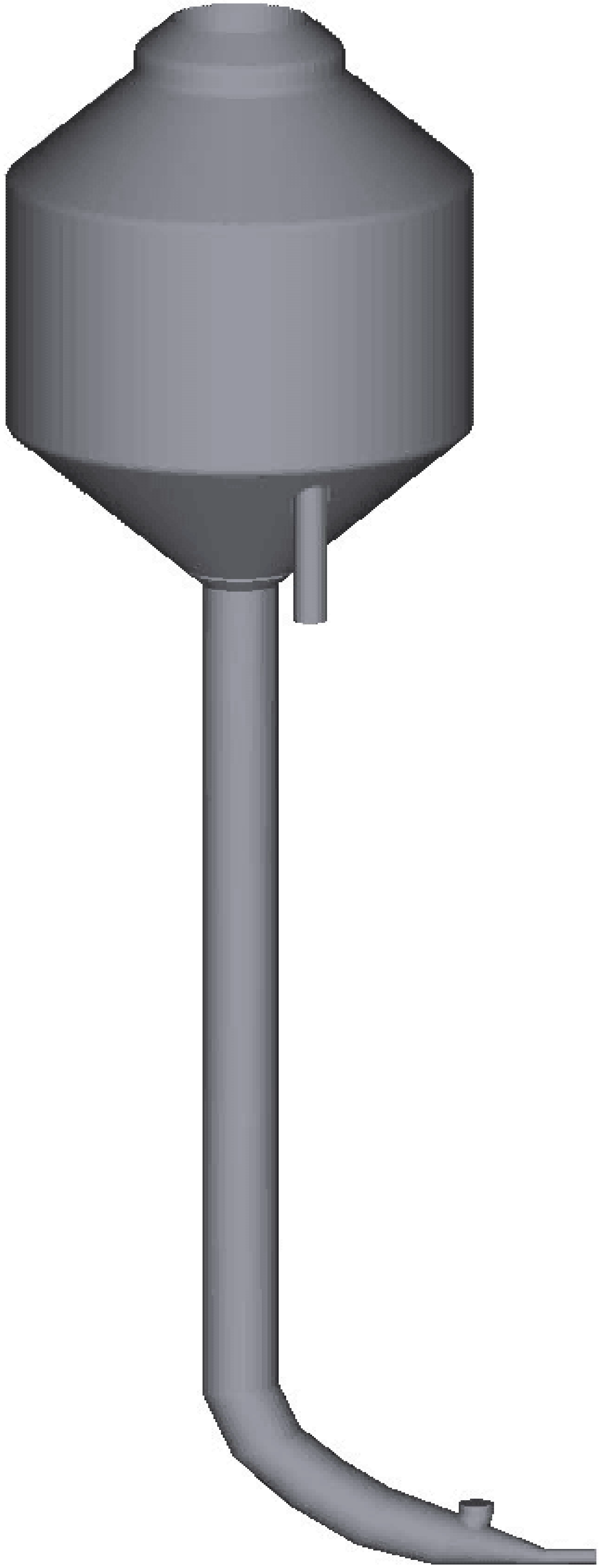


Case Study 1: Full-Scale, 3D Reacting Gas-Particle Simulation of a Commercial FCC Regenerator

- **Regenerator configuration**
  - Height ~70 ft, width ~50 ft
  - 12 cyclone pairs, 24 total cyclones
  - Spent catalyst distributor consisting of distributor 17 arms each containing multiple nozzles
  - Two supplemental air rings
  - Very long spent catalyst riser

- **Operations**
  - Combustion air ~100 MSCFM
  - Flue gas composition:
    - *O_2 = 1.5%*
    - *CO_2 = 17.4%*
    - *SOx = 30 ppm*
    - *NOx = 40 ppm*

Example courtesy of INTERCAT



Problem Definition

- **Driving Force for Simulation:**
  - Determine root cause for extreme afterburning (90-100 ^{o}F)
- **Potential Causes:**
  - Spent catalyst riser delivers catalyst to distributor with a highly mal-distributed flow pattern
  - Limited regenerator height may result in insufficient dense-bed residence time

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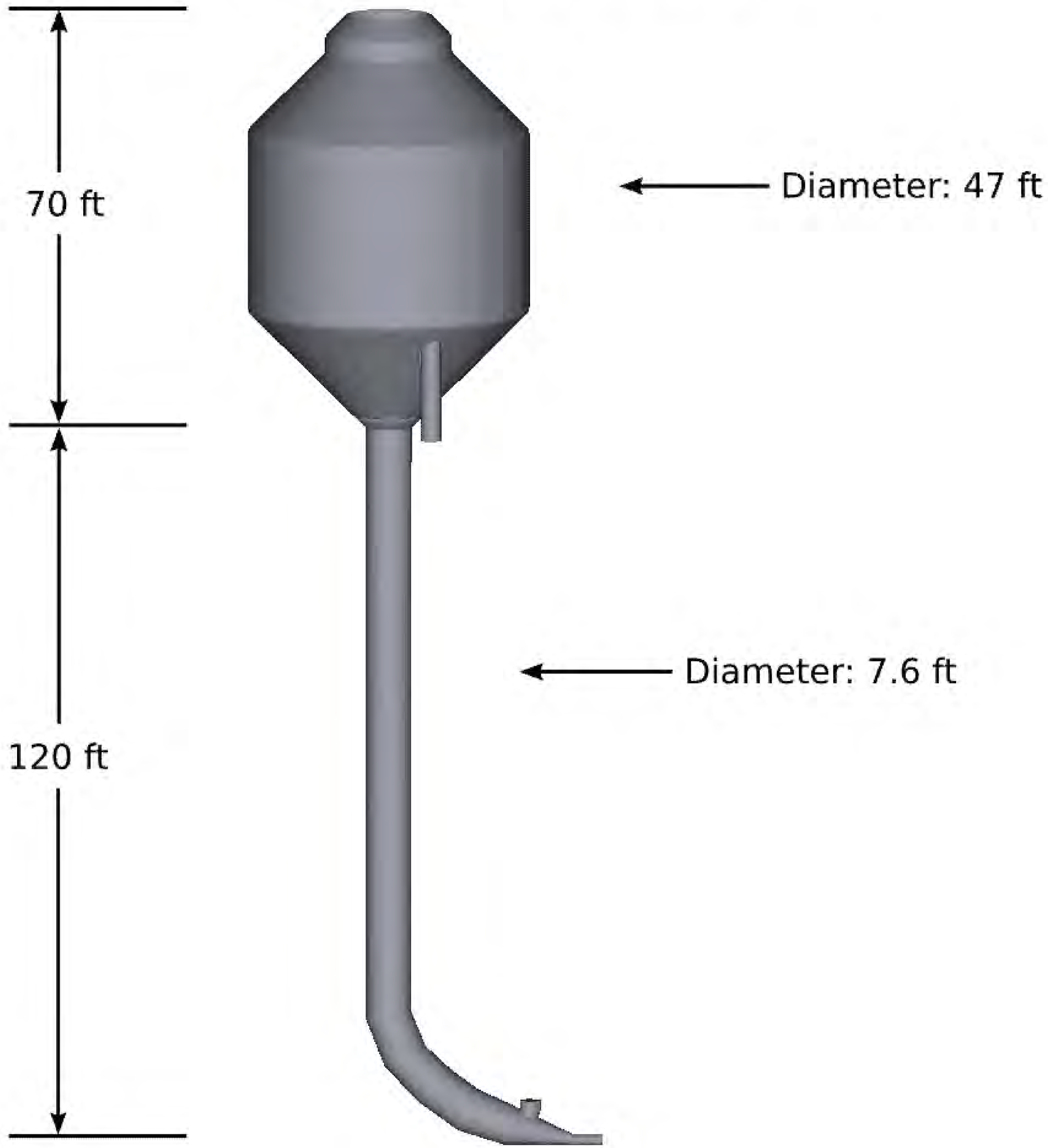
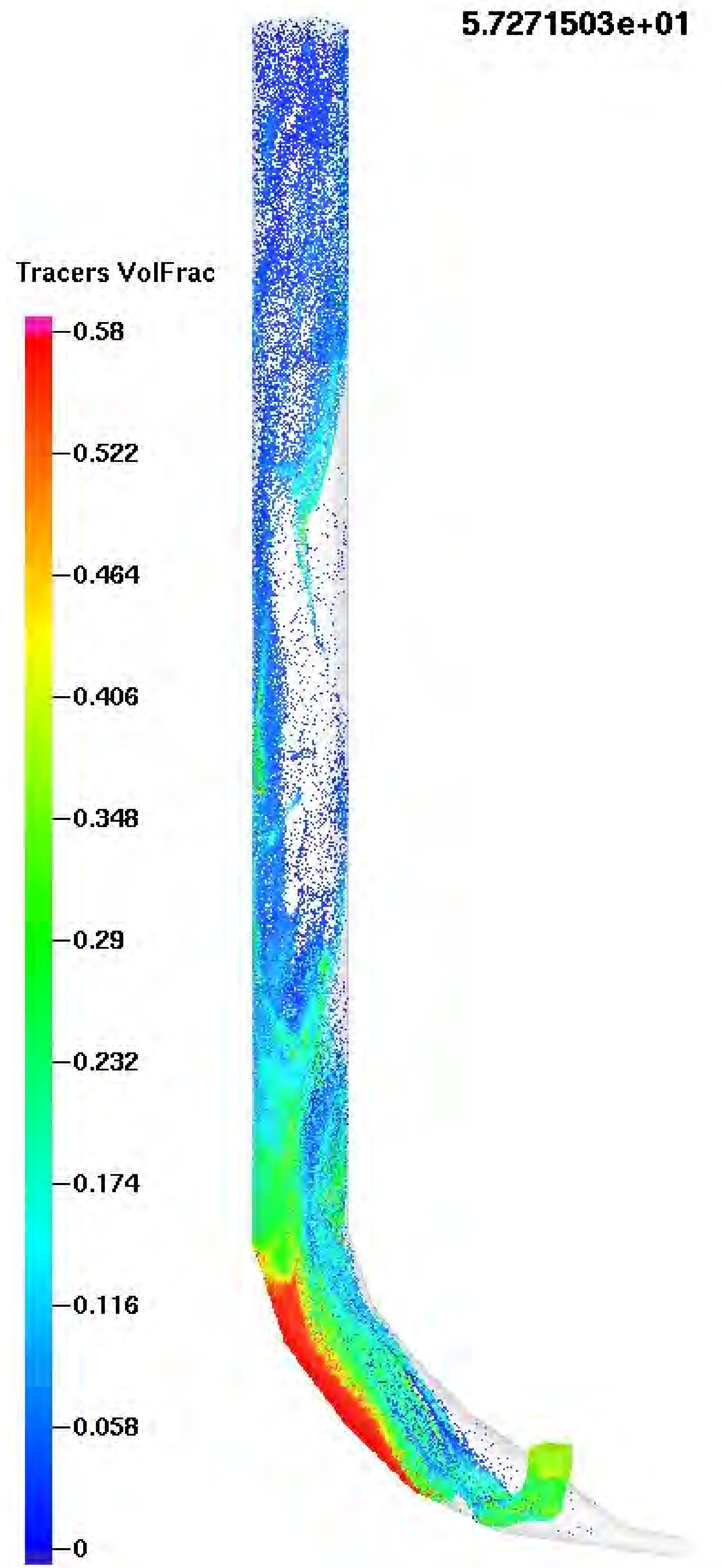
Commercial FCC Regenerator Simulation

INTERCAT JM



Combined Geometry: Spent Cat Riser + Regenerator



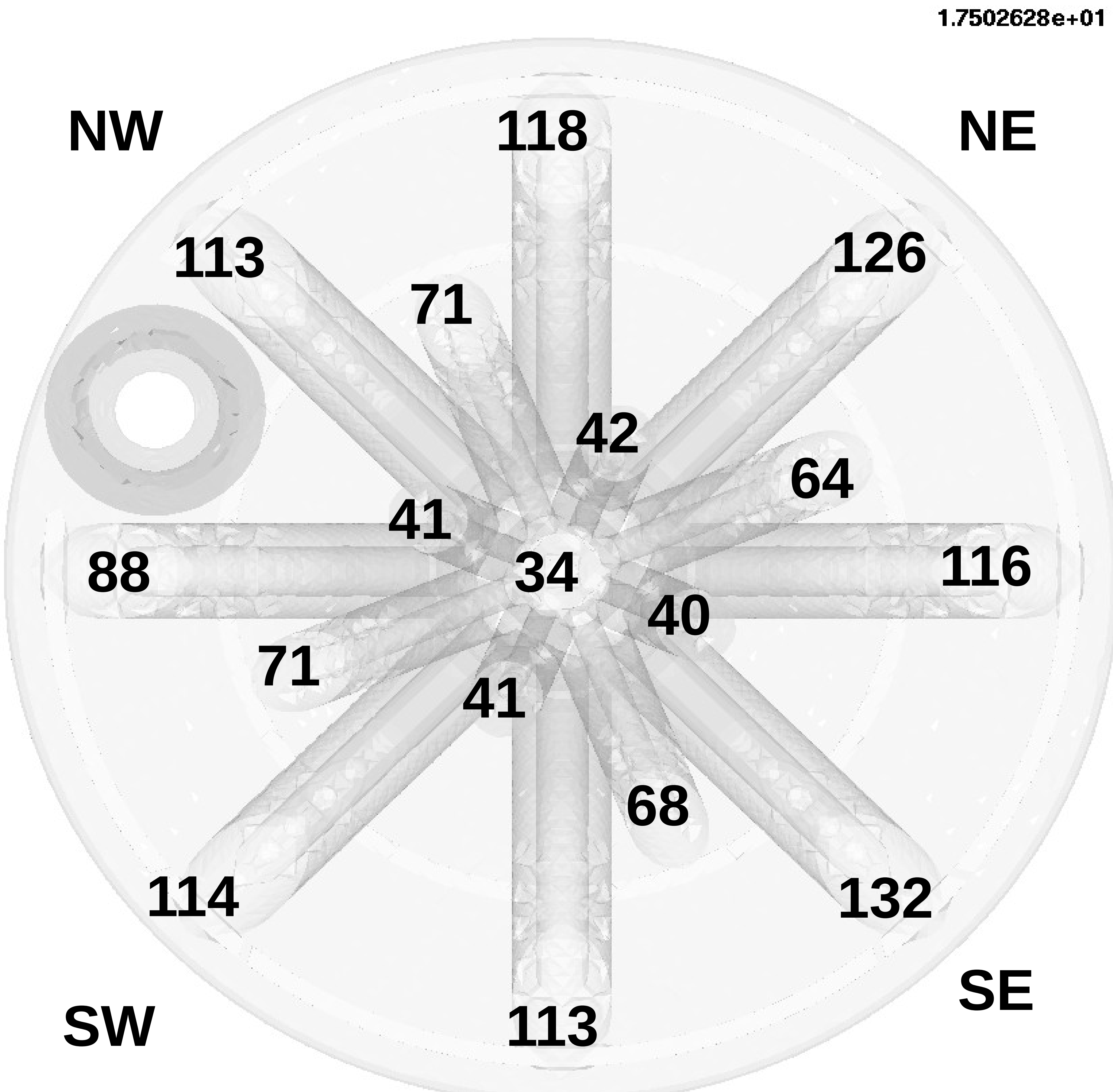
Regenerator Entry Maldistribution

- **Spent cat riser flow analysis**
  - Sloped entry design causes catalyst to flow up the opposite wall
  - Substantial maldistribution of catalyst entering regenerator

- **Is this maldistribution amplified in the distributor arms?**

Catalyst volume fraction

Spent Catalyst Distributor Mass Loadings



Spent catalyst loadings (lb/s)

- **Spent catalyst distribution is remarkably homogeneous**
  - Loadings are slightly higher side opposite to regen standpipe
  - Consistent with spent riser orientation
- **Spent catalyst flux rates highest in the center**
  - Combustion air rate is not proportional

Spent Cat Distributor Fluxes		
Ring	Catalyst	Air
Outer ring	0.682	0.0664
Middle ring	1.012	0.0854
Inner ring	1.690	0.0896

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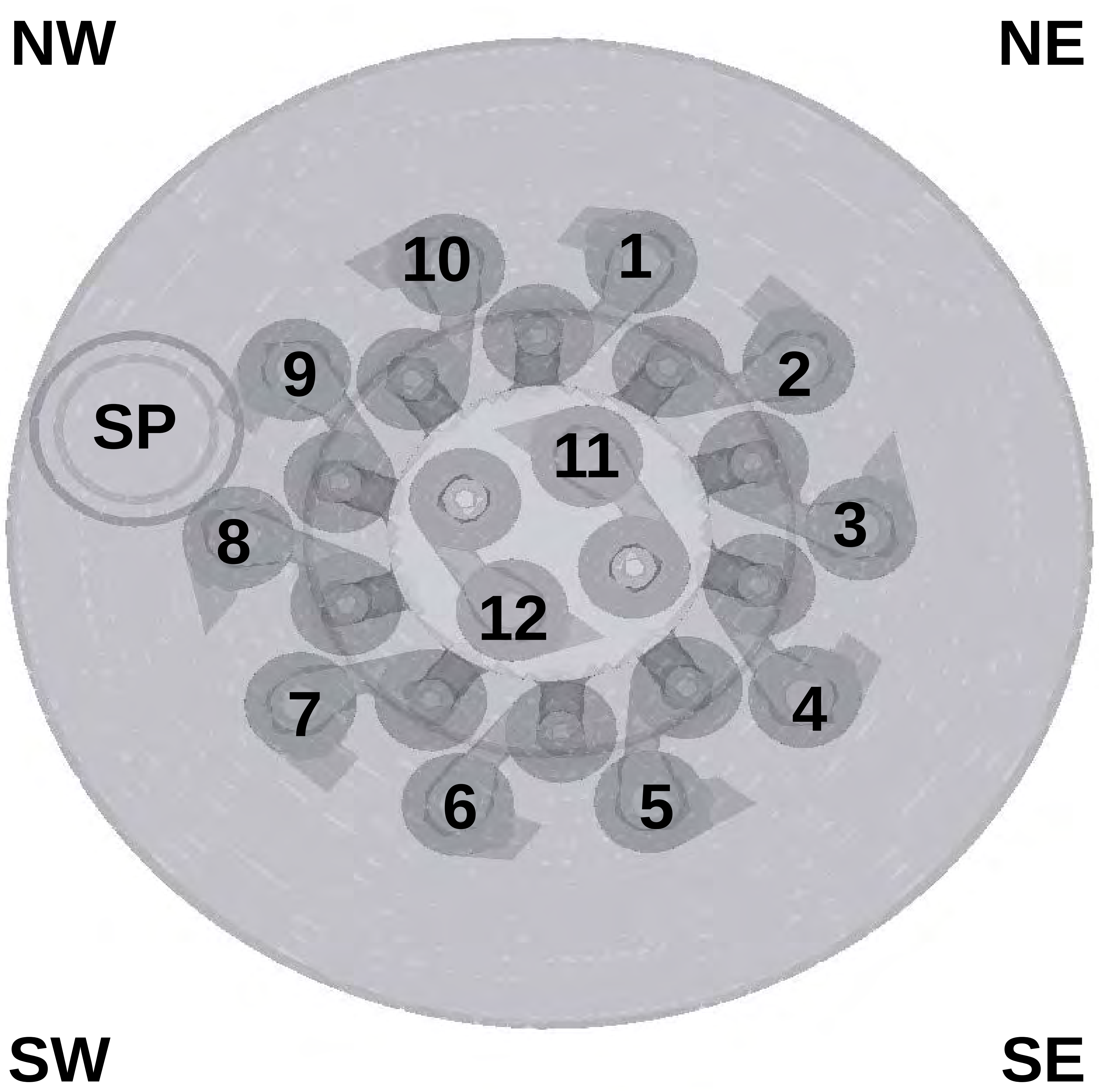
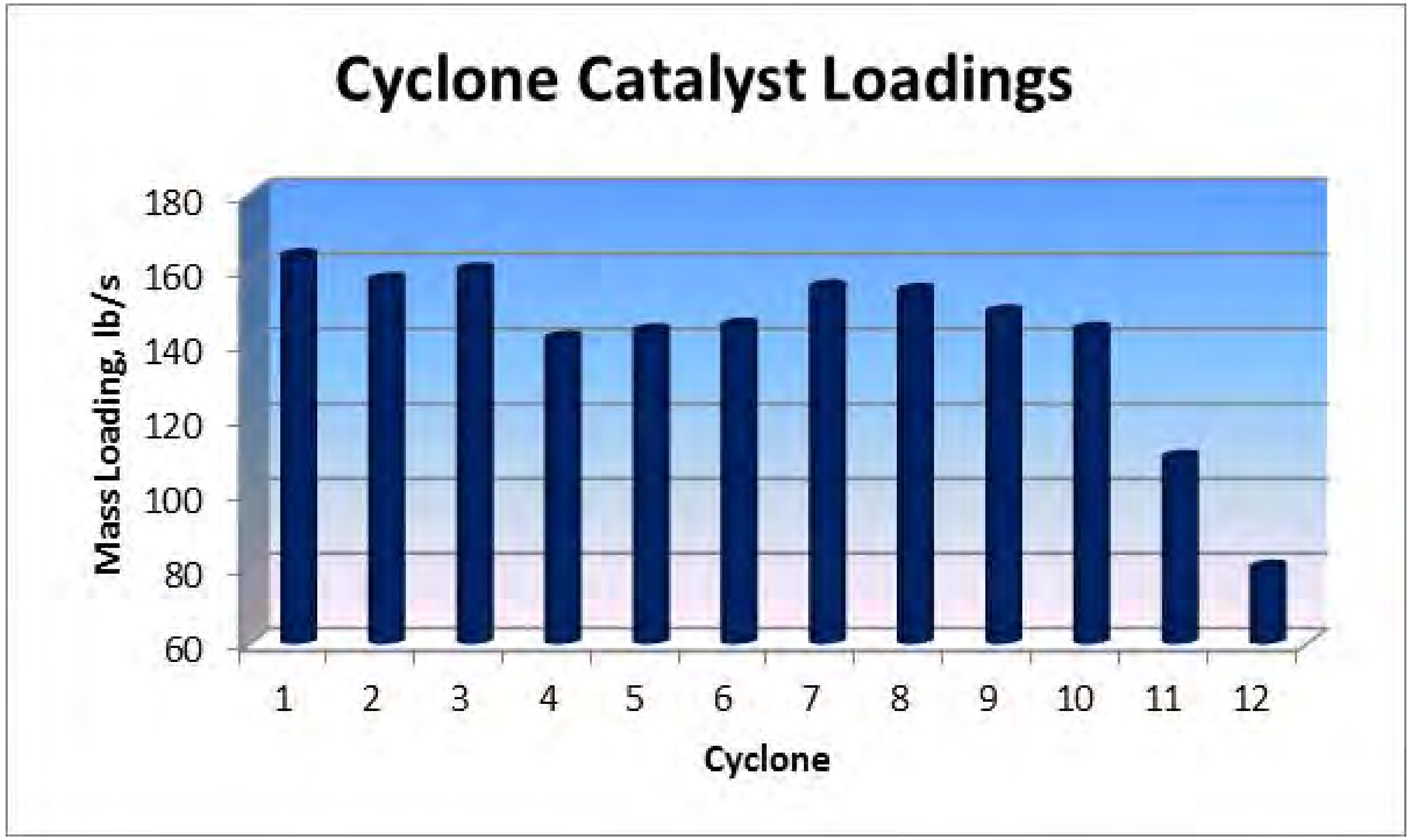
Cyclone Catalyst Loadings

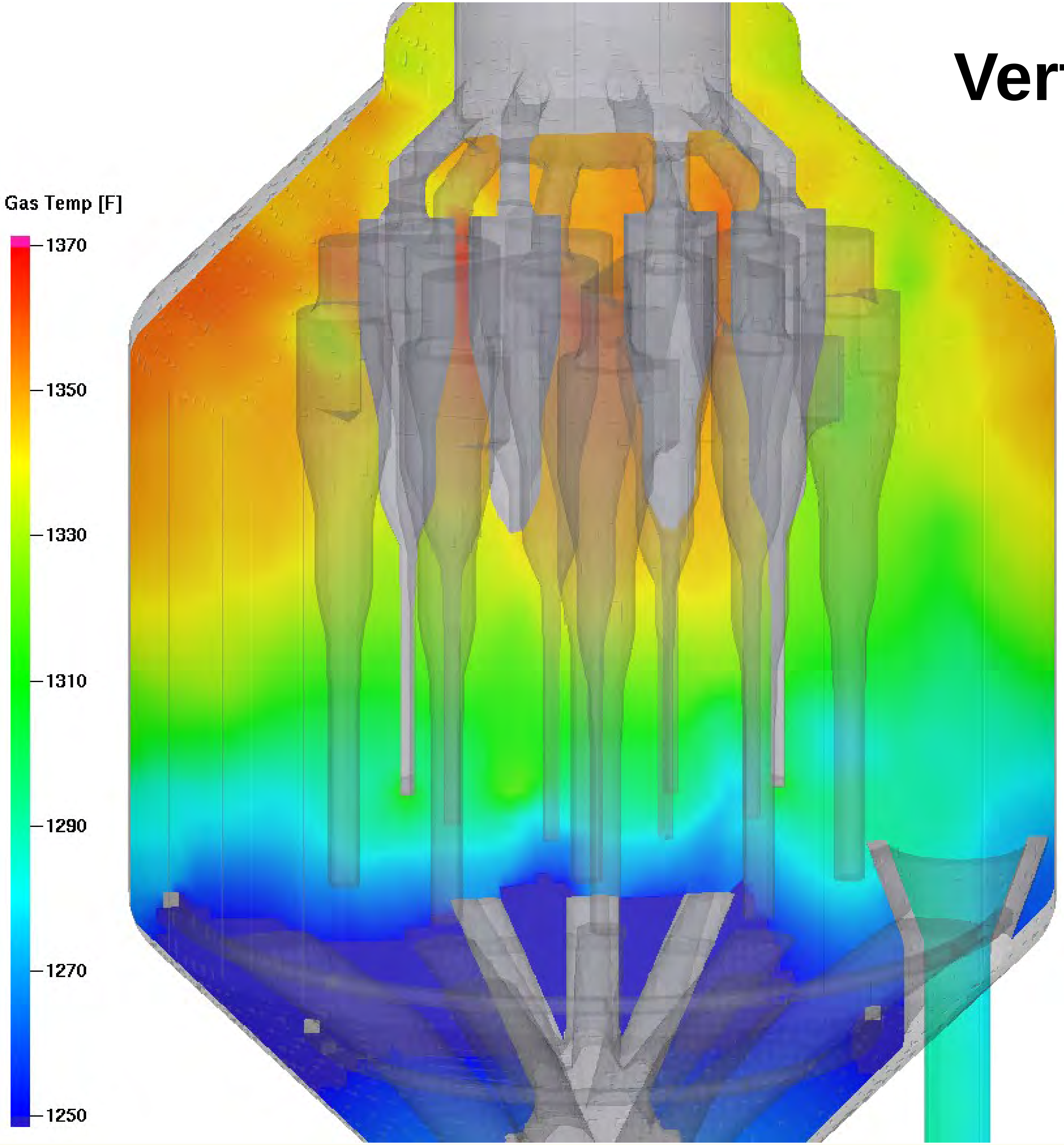




Mass loadings into each cyclone are balanced with the exception of the two central cyclone sets

The inlet horns for cyclones #11 & #12 are partially obstructed leading to lower mass loadings.

Vertical Temperature Profile



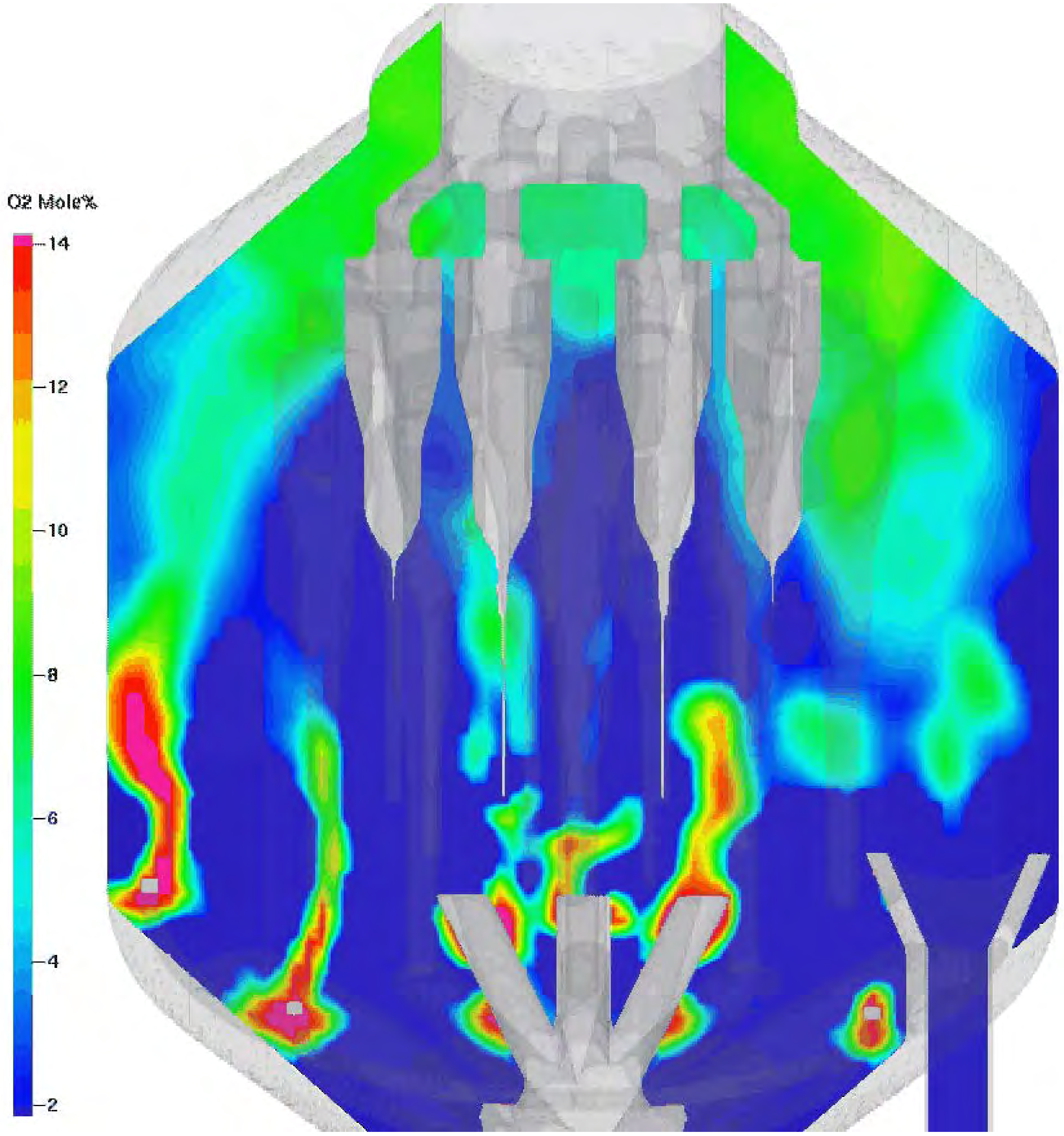
CPFD correctly models the vertical temperature profile

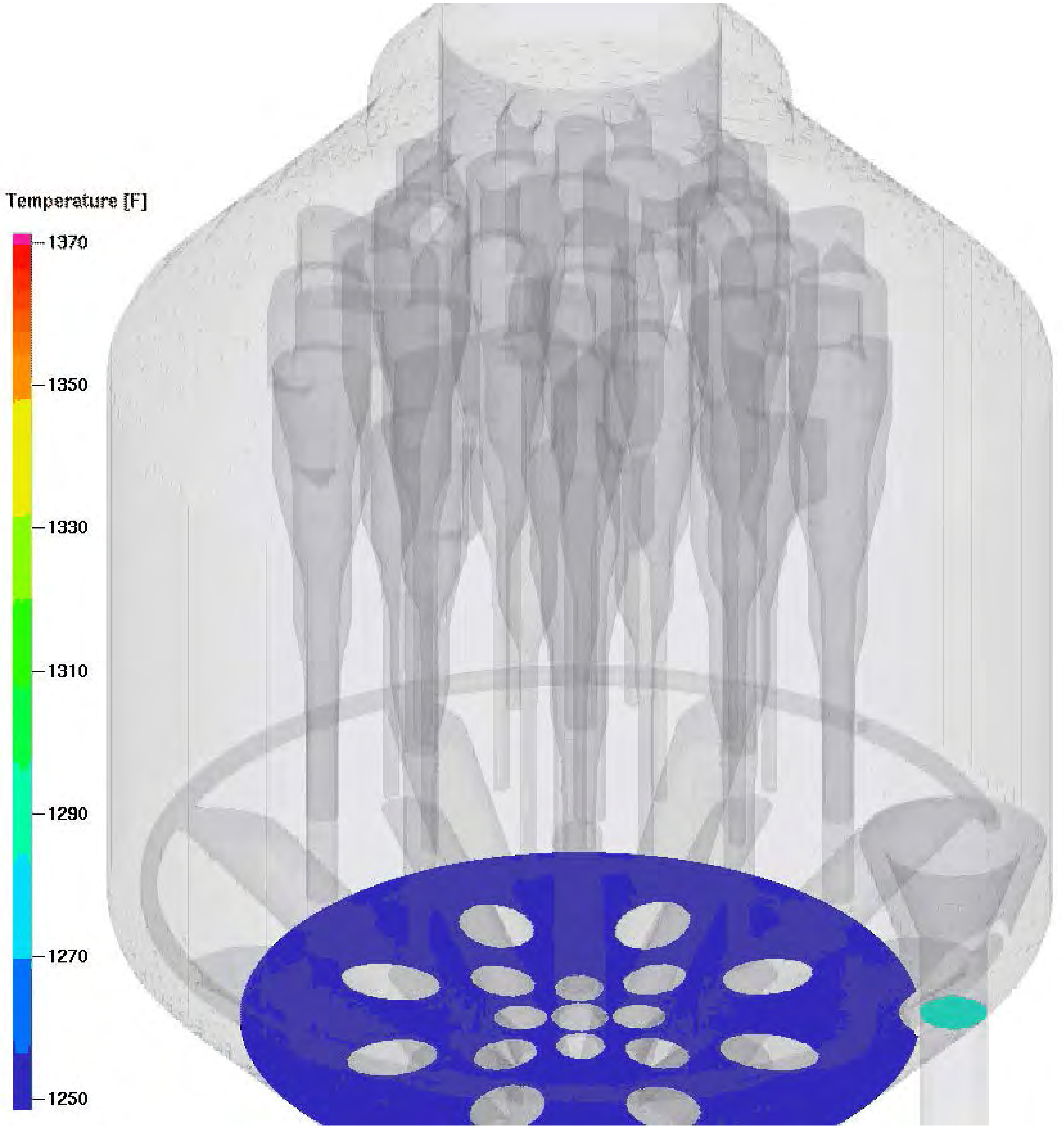
- Afterburn ~ 100 F
- Cooler temperatures observed in dense bed at and just above the spent catalyst distributor arms & air rings
- Highest temperatures observed in the dilute phase center and side opposite of the regenerator standpipe

Regenerator vertical temperature profile

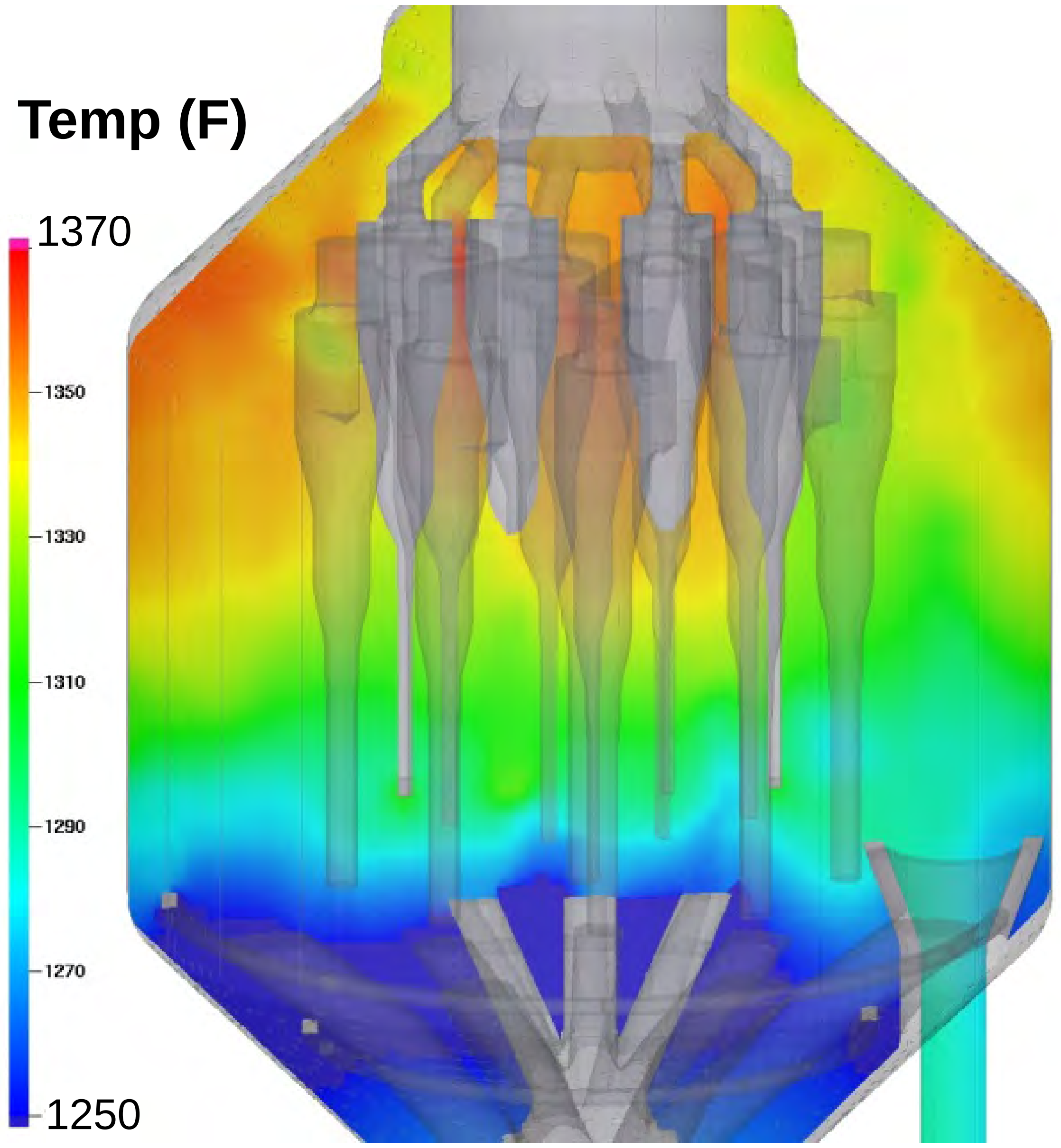
Coke Combustion Overview

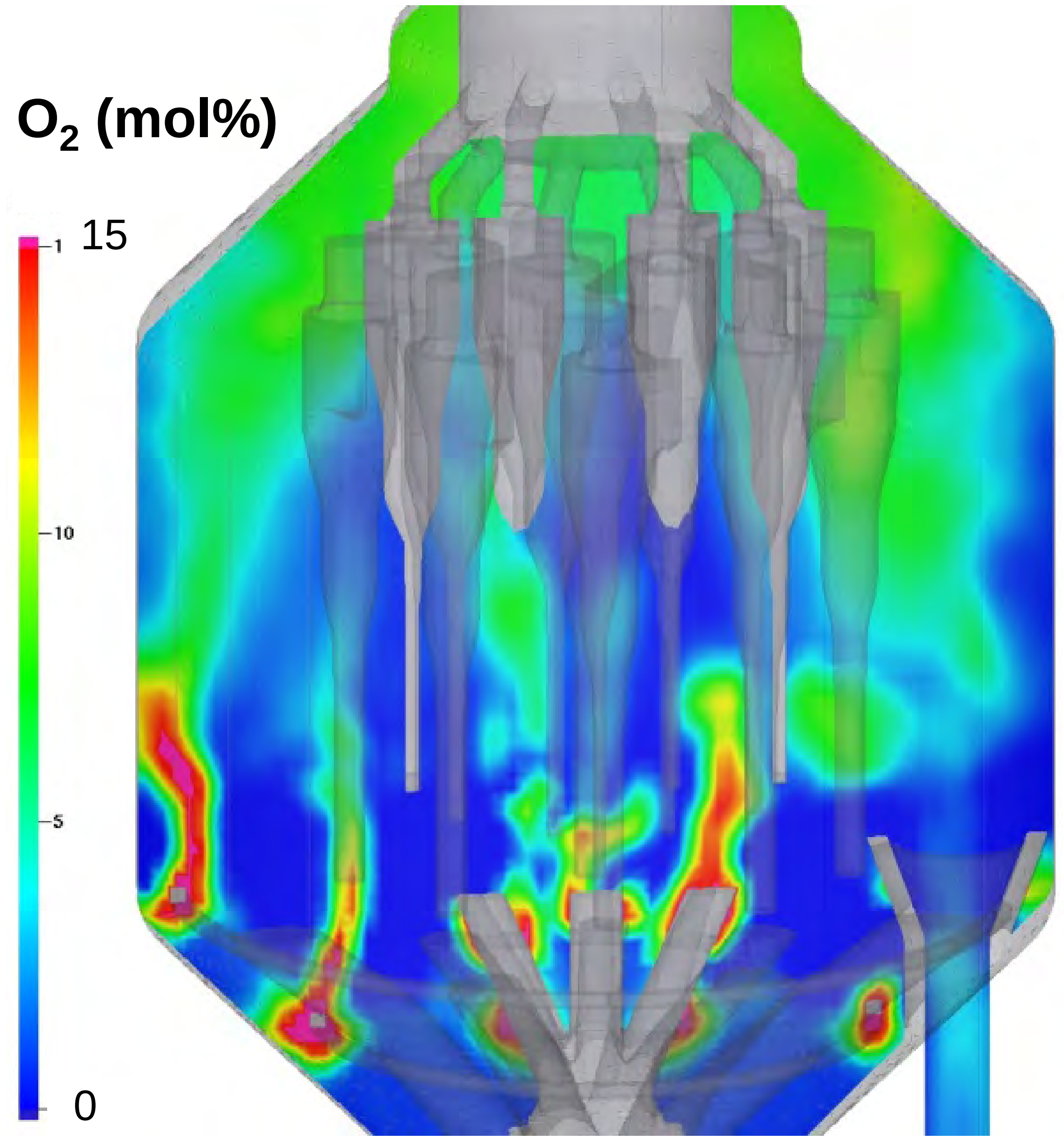
Coke combustion kinetics strongly indicate that combustion air flow at the outer ring dominates regenerator performance

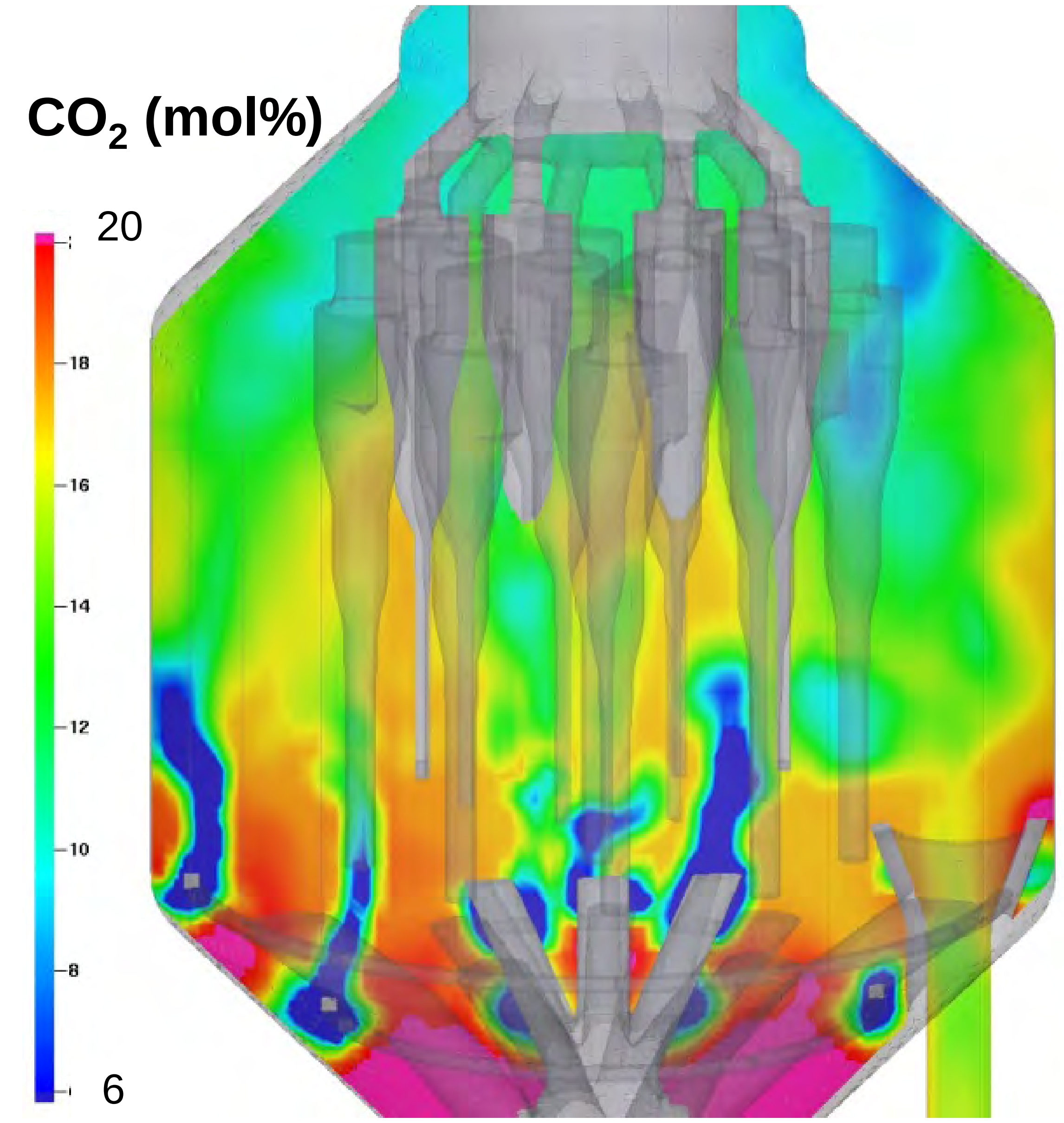


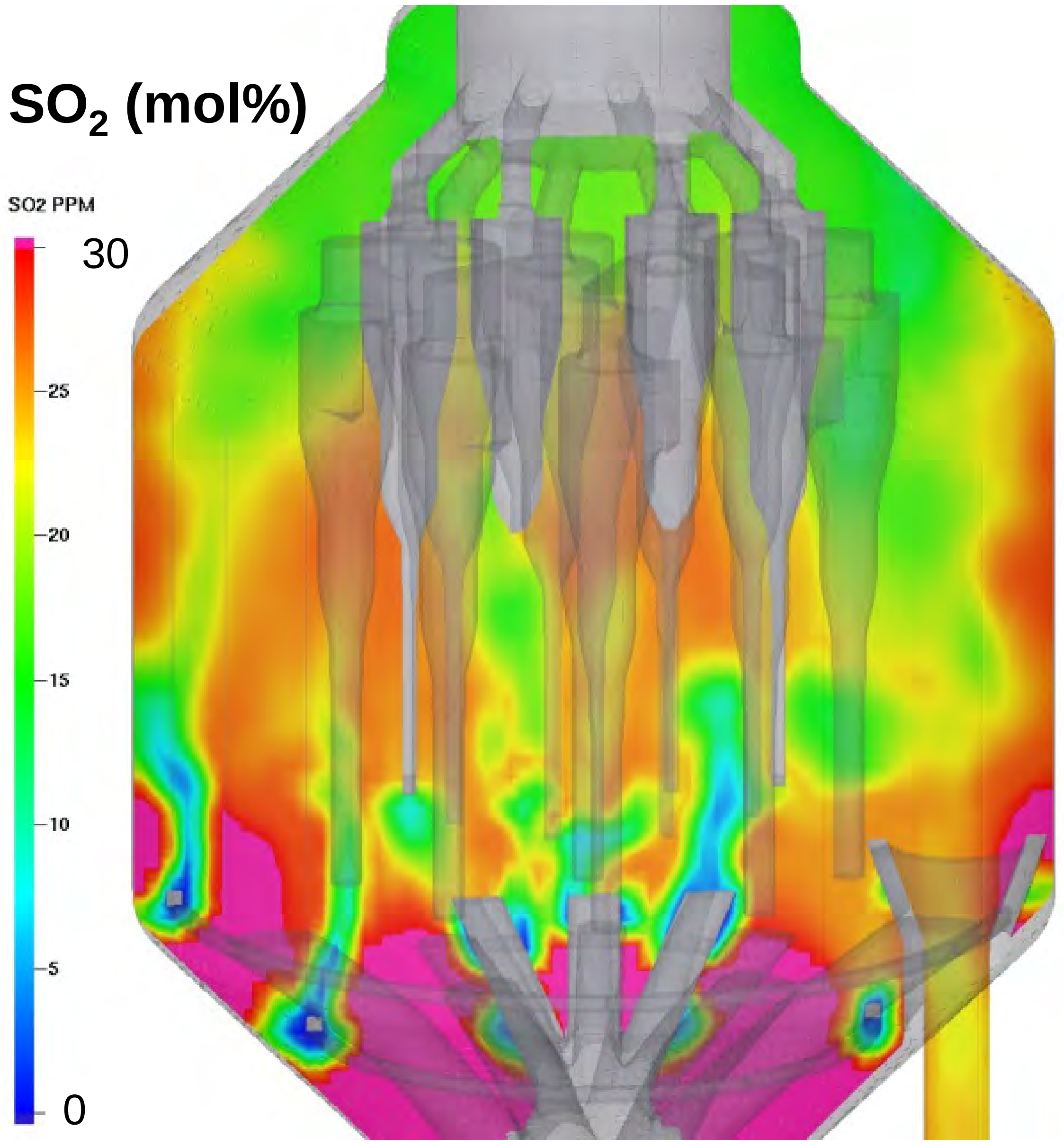


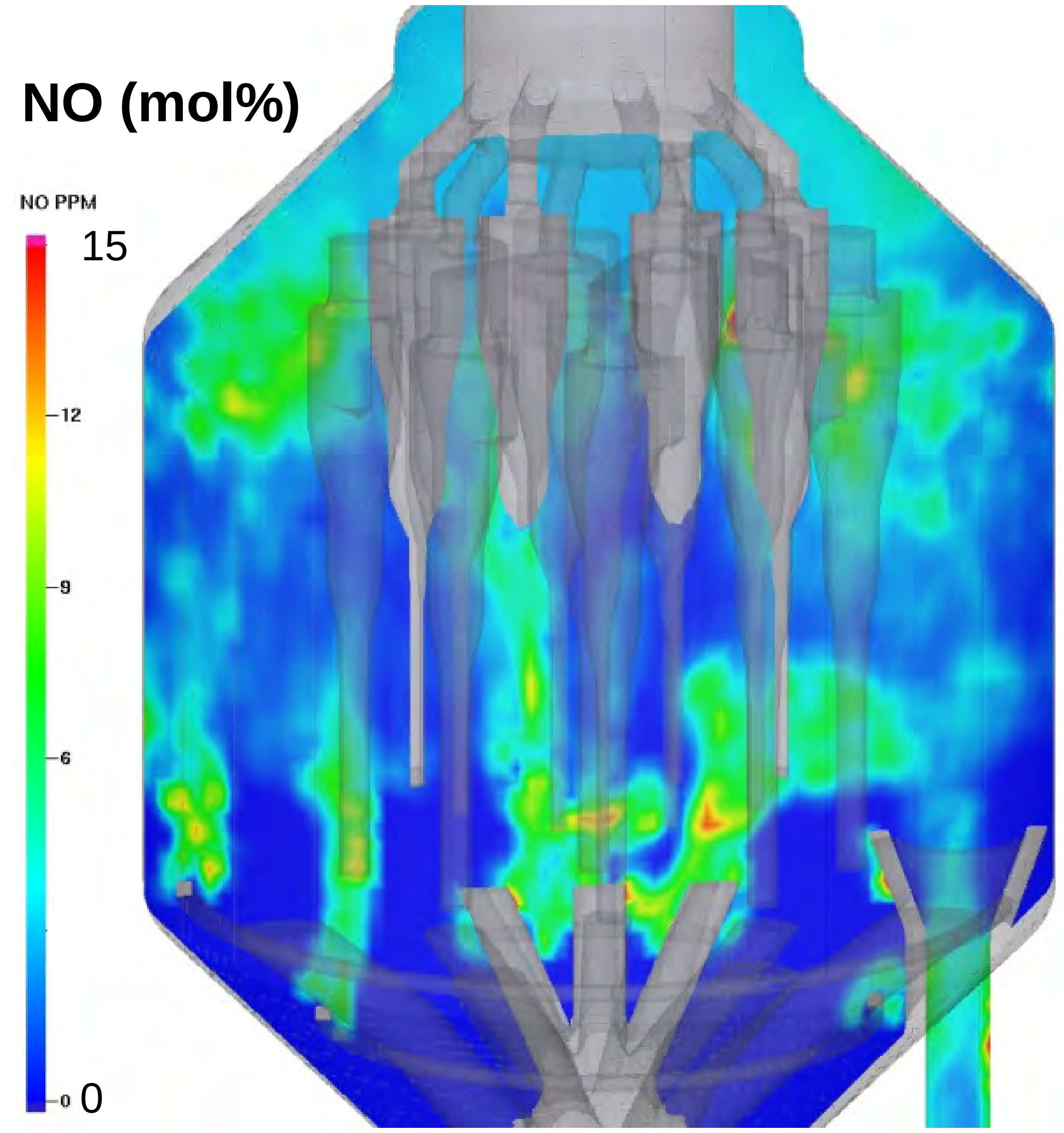
Vertical Chemistry Cut Planes





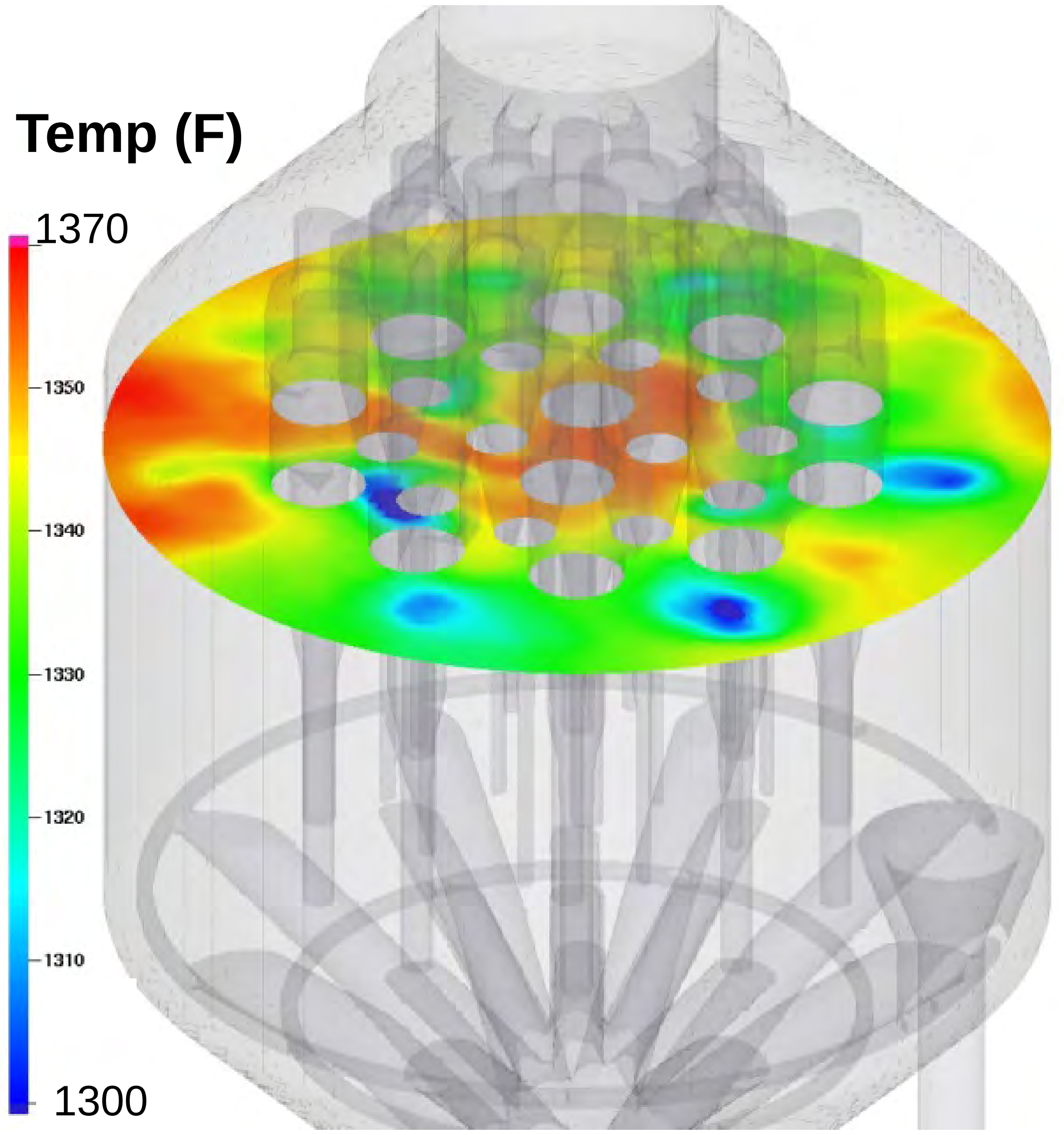


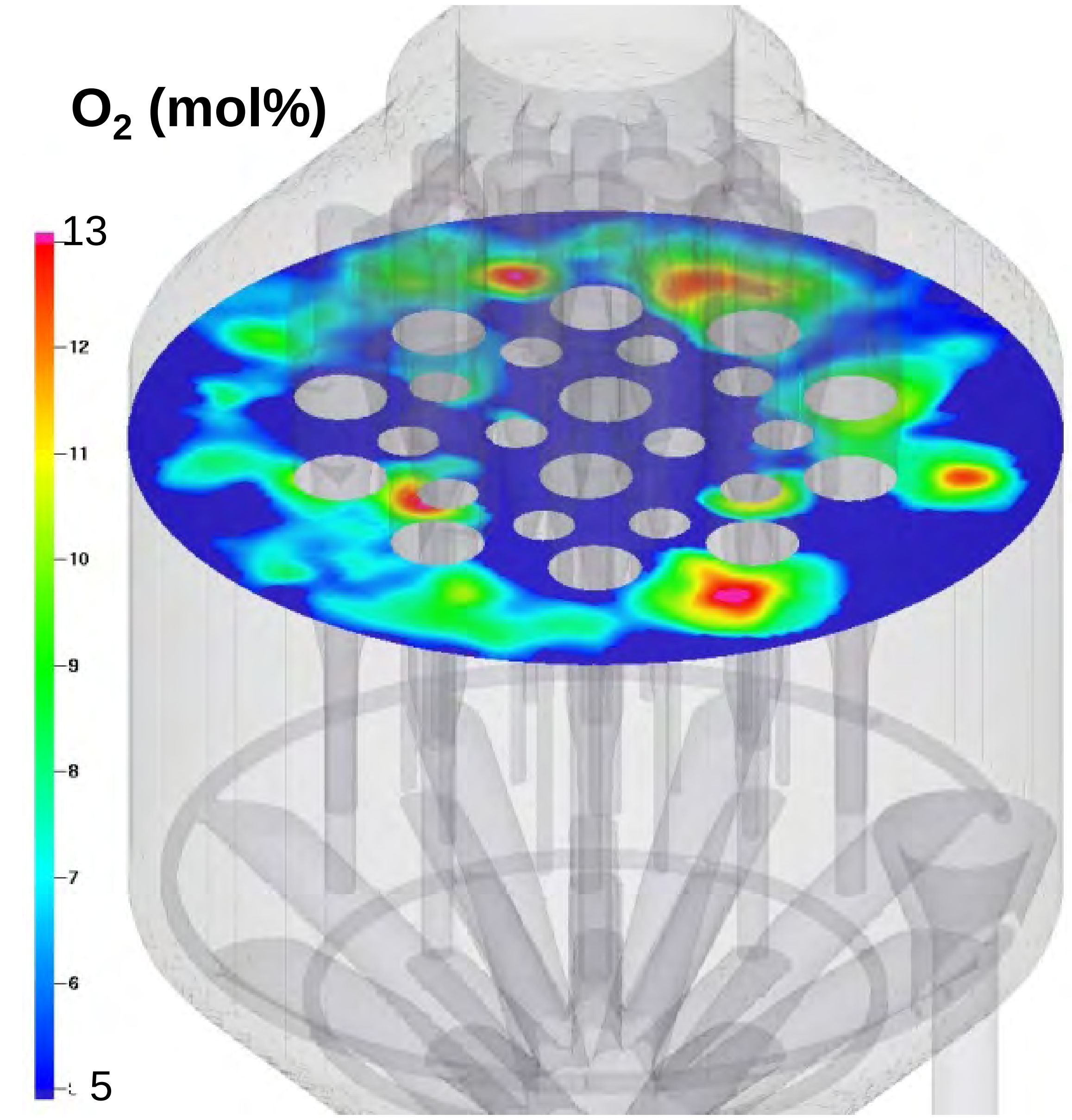


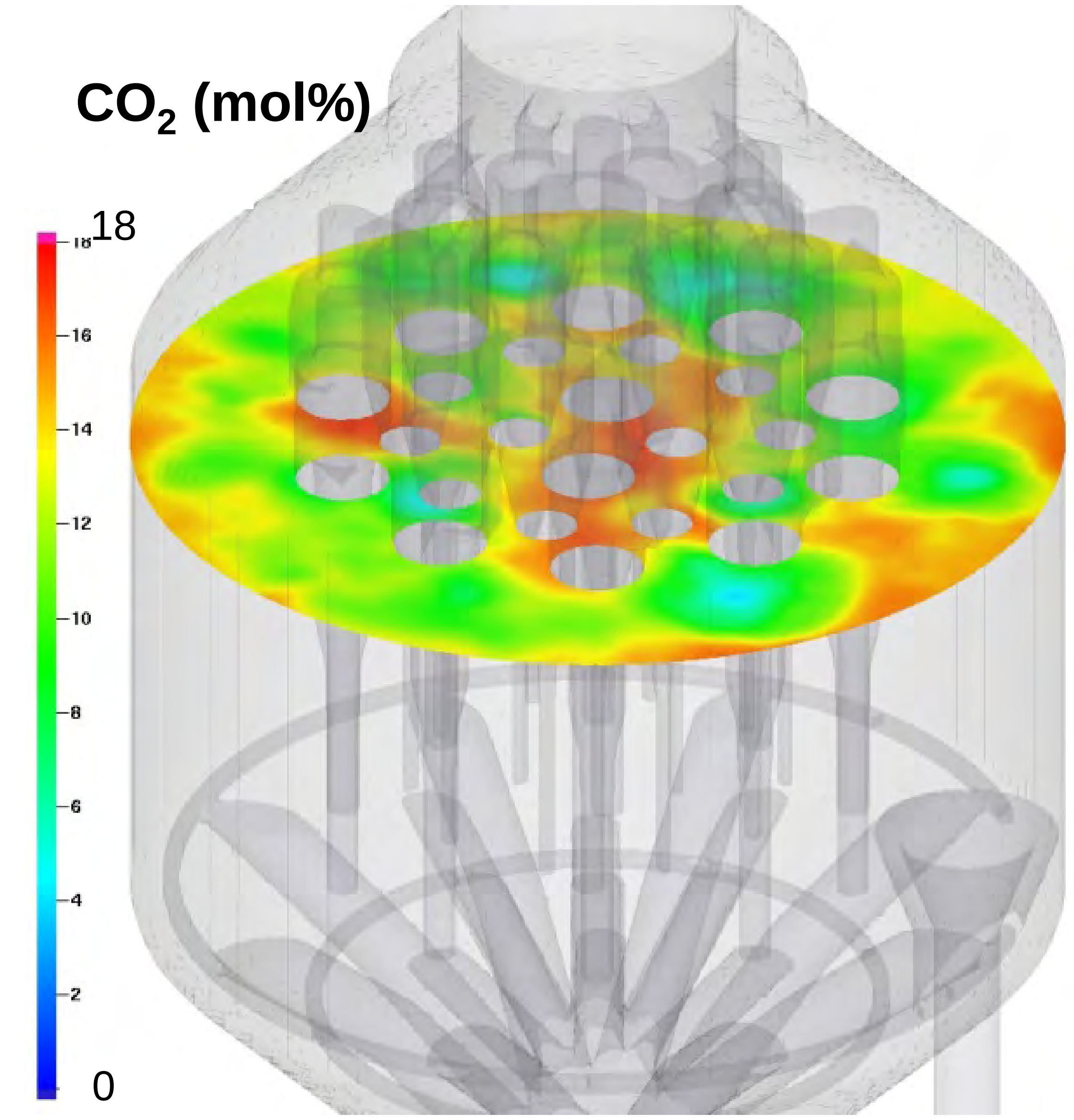


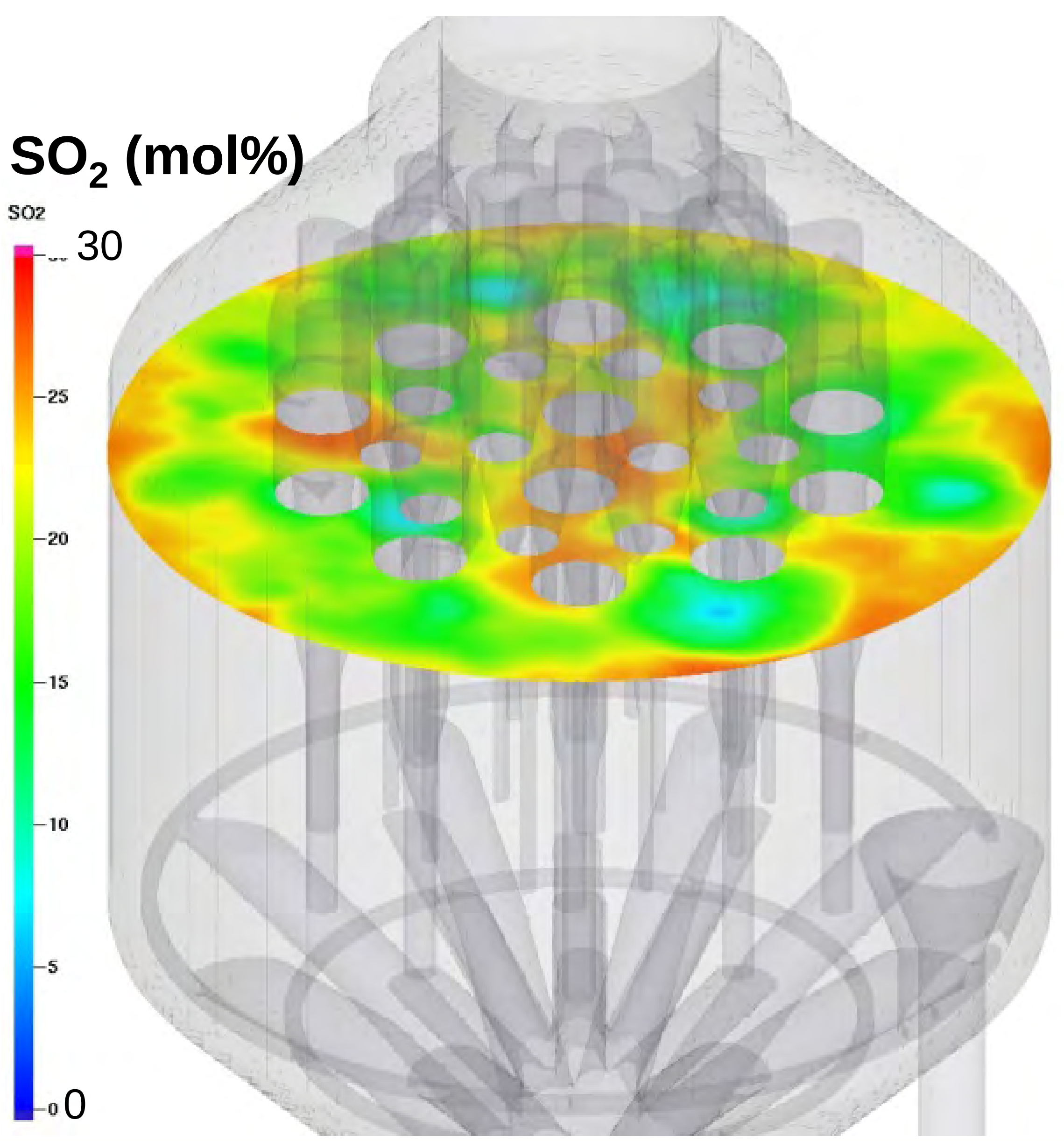
Outer ring combustion air dominates flow & combustion patterns

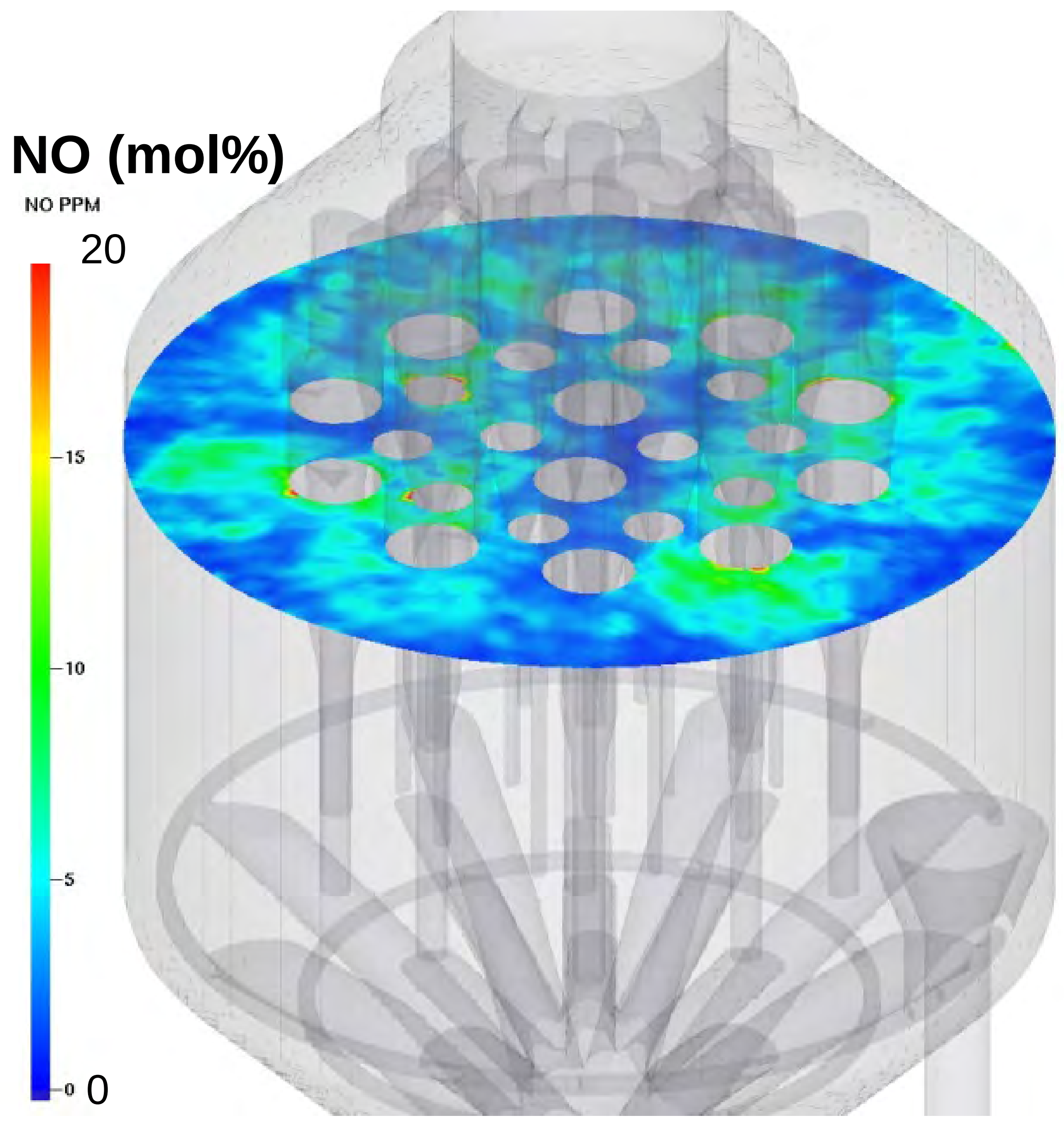
Horizontal Chemistry Cut Planes





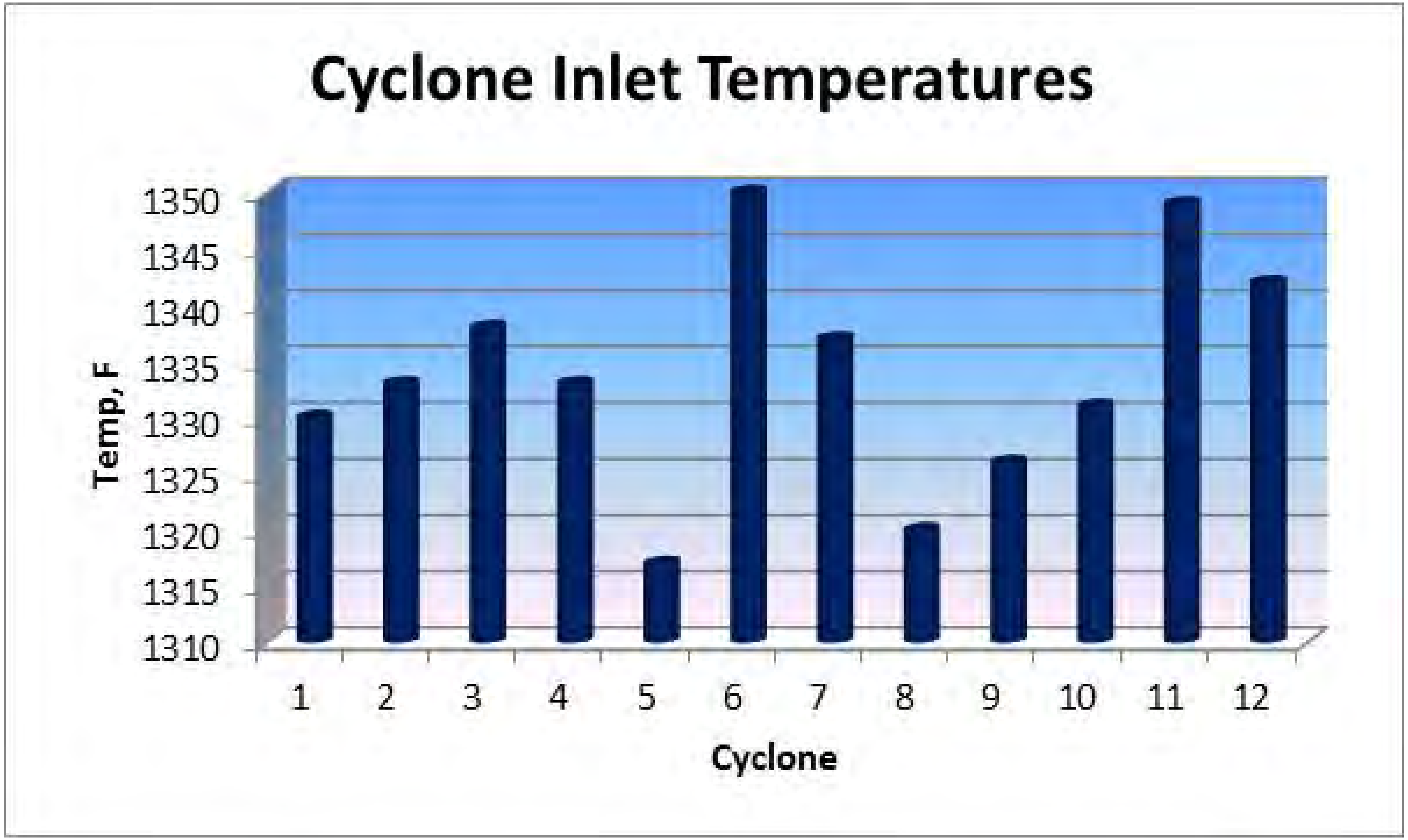






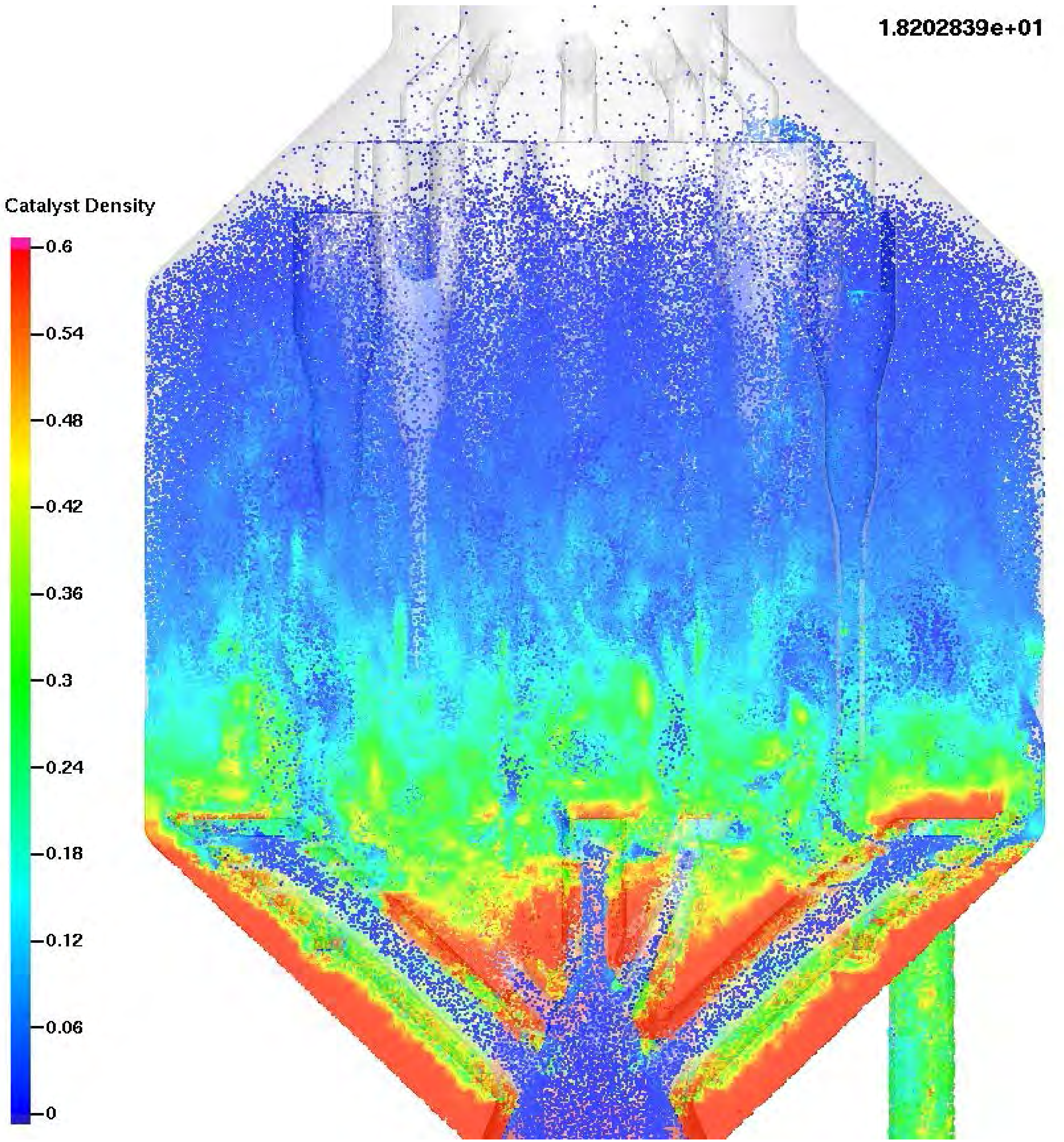
Maldistribution patterns repeated at cyclone inlet horns

Temperature Profile



Cyclone temperatures confirm observed maldistribution

- Highest temperatures observed with cyclones #6, #11 & #12
- Average temperature of the last 10 simulation seconds



Vertical cut plane catalyst volume fraction profile

Dense Bed Residence Time

- **Insufficient dense bed residence time likely contributes to afterburning**
- **Observations include:**
  - Extremely shallow dense bed
  - Large non-fluidized zone at base of regenerator
    - *Highly dense "red" zones*
- **Supporting evidence includes:**
  - High levels of O_2 exiting the dense bed
  - Significant jetting through the bed

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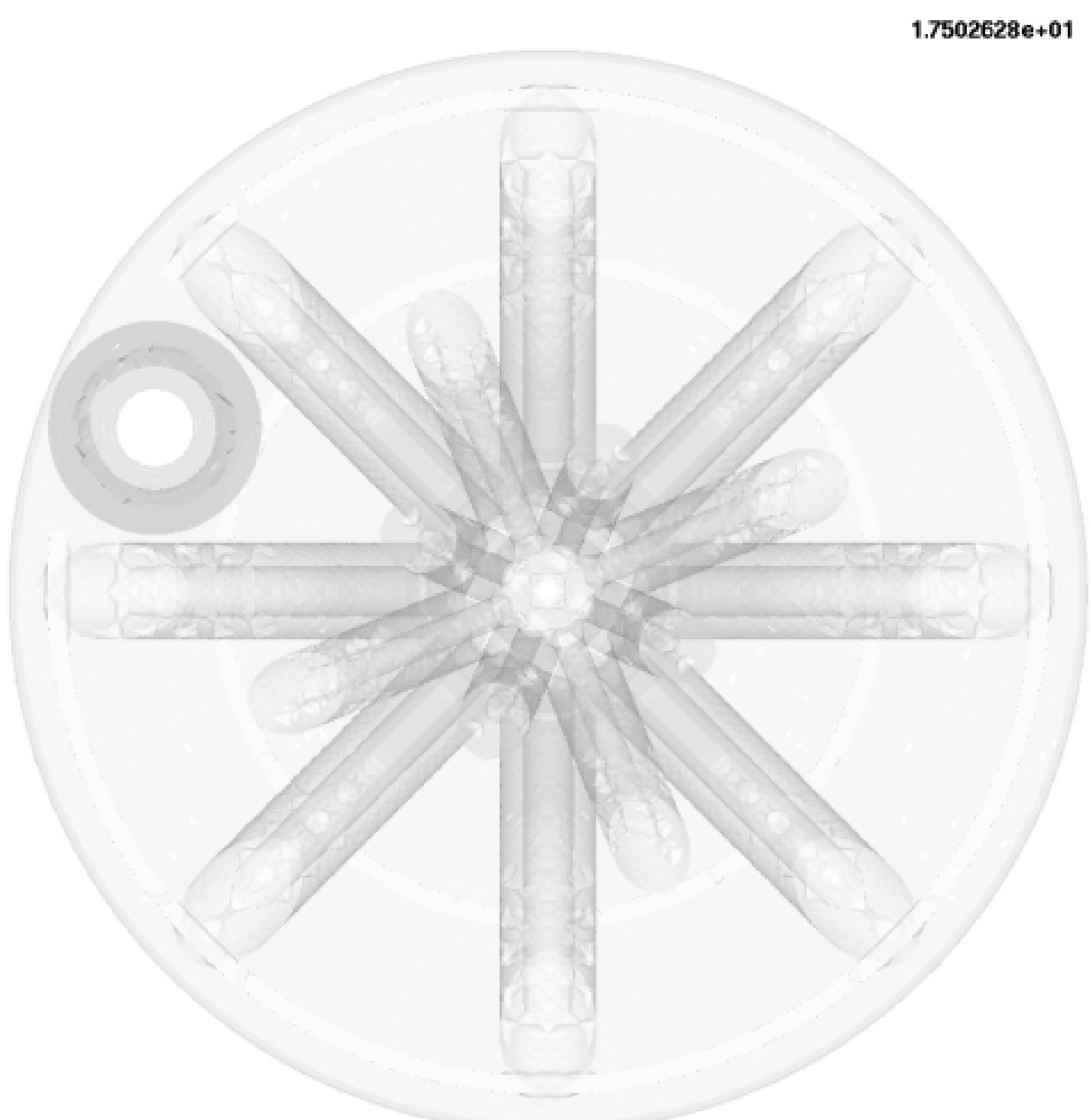
Afterburn Analysis

Low combustion air delivery to the center of the regenerator appears to be the significant contributing factor leading to afterburn

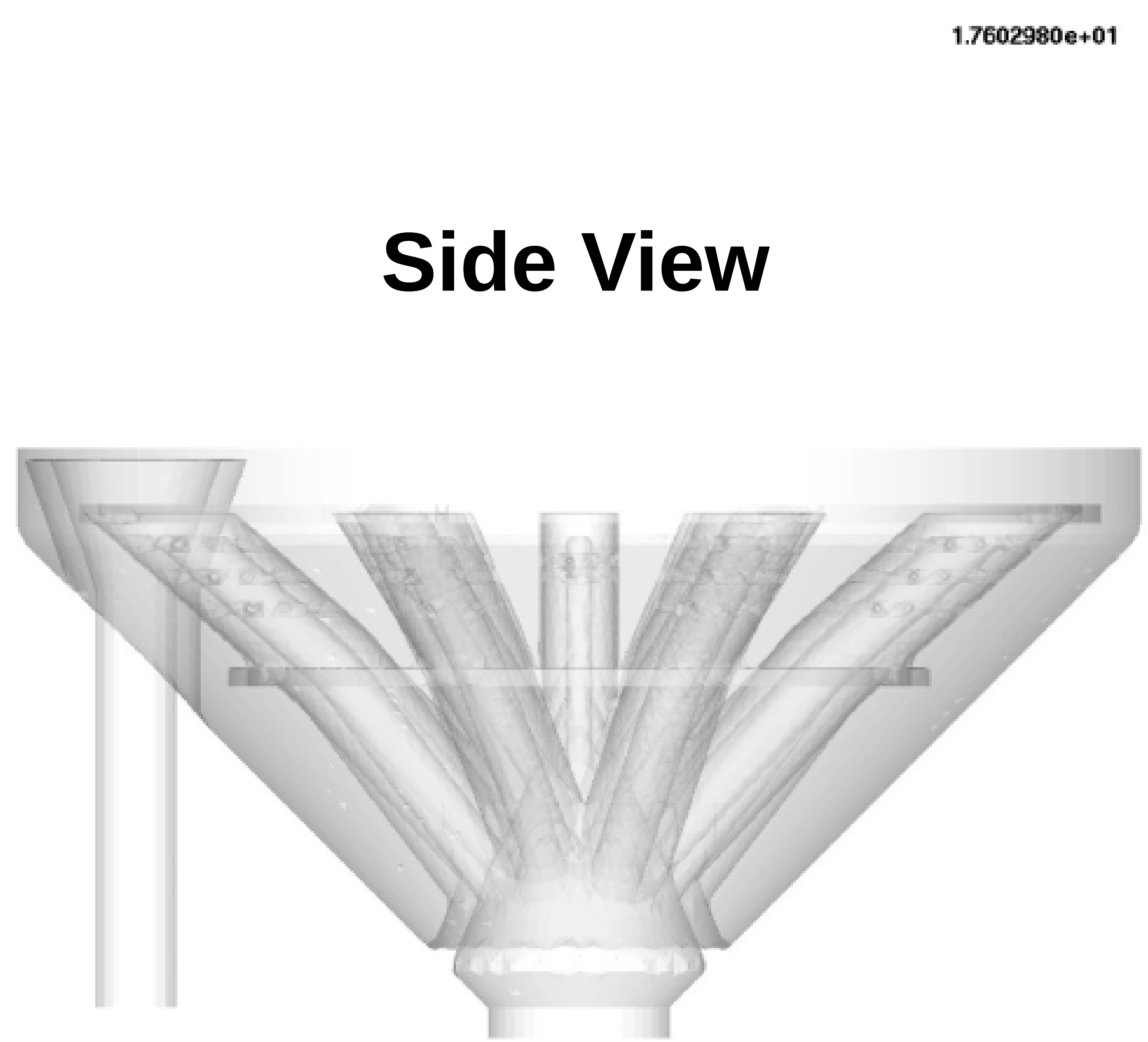
- An additional air ring in the center of the distributor is suggested
- Subsequent balancing of combustion air flow recommended

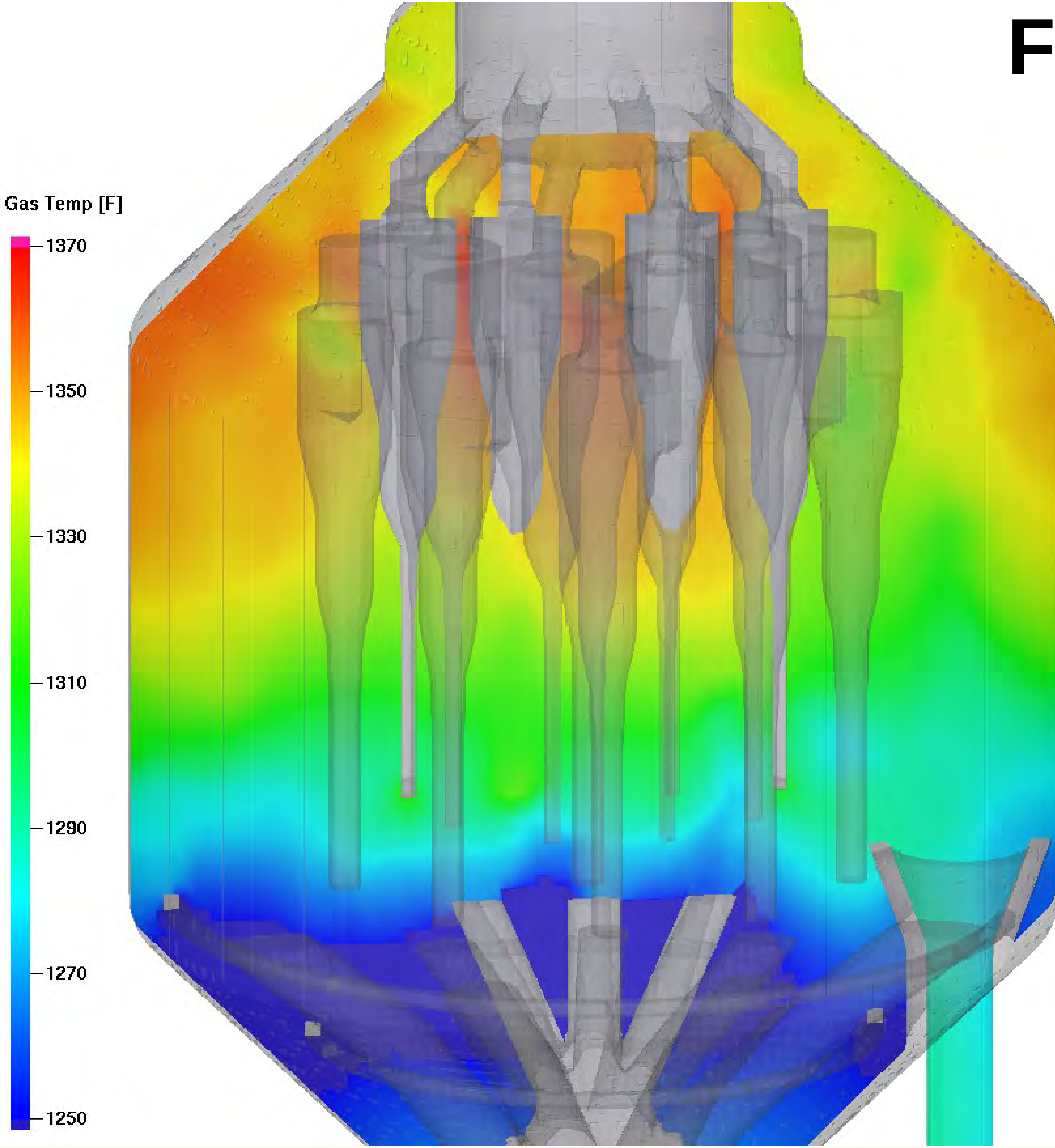
Shallow dense bed also likely contributing to afterburning



Top View

Side View





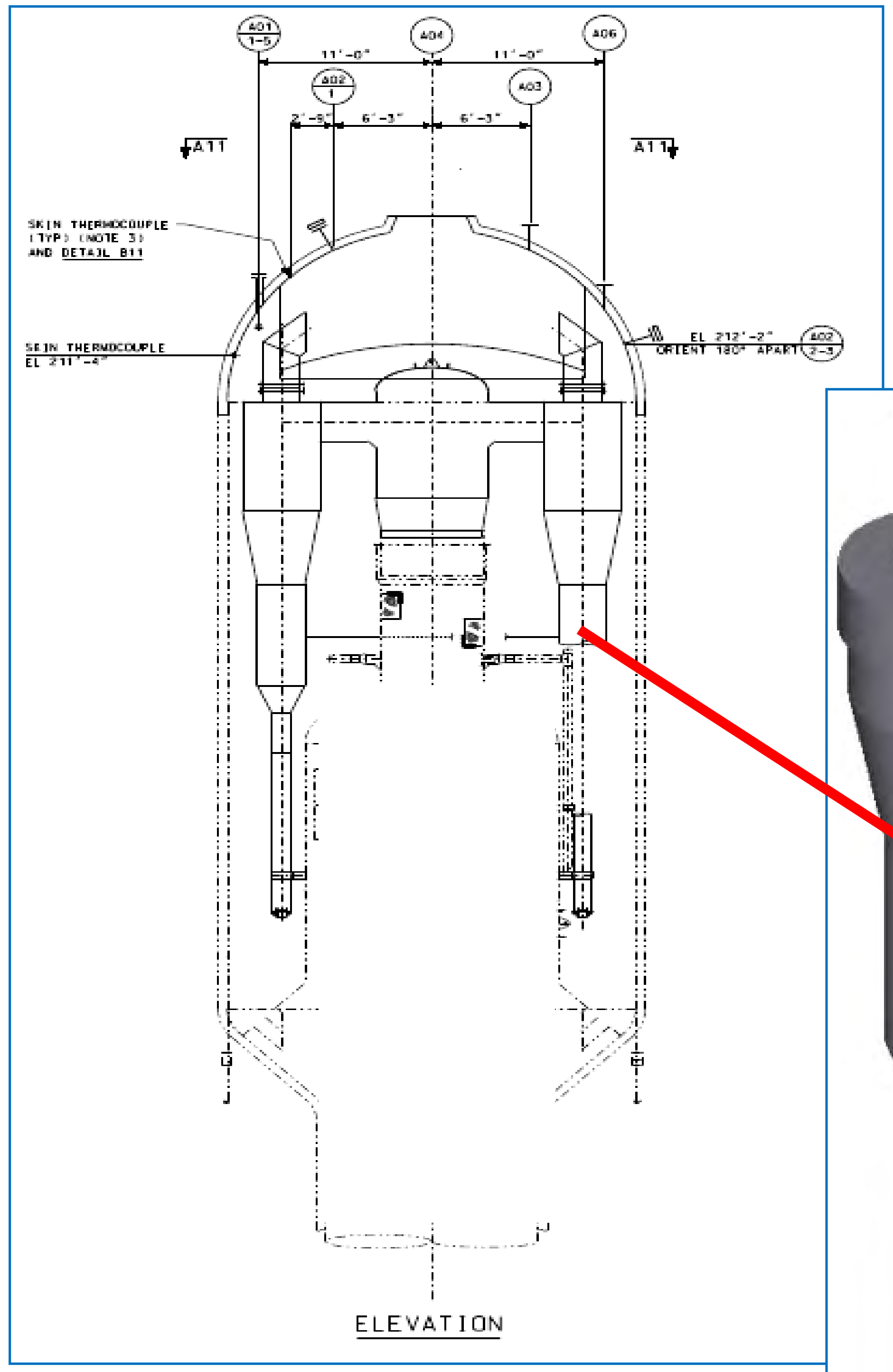
FCC Regenerator Case Conclusions

Barracuda VR accurately modeled both the gas-particle hydrodynamics and coke combustion chemistry

- Full-scale commercial unit
- Compared to operational data
- Captured afterburn phenomena
- Identified temperature gradients measured in cyclone inlets.
- Provided insight to help solve a problem that has been ongoing for over 70 years.

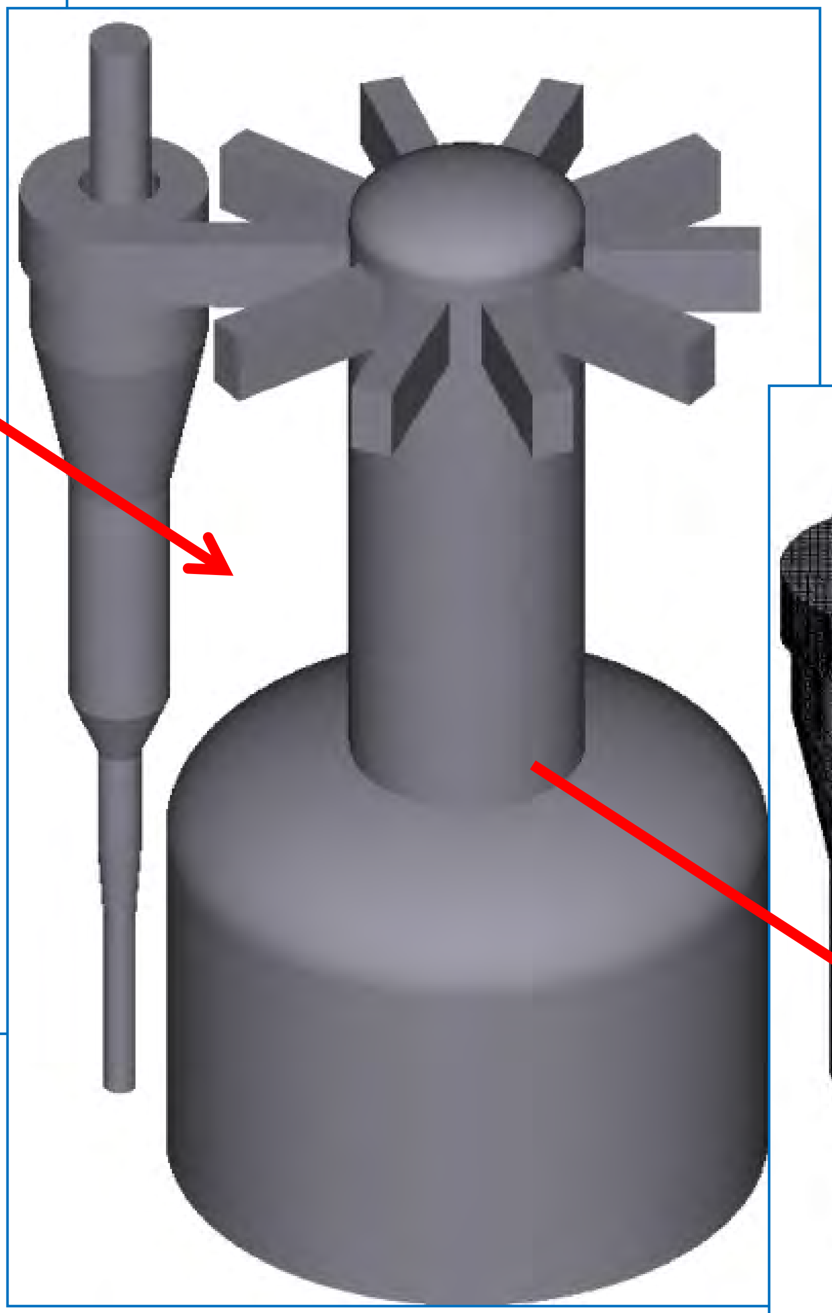
Case Study 2: FCC Reactor Cyclone Erosion Reduction

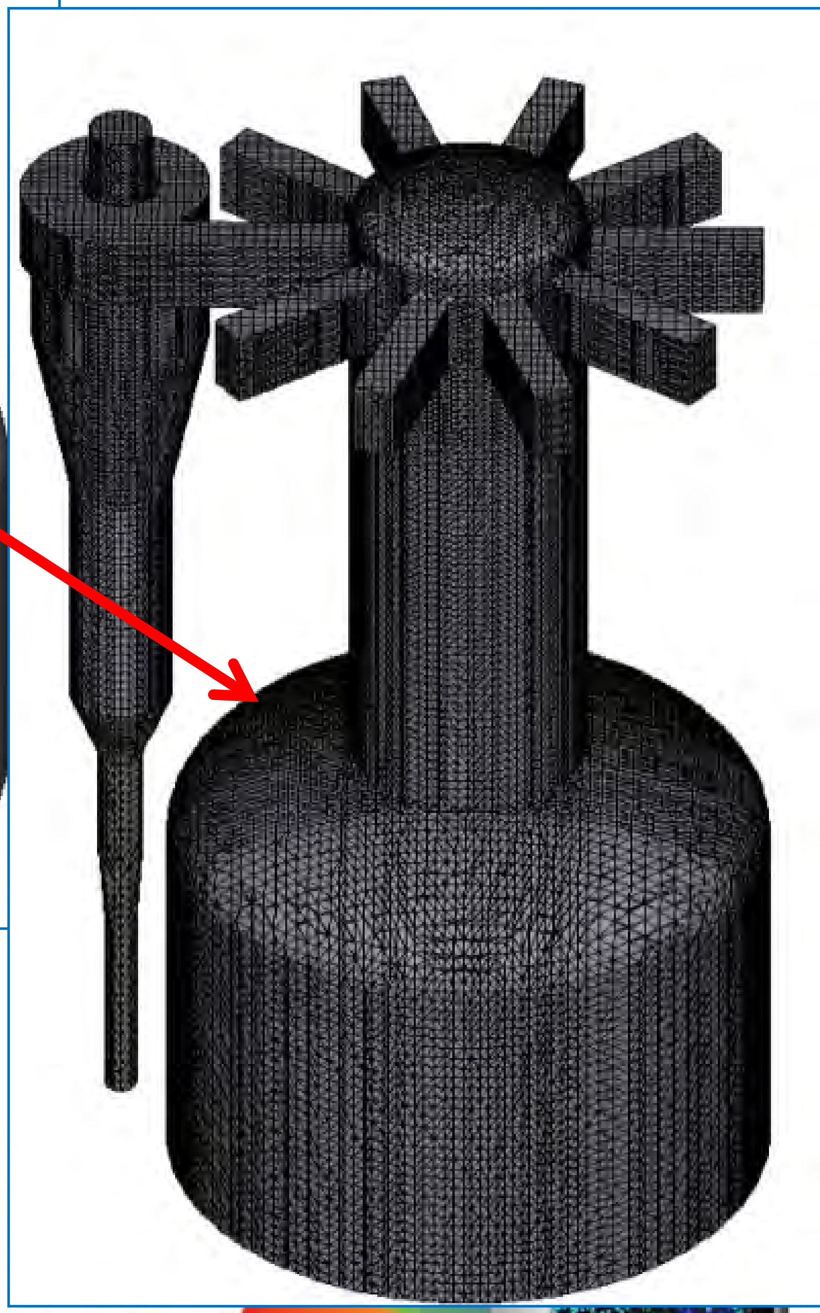
- A revamp was scheduled for a UOP-designed fluid catalytic cracking process unit at Marathon Petroleum's Catlettsburg Refining facility.
- Part of the scope of the revamp includes the installation of new reactor cyclones. The overall objective of this work was to demonstrate what affect the proposed reactor modifications would be likely to have on erosion behavior and operational life.
- Three configurations were analyzed and compared:
  1. Baseline analysis – existing operation
  2. Alternate Design #1
     - Larger diameter outlet riser
     - Anti-vortex baffles installed in outlet riser
     - Cyclone inlets expanded to have larger cross-sectional areas
     - New cyclones
  3. Alternate design #2
     - Same changes as Alternate #1, plus
     - Sloped cyclone inlets



Example Courtesy of:

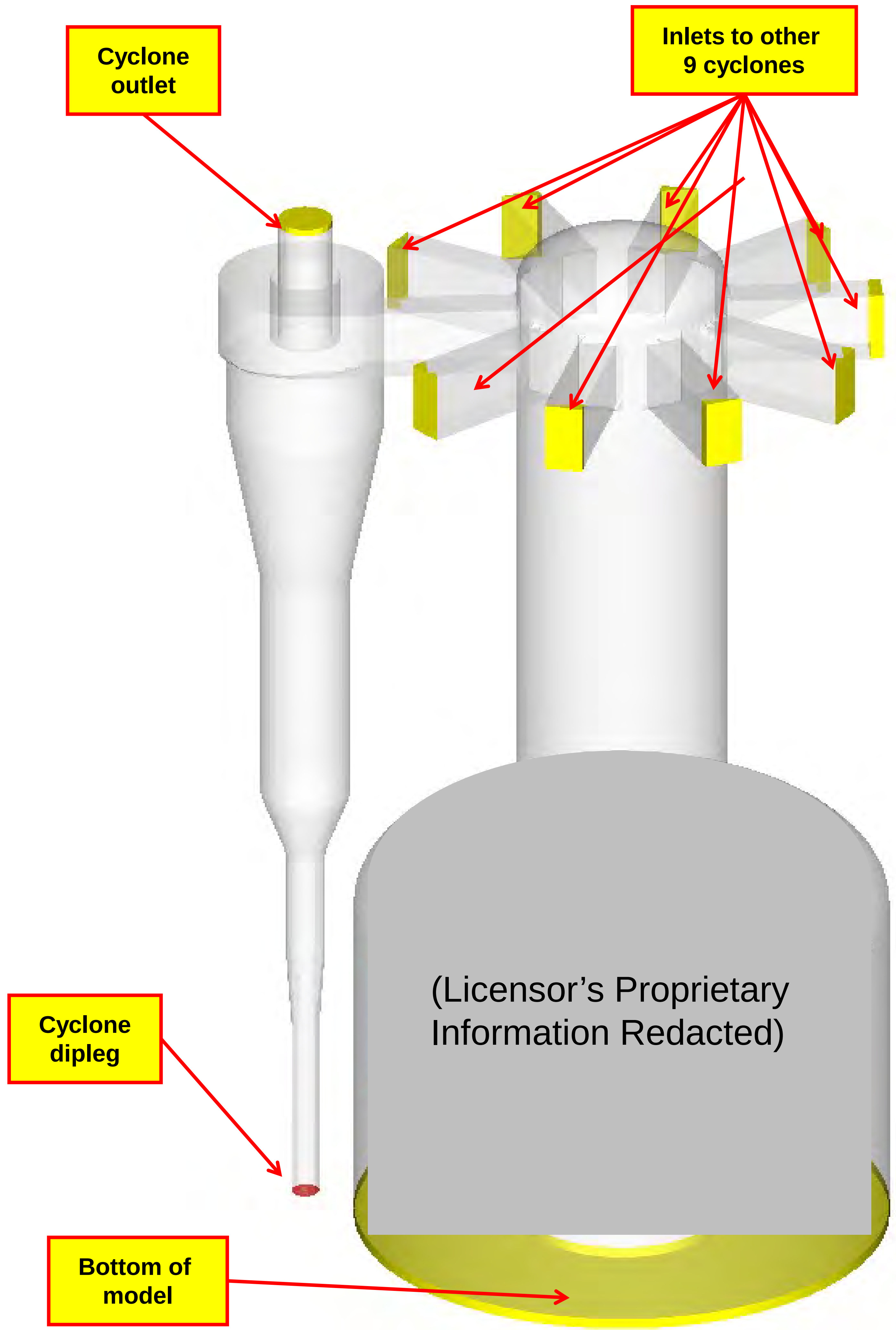
Marathon Petroleum Corporation





Reference: Blaser, P., and Sexton, J. *"CFD Reactor Case Study: Comparison of Cyclone Erosion Characteristics for Proposed Redesigns for the Marathon Petroleum Catlettsburg Refinery FCC Reactor"*, presented at American Fuel and Petrochemical Manufacturers' Cat Cracker Seminar and Exhibition, Houston, TX, (2012).

Gas Boundary Conditions

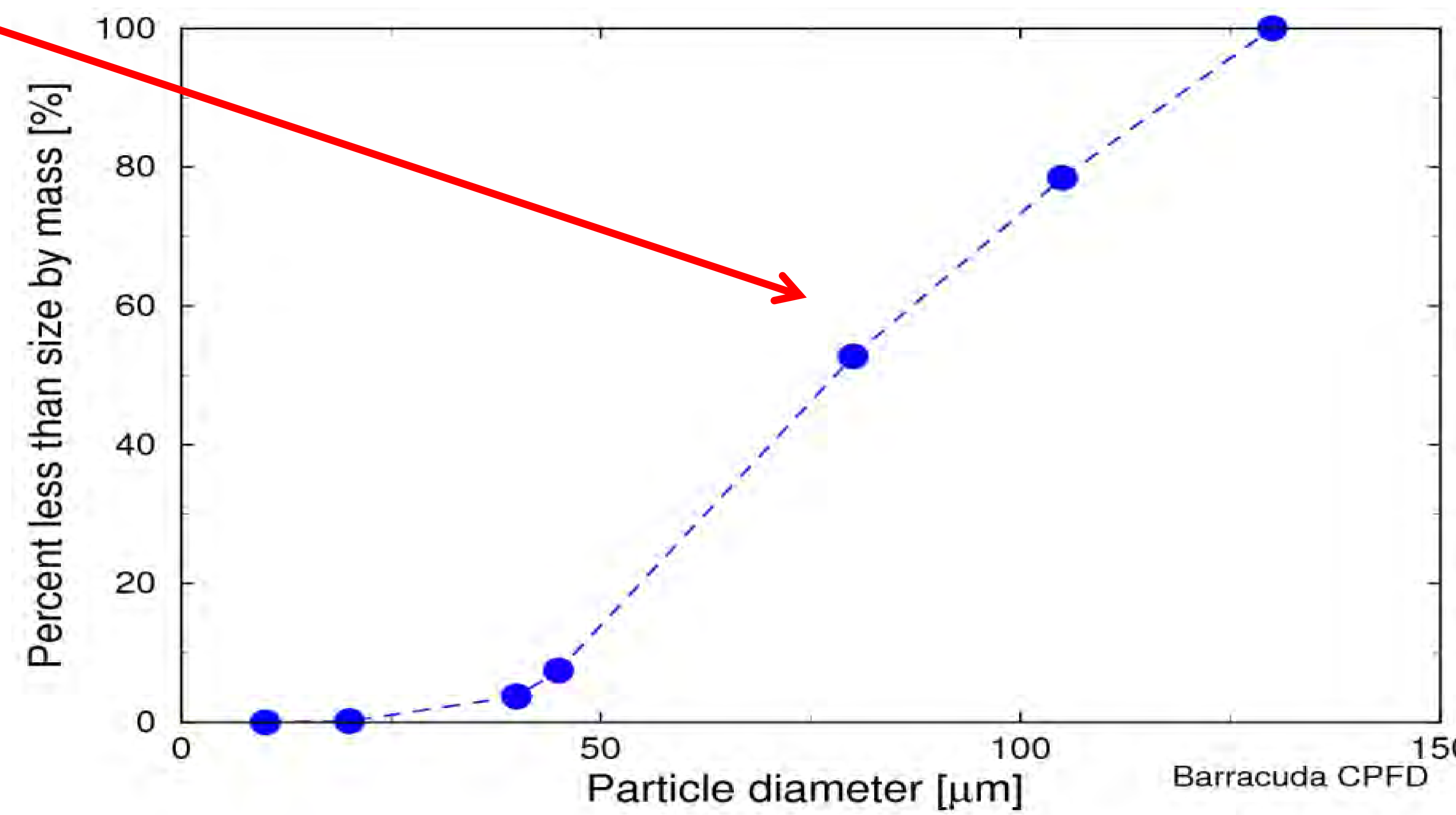


- **Gas properties**
  - Molecular weight = 70.59 g/mol
  - Viscosity = 0.019 cp
  - Temperature = 990° F (805K)

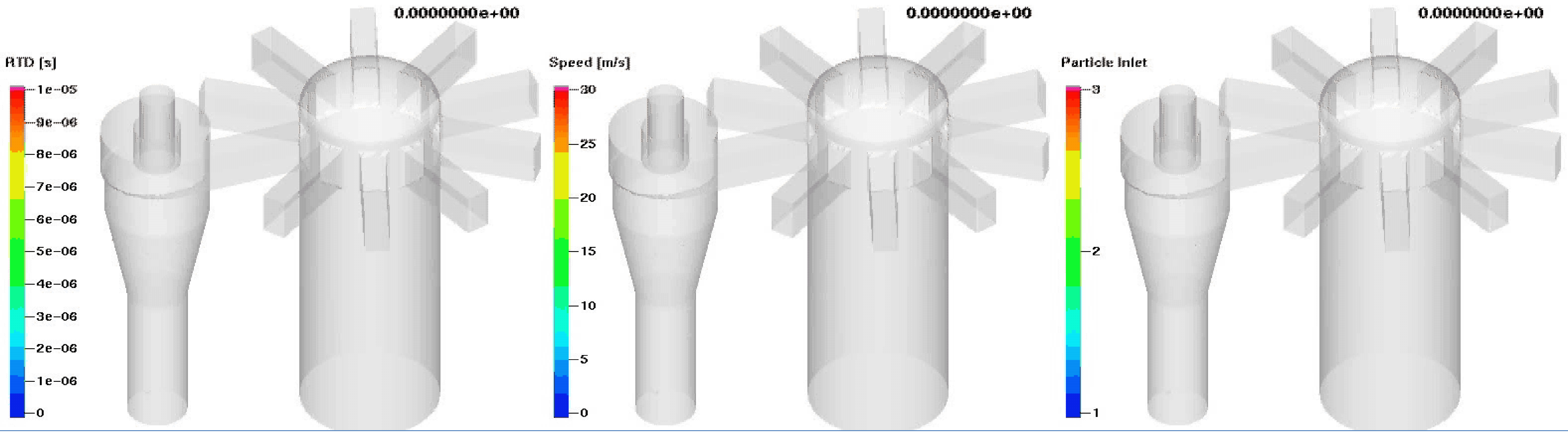
- **Gas boundary conditions:**
  - **Disengager arms**: gas enters through the arms at a total rate of 1920 ACFS (125.156 kg/s)
  - **Cyclone outlet**: the cyclone outlet pressure is held constant at 211,386 Pa absolute. This represents a 1.1 PSI pressure drop from an inlet pressure of 24.65 PSIG.
  - **Bottom of model**: A pressure boundary condition was used here to allow for particle outlet and some gas inlet. The boundary pressure was chosen to result in approximately 2060 ACFS of flow up the riser
  - **Other cyclone inlets:** Pressure boundary conditions were used for the inlets to the other 9 cyclones. The actual pressure values were set to maintain equal gas flows through the cyclones.
  - **Cyclone dipleg**: A minimal amount of gas flow exited at the cyclone dipleg

Particle Properties and Boundary Conditions

- The Particle Size Distribution (PSD) of solids used in the calculation is shown at right. Note that this is the size distribution entering through the disengager arms.
- The CPFD method computes the particle phase with discrete, Lagrangian entities. Thus, each computational particle has its own, unique size, determined at random from the PSD curve.
- The solids material are catalyst with a particle density of 90 pcf (1,450 kg/m^3).
- Up to 1.6 million computational particles were used to represent the solids phase.
- Particles entered at a total rate in excess of one million lb/hour and could exit at any other boundary condition location.



Baseline Particle Flow Results

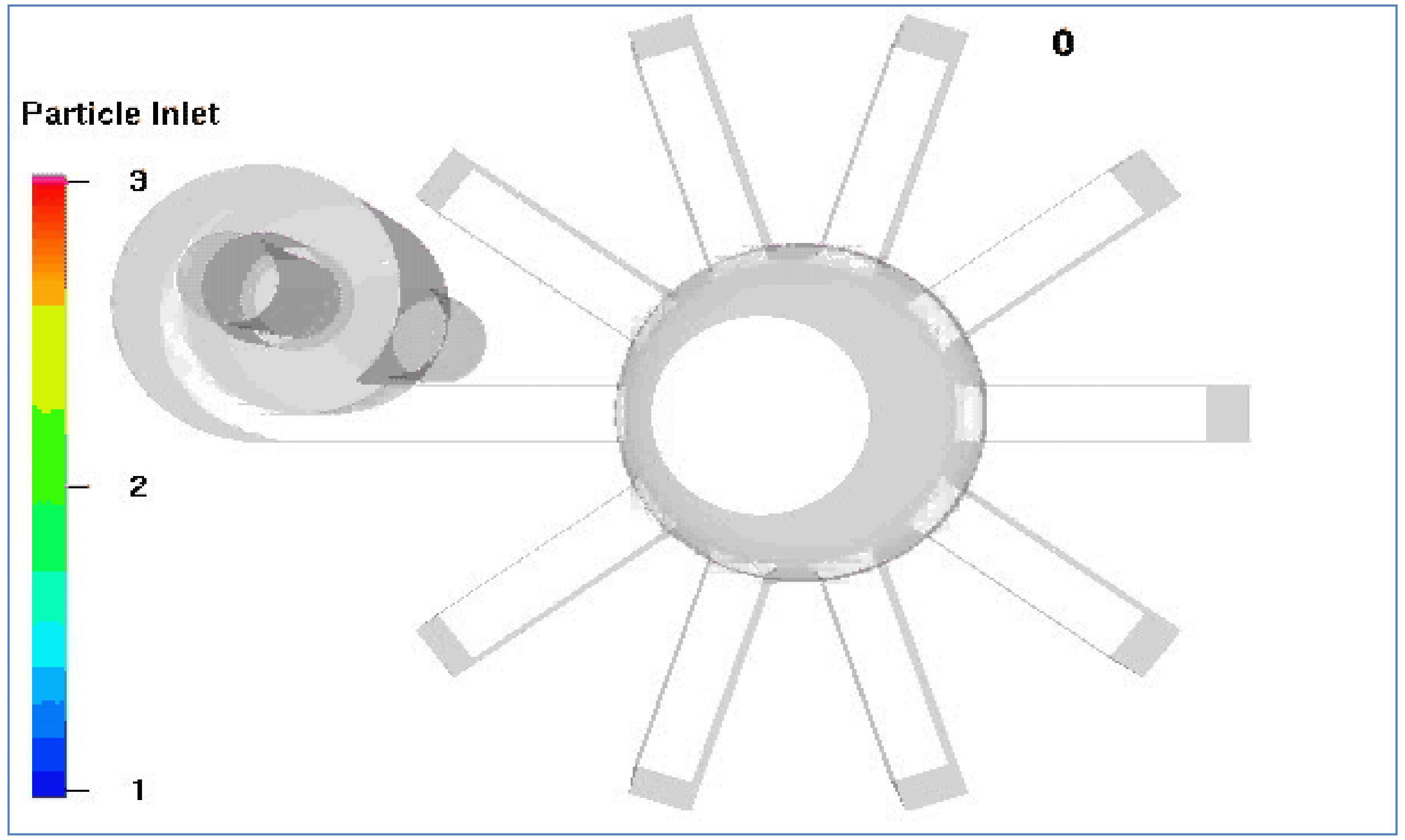


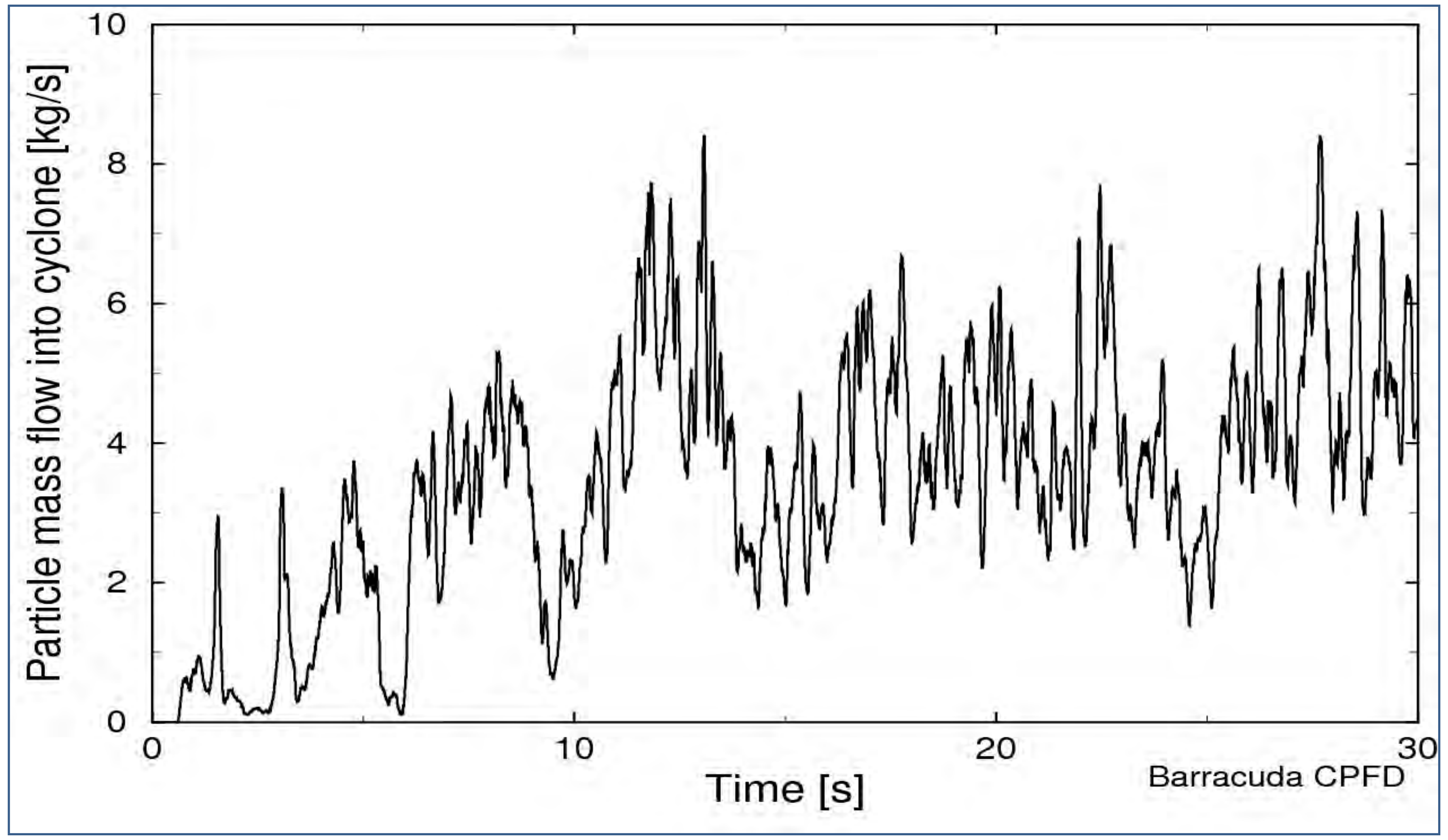
Residence Time Distribution (sec) | **Particle Speed (m/s)** | **Disengager Arm Inlet (1, 2, or 3)**

- The animation shows particle Residence Time Distribution (RTD) in seconds, particle speed in m/s and particles colored by the disengager arm through which they originated, from left to right, respectively

- The solids flow field is observed to have significant transient fluctuations

Cyclone Loading Observations

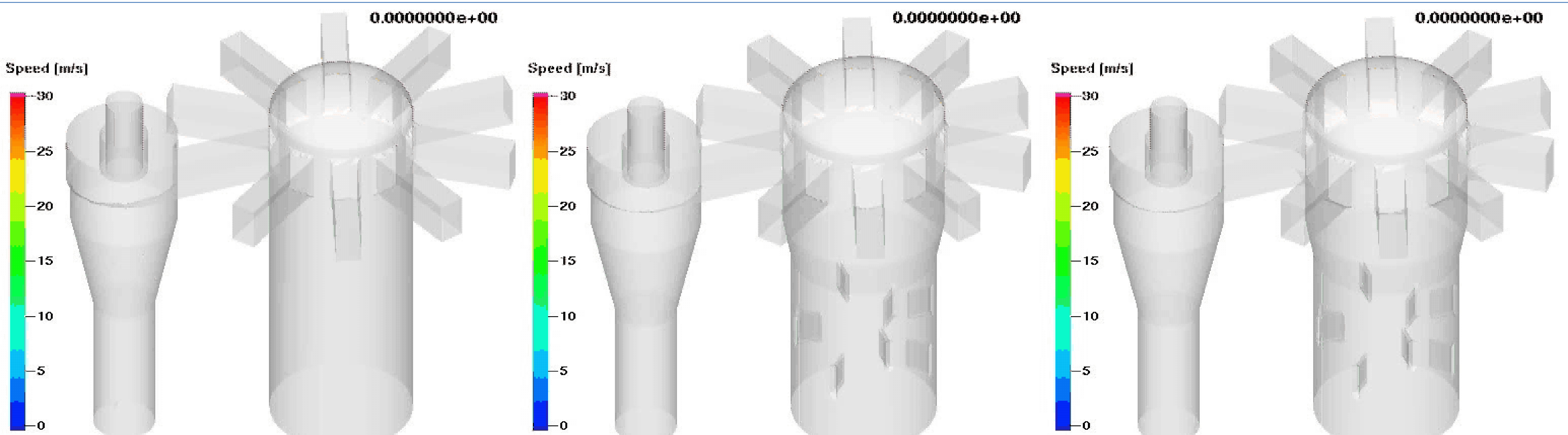




- The solids loading into the cyclones fluctuates with time
- The mass of solids into the cyclone is shown vs time

Effect of Alternate Designs on Bulk Flow Behavior

- The changes proposed in the alternative designs do not have an obvious impact on the bulk flows through the unit, which was desired because unit yield was not the issue but rather service interval.
- Some changes that are observed include:
  - Lower velocities in the cyclone inlets
  - A difference in the particle streams flowing up the riser (due to the flow straighteners)



Baseline | Alternative 1 | Alternative 2

Erosion Index Calculations

- Barracuda's erosion model was used to quantify particle impacts on surfaces. The functional form is dependent on:

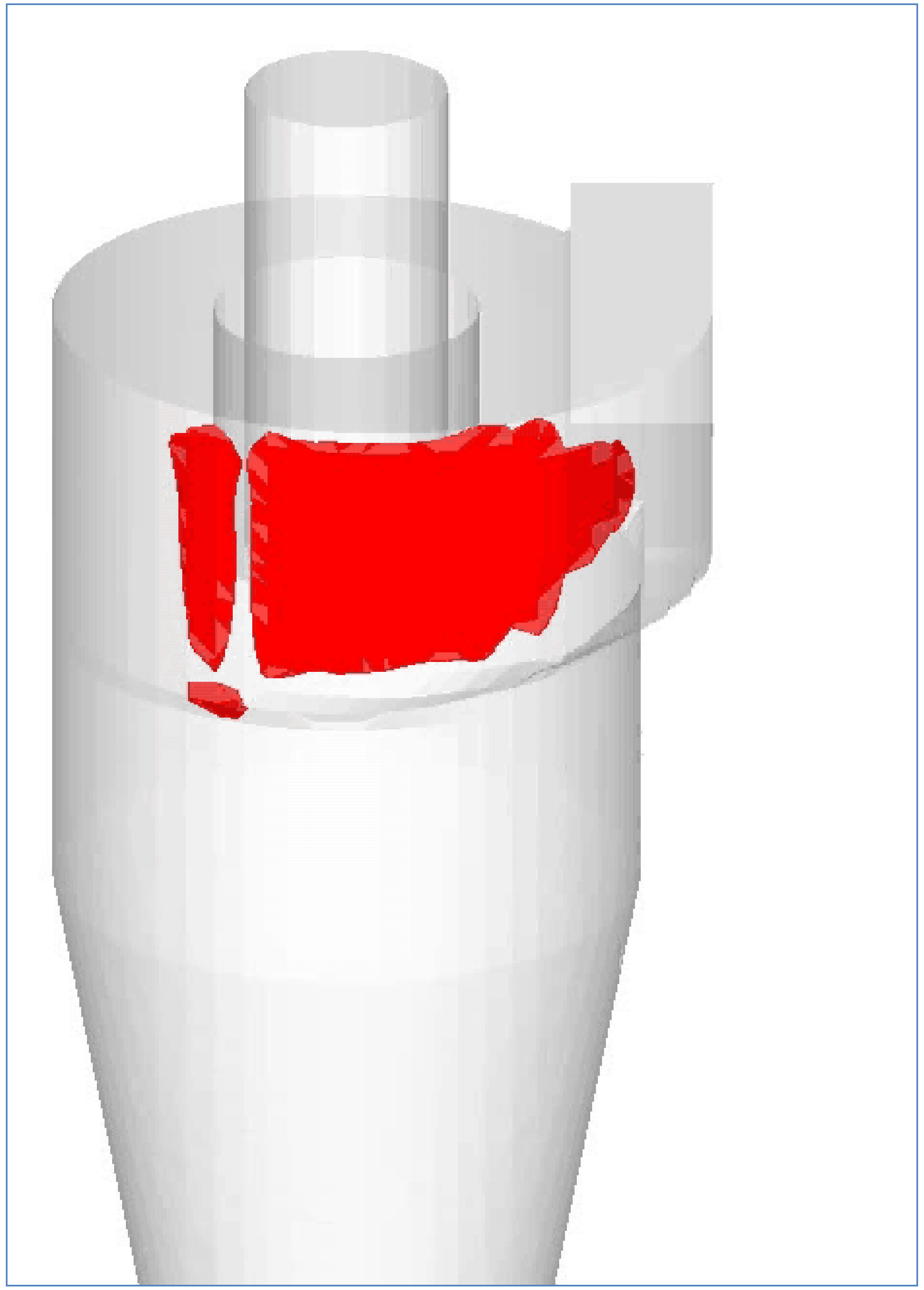
$$C_\alpha m^{1.5} v^{3.5}$$

where ***m*** is the particle mass, ***v*** is the particle velocity and $\boldsymbol{C_\alpha}$ is a coefficient as a function of impact angle, $\boldsymbol{\alpha}$. Since the cyclones and inlets are refractory lined, the coefficient is higher for normal impacts and lower for tangential ones.

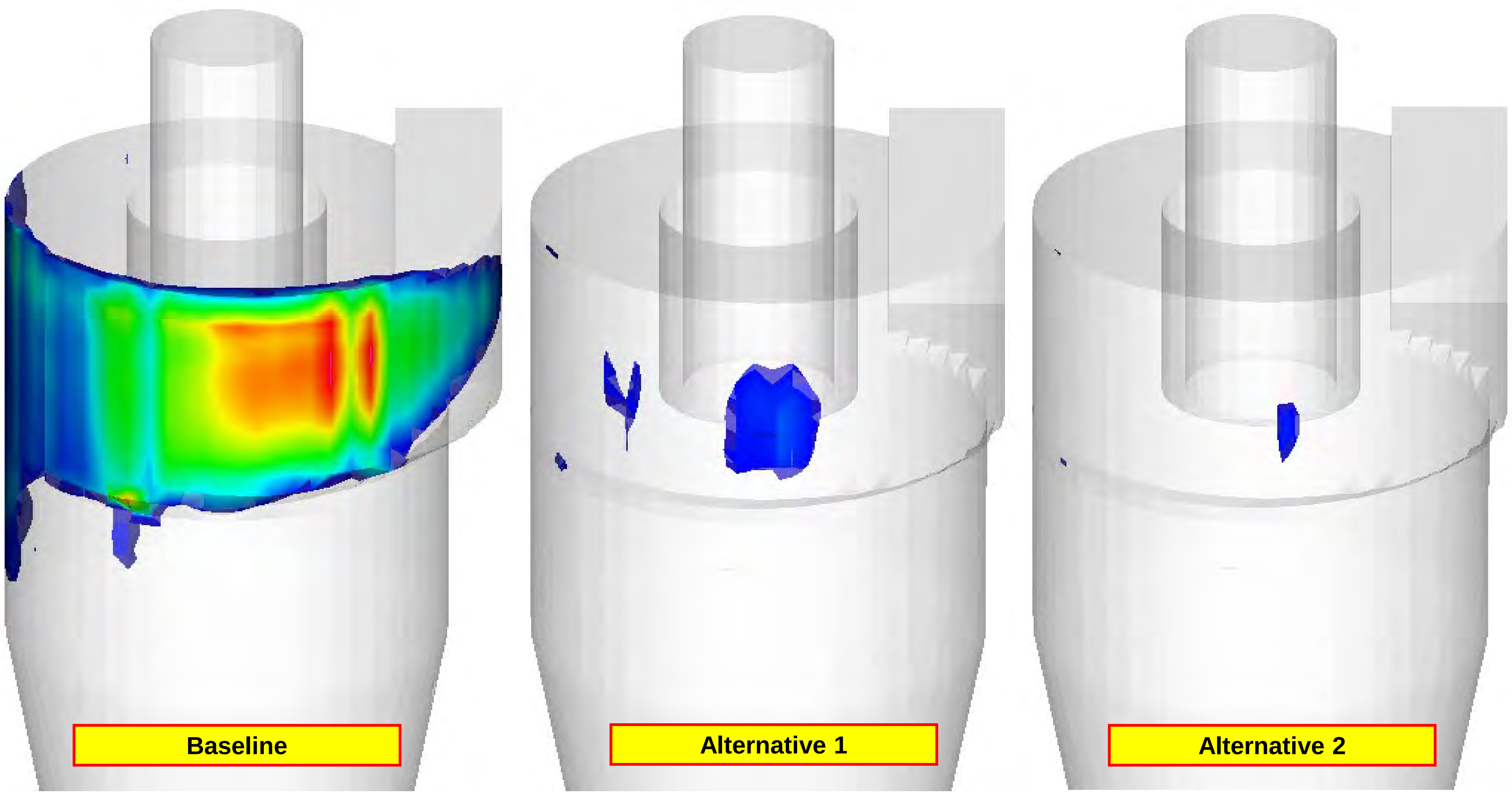
- Regions with an erosion index (exceeding a given tolerance level) have been plotted and compared for different the different geometries and designs on the following slide

- It should be noted, that although the Barracuda erosion model is quantitative, erosion in terms of material removal on the actual unit is dependent upon many variables, including:
  - Particle material
  - Particle shape
  - Refractory material
  - Quality of refractory installation
  - Time in service
  - Etc.

- Thus, the best use of the erosion index results is for **direct comparisons between alternate designs or operating conditions**, rather than for a strict quantification of improvement



Comparison of Predicted Cyclone Erosion Index



- The predicted regions of maximum erosion are shown for the baseline and alternate design cases.
- Erosion for both alternatives is lower than that for the baseline case.
- Alternative 2 may have slightly less erosion than Alternative 1, but those differences are minor compared to the improvement versus the base case.

FCC Reactor Cyclone Erosion Case Conclusions

- The CPFD method was used to compute the multiphase, 3D, transient flows within the outlet riser and cyclones and resulting erosion index values.
- Significant fluctuations are present in the solids flow into the cyclones.
- Both alternative designs are expected to reduce the cyclone inlet erosion significantly compared with the existing design.
- Both alternative designs are expected to have similar erosion resistance, with Alternative 2 perhaps performing slightly better than Alternative 1.
- The particle streams tend to be directed toward the cyclone centers. This could lead to poor cyclone efficiency and high fines loss. Some changes to the licensor's proprietary primary separator design were suggested.

Barracuda VR - Delivering Value Across all Segments

Oil & Gas Refining	Technip, UOP, Shell, Total, Marathon, Valero, IFP (Innovation Energie Environnement), EnCana, Intercat
Chemical Producers	DuPont, Dow, BASF The Chemical Company, Samsung Total, SABIC, INEOS, Momentive, Hanwha Chemical
Power Gen OEM's	B&W thebabcock&wilcoxcompany, Alstom, BHEL, Doosan, CISDI, Mitsubishi Heavy Industries, Ltd.
Polysilicon Manufacturers	Dow Corning, REC Energizing Life Together, Reactech Fluidization and Reaction Engineering, GT Advanced Technologies, Siliken innovation experience, 協鑫光伏 GCL Solar
Metals & Mining Operations	Cristal, FLSmidth, Technip, Hatch, Outotec More out of ore, POSCO
R&D Organizations	PSRI Particulate Solid Research, Inc., NETL, KITECH, CH2M•WG Idaho, LLC, CMERI Central Mechanical Engineering Research Institute, INL Idaho National Laboratory, CSIRO, 中国科学院 Chinese Academy of Sciences
Gasifiers & Unconventional Fuels	ENN 新奥, KiOR, Rentech, Uhde ThyssenKrupp, NICE National Institute of Clean and Low-Carbon Energy, TRI, Thermax, Vale, Ebara, GreatPoint Energy, UBE Industries, Ltd.

Conclusions

- Refiners face many challenges in optimizing FCCU design and performance in a **demanding operational and regulatory environment**.

- Among the key challenges in optimizing or troubleshooting FCC systems is the need to **understand fully the root causes of operational issues**. Best practices demand decisions based on <u>facts</u>.

- These case studies demonstrate that Barracuda Virtual Reactor™ models provide engineers the insight required to diagnose and solve problems with **reliability, operations, and emissions in FCC units**.

- Barracuda VR is a **proven technology** already in use by some of the world's leading manufacturers.

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