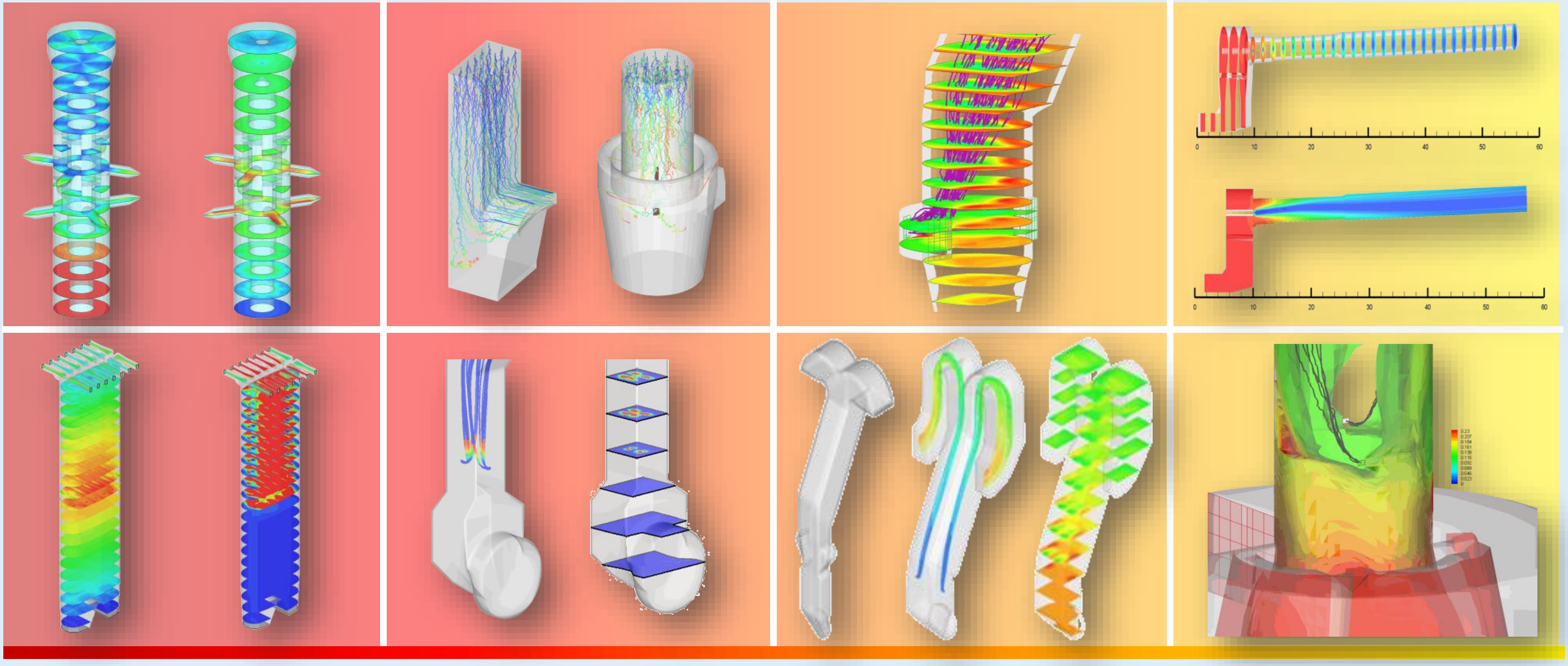

Reducing kiln CO

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Volatiles and Carbon are Released in Large Quantities ‘Puff’

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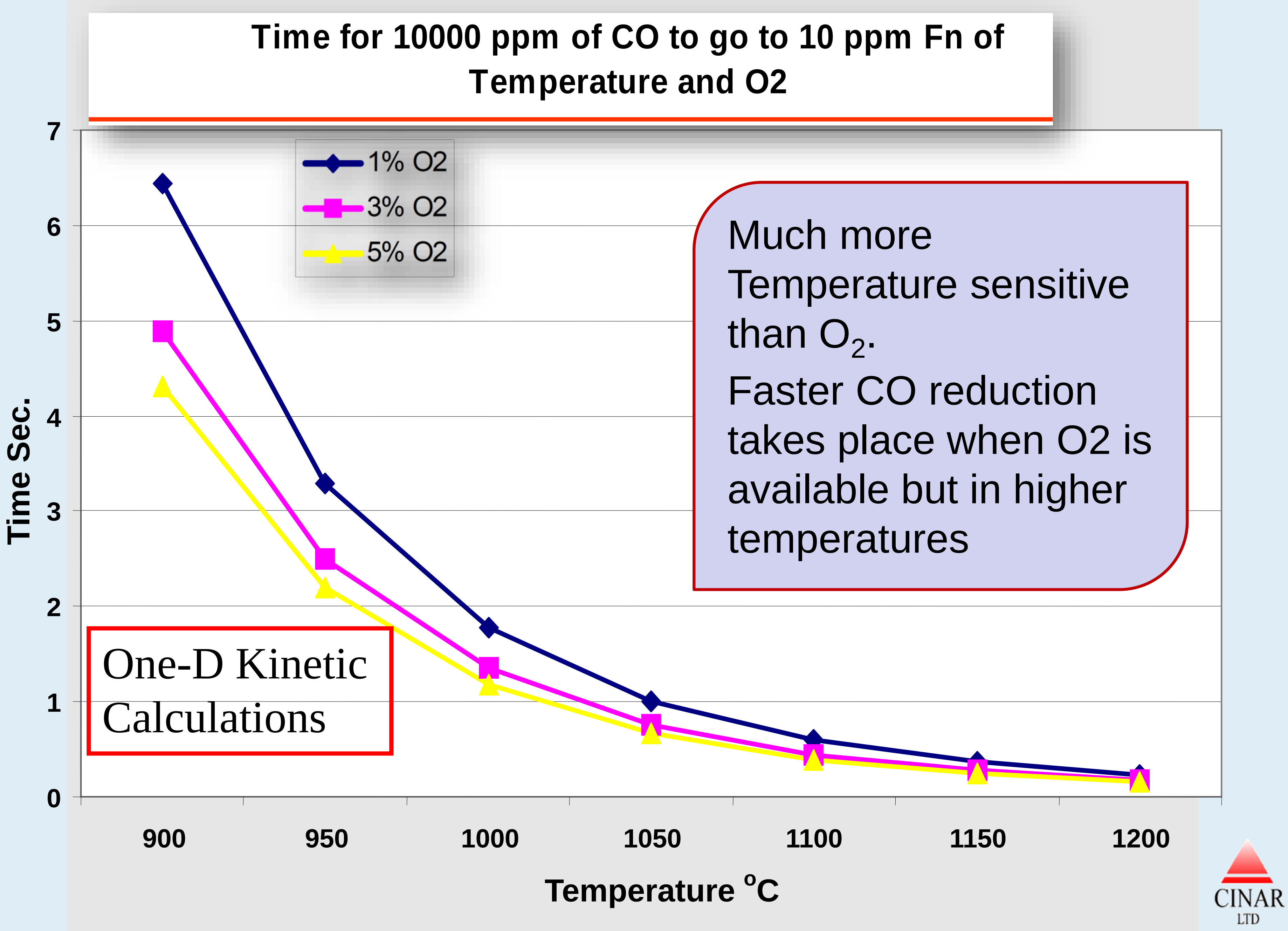
Time for 10000 ppm of CO to go to 10 ppm Fn of Temperature and O2
1% O2
3% O2
5% O2
Much more Temperature sensitive than O_2.
Faster CO reduction takes place when O2 is available but in higher temperatures
One-D Kinetic Calculations
Time Sec.
0
1
2
3
4
5
6
7
900
950
1000
1050
1100
1150
1200
Temperature ^oC
CINAR
LTD

CO Reduction

- $CO + OH \longrightarrow CO_2 + H$ (1)
- $O_2 + H + M \longrightarrow HO_2 + M$ (2)
- $O_2 + H \longrightarrow OH + O$ (3)
- $HO_2 + OH \longrightarrow O_2 + H_2O$ (4)

Reactions 1-4 are the most important for the CO consumption as well as to OH yield,

- $HO_2 + HO_2 \longrightarrow H_2O_2 + O_2$ (5)
- $H_2O + O \longrightarrow OH + OH$ (6)
- $CO + O + M \longrightarrow CO_2 + M$ (7)

Reactions 5-7 are of moderate to weak importance; Thornton et al. (Combust. Sci, and Tech., 1987),

$$CO + OH \longrightarrow CO_2 + H$$

The most effective CO reduction reaction

$$CO + O_2 \longrightarrow CO_2 + O$$

The least important reaction

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CO Modelling Approach

- Time averaged general equation of [CO]
- Source term:

$$\tilde{S}_{[CO]} = S_{gen} + S_{destr}[CO]$$

  - For the formation based on the remaining volatiles and char burnt

$$S_{gen} = A_1 \exp\left(-\frac{E_1}{RT}\right) \cdot [C - vols] + A_2 \exp\left(-\frac{E_2}{RT}\right) \cdot [C - char_b]$$

  - For the destruction of CO based in the availability of O2, OH-radicals and levels of temperature

$$S_{destr} = -A_3 [O][OH] \left(\frac{P}{RT}\right) \exp\left(-\frac{E_3}{RT}\right)$$

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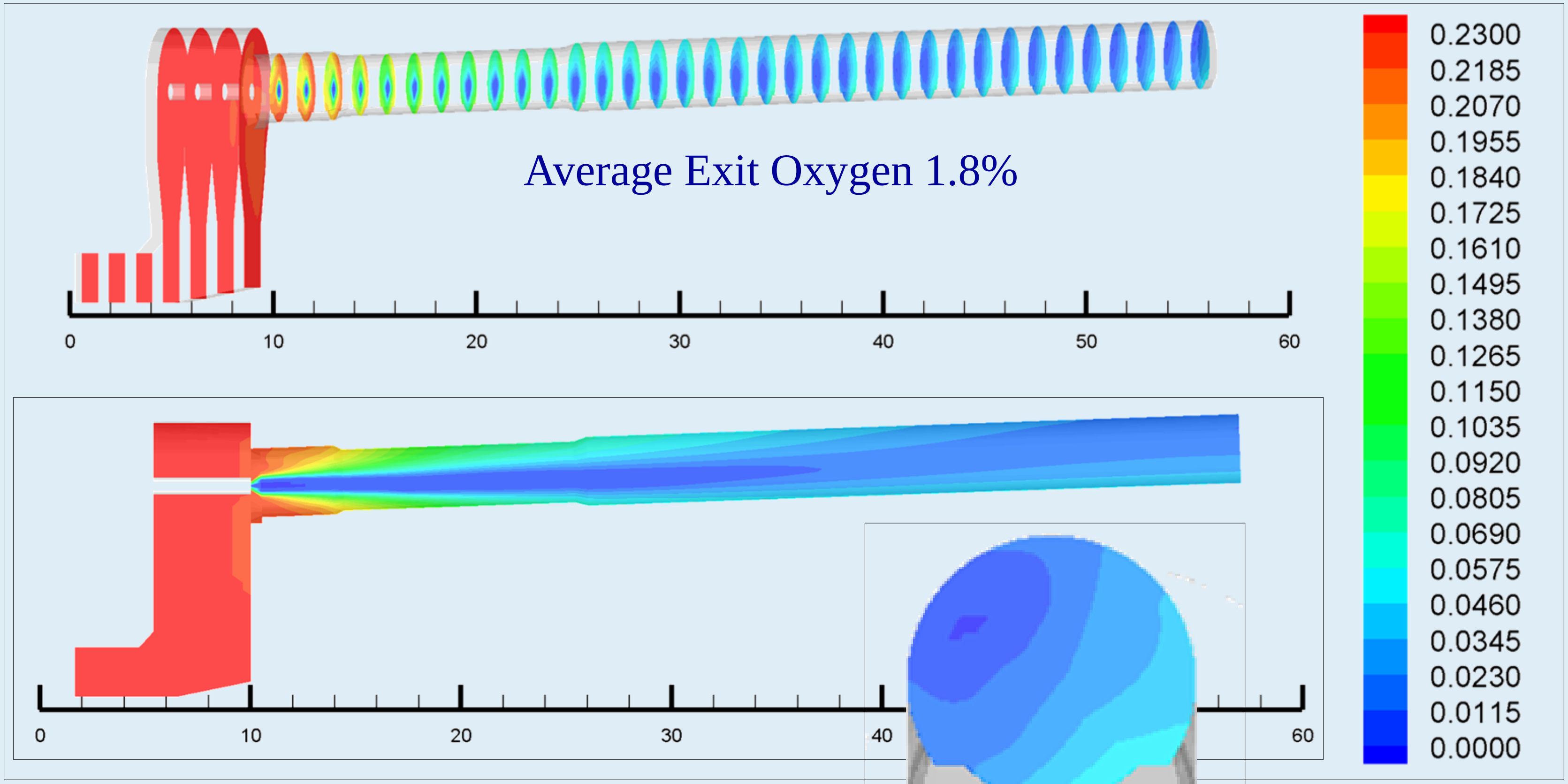
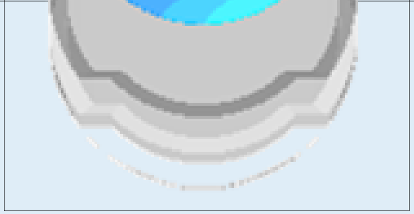
Reduction of CO Emissions from Kilns

CINAR LTD

Oxygen Mass Fraction [-]





At Exit,
O_2 varies from
0.1% to 4%

CO: 2000 ppmv

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Kiln Geometry

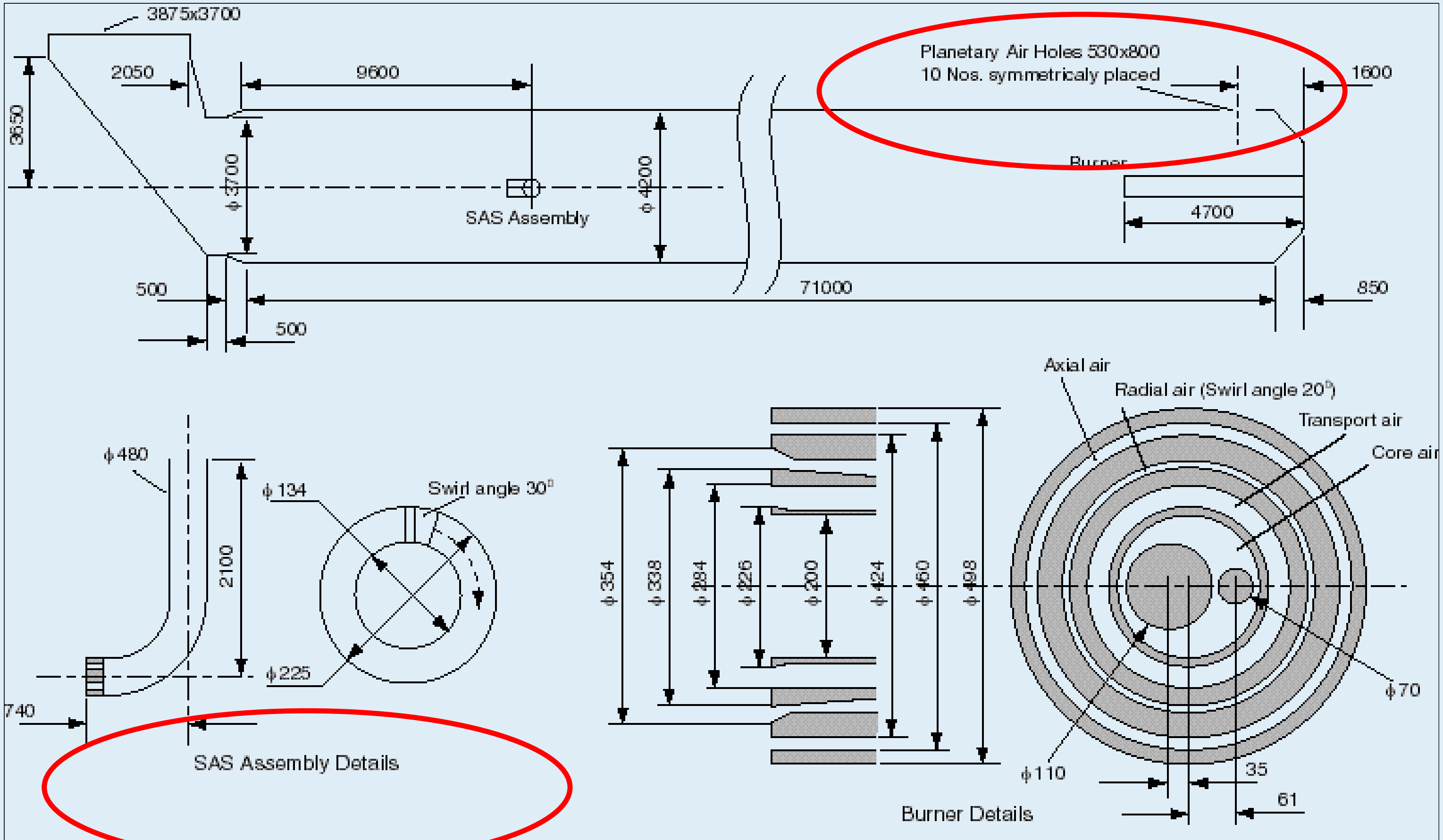

Figure 1 - Orizaba Kiln Geometry

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SAS Geometry

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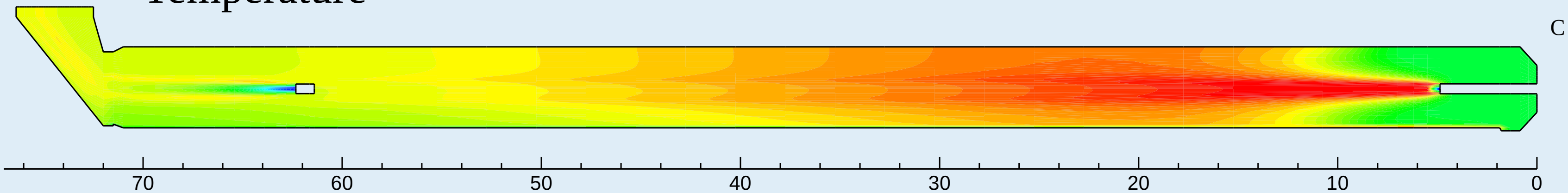
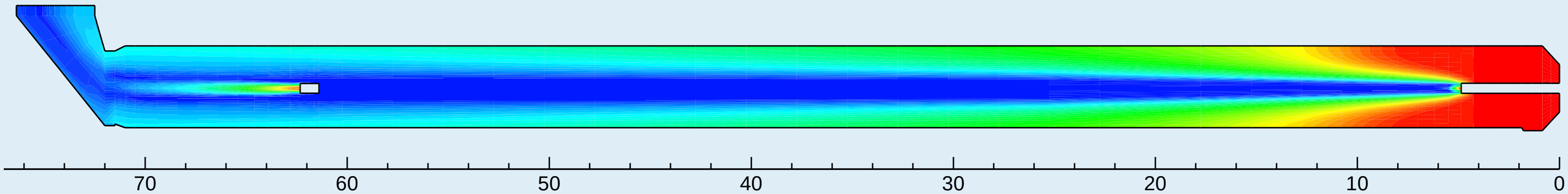
Flow Stratification leading to higher CO emissions

Temperature

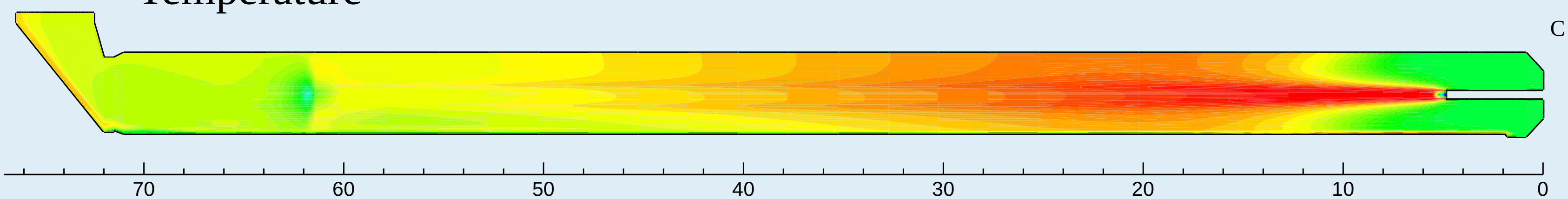


Oxygen Concentration

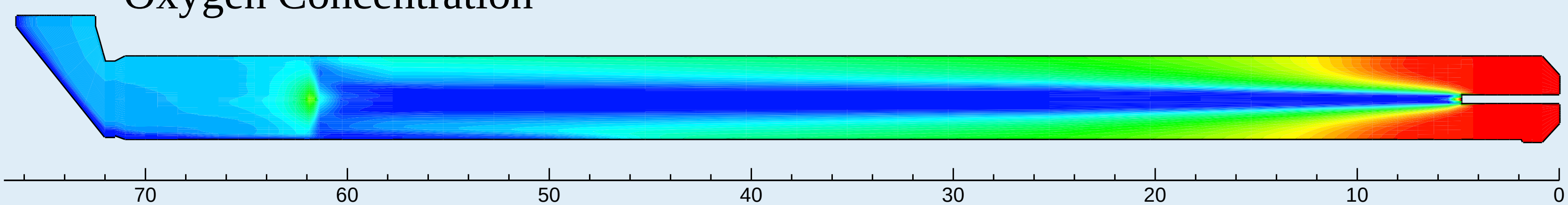


Velocity vectors

Temperature



Oxygen Concentration



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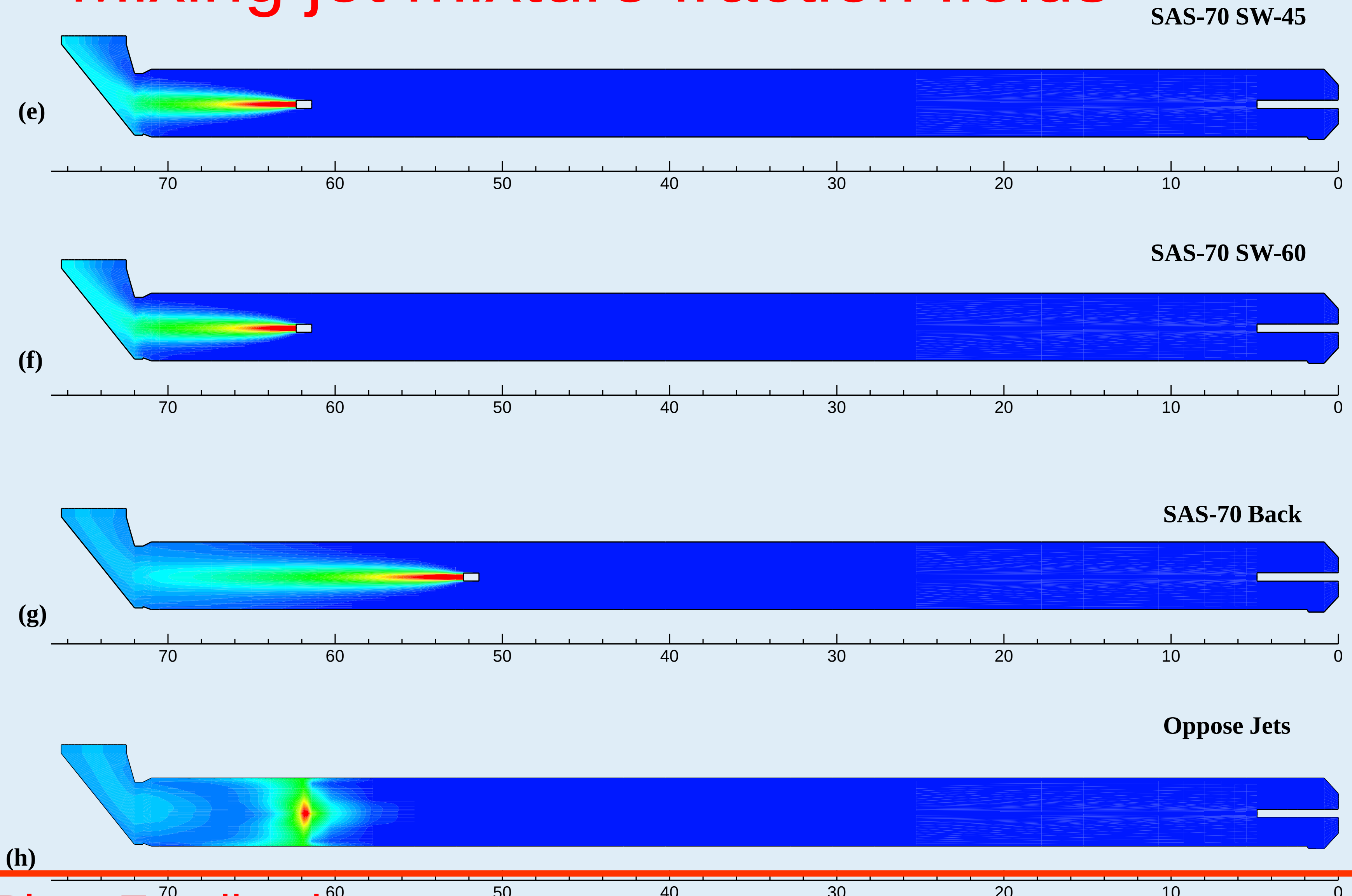
Mixing jet mixture fraction fields



Plant Feedback:

JEMS (oppose jets) work much better - CO reduction by 70%

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Reduction of CO Emissions from an In-Line Precalciner

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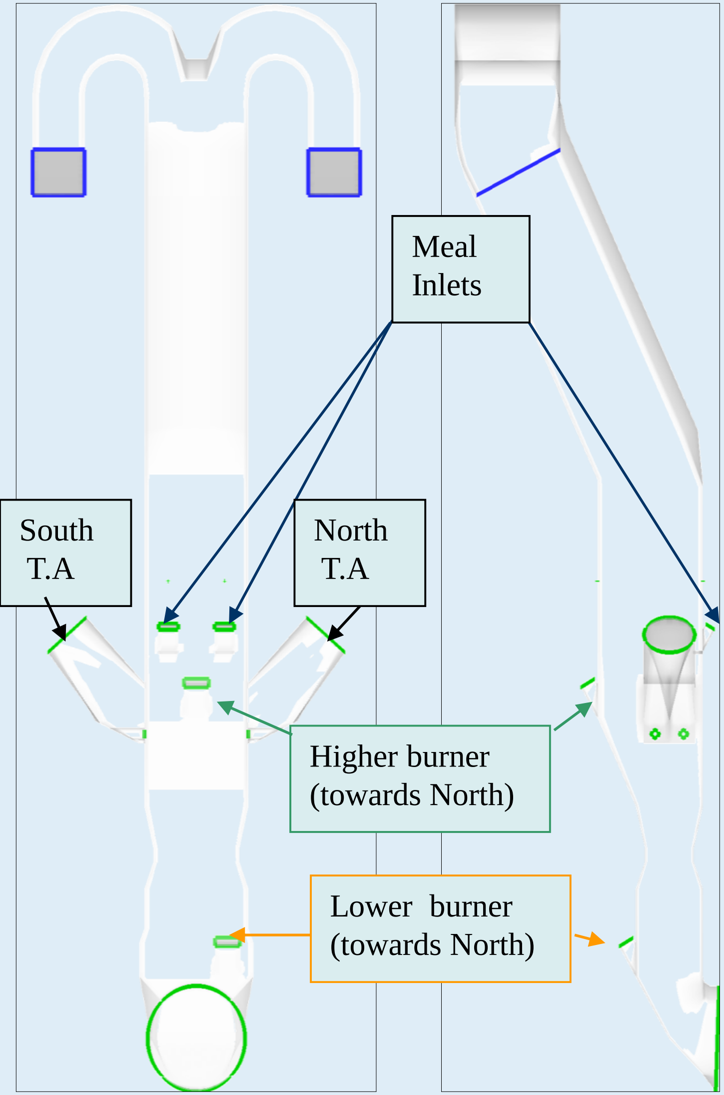
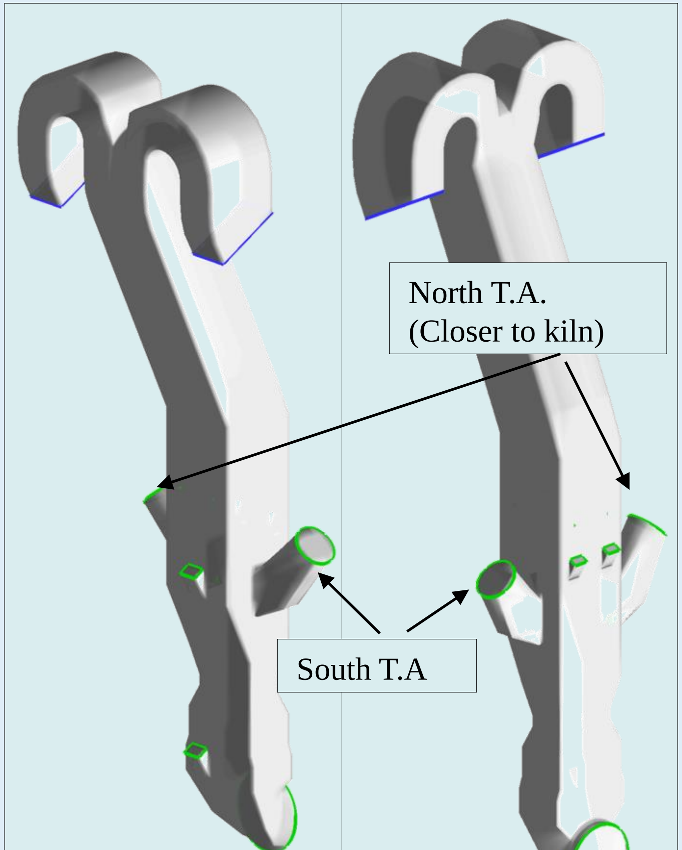
Background – Asymmetry



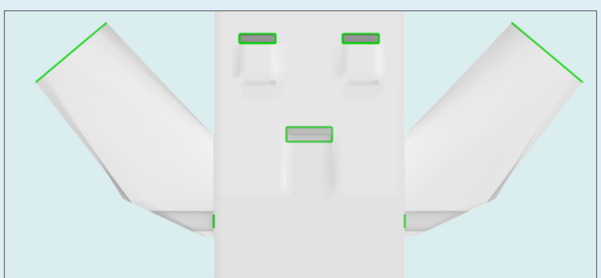
A 4500 tpd calciner plant, faced with a new CO regulation of 1200 mg/Nm3

The Plant is Polysius of the 80's vintage with @ 2 secs RT in the calciner

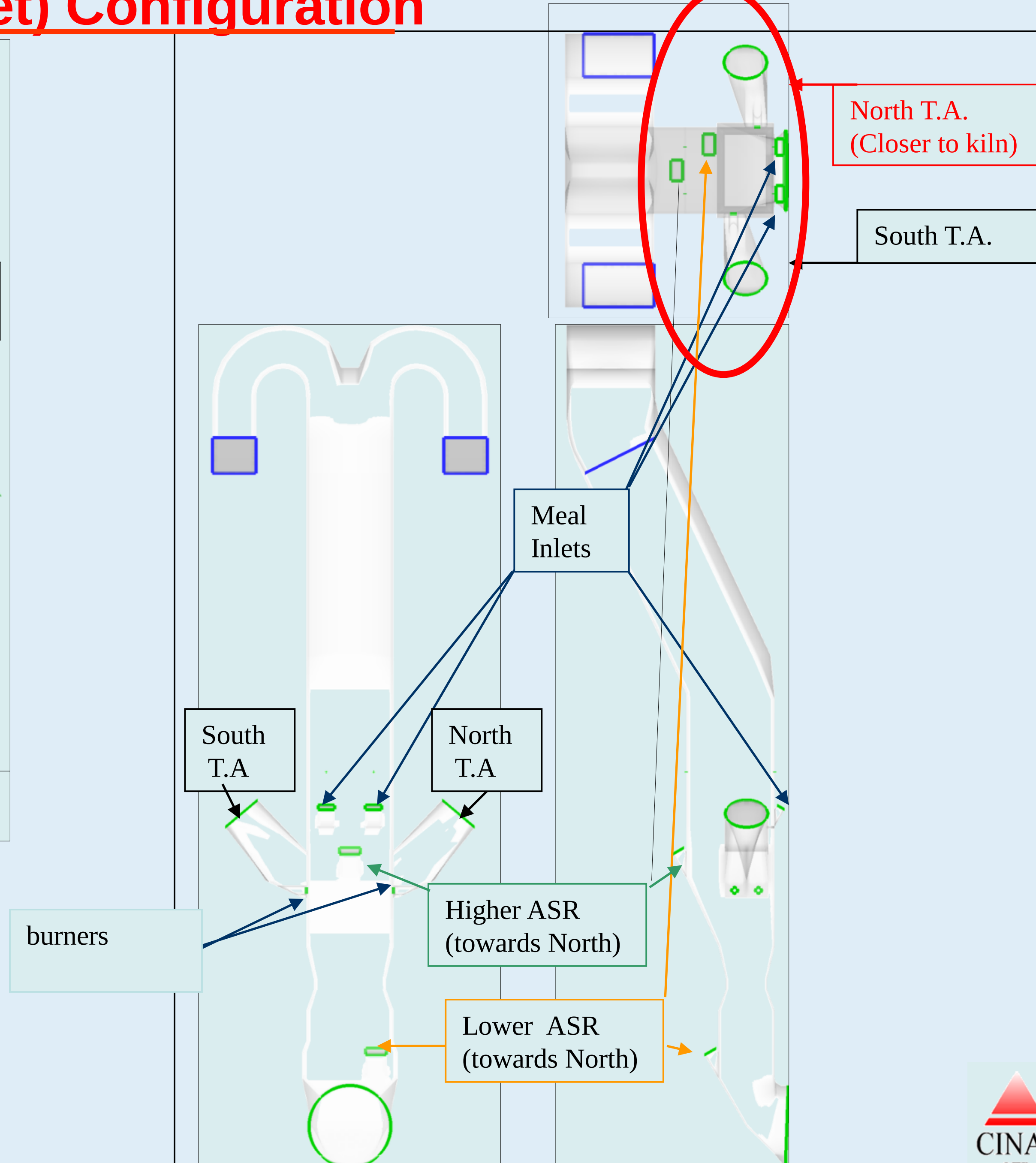
Oppose TA (Off-set) Configuration



View opposite from Kiln (West) | View from Kiln (East)



Detailed section of the TA region



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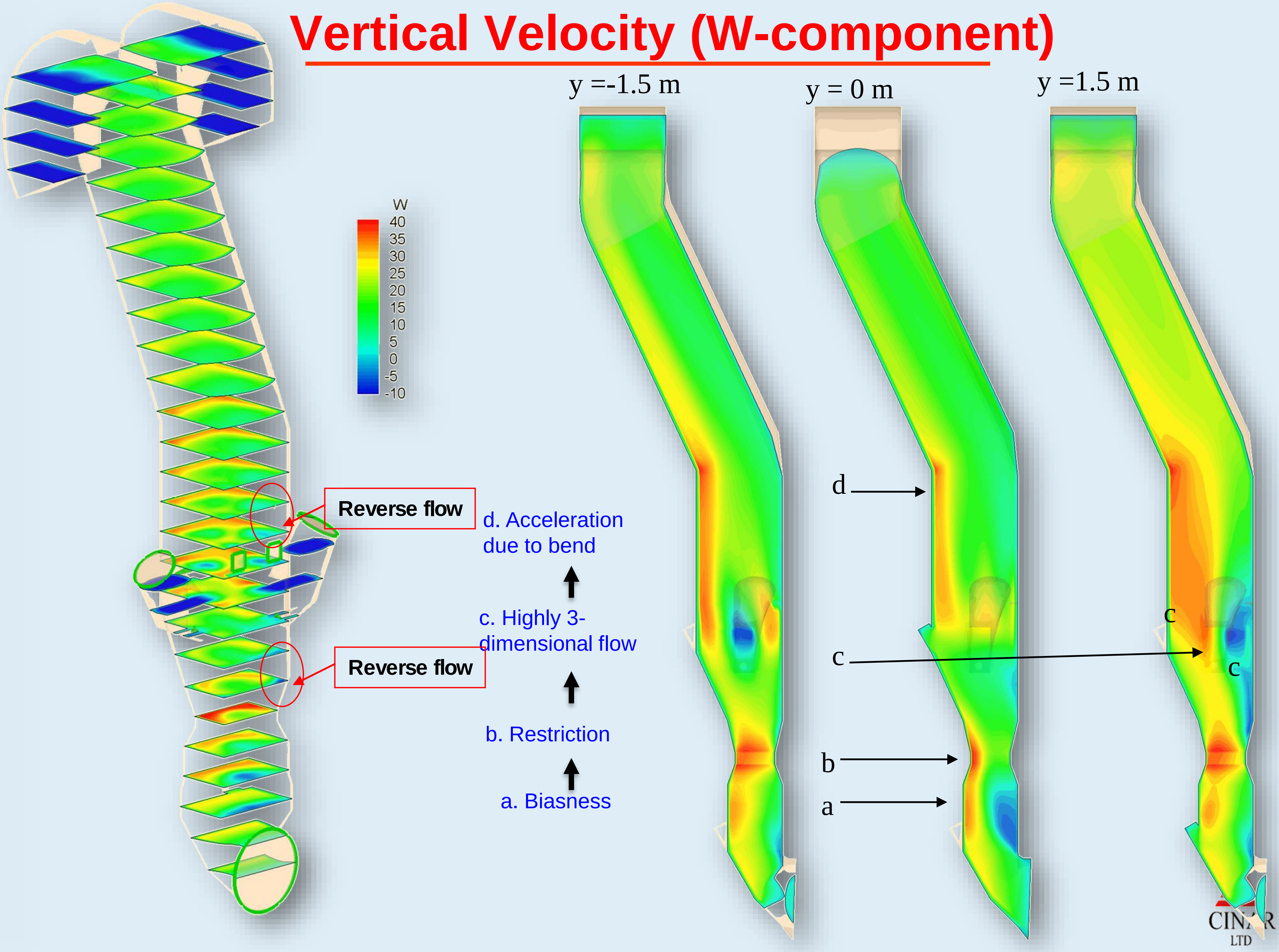
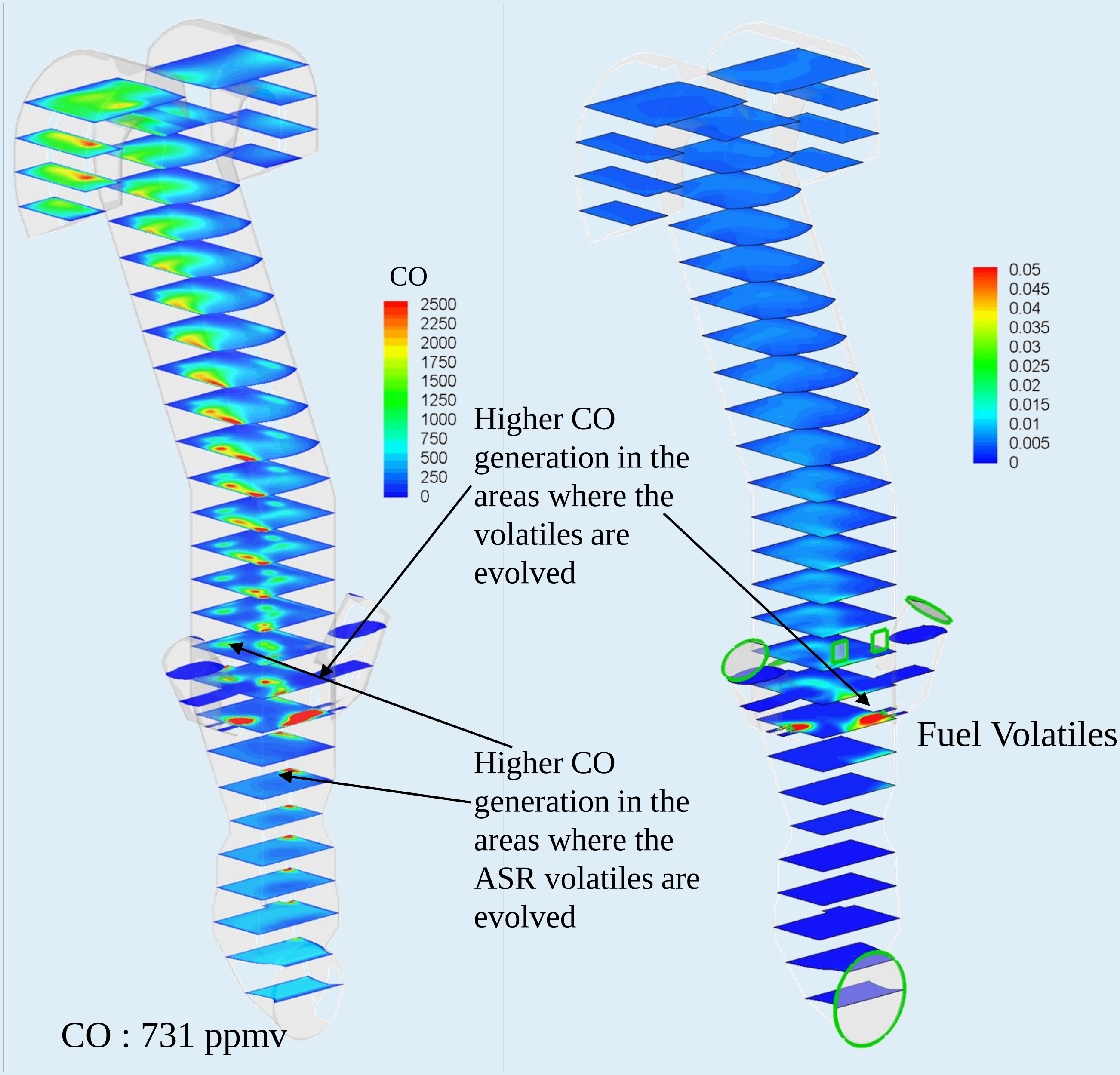
Vertical Velocity (W-component)



CO Formation Follows the Fuel Volatile Release



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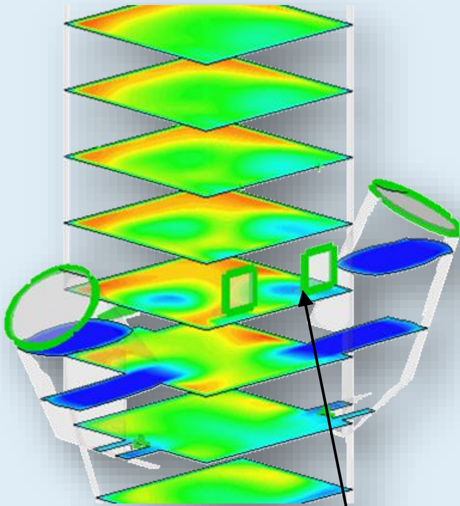
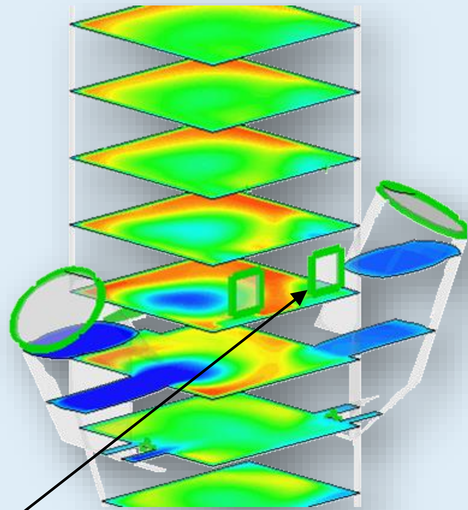
Vertical Velocity (W-component) (Comparison)

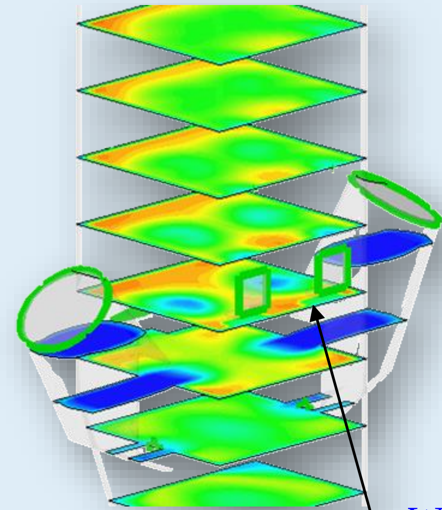
Base Case

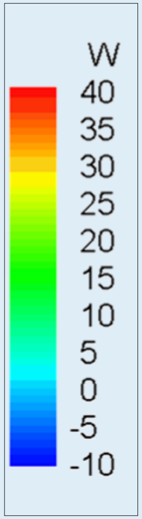


75-25% (TA)



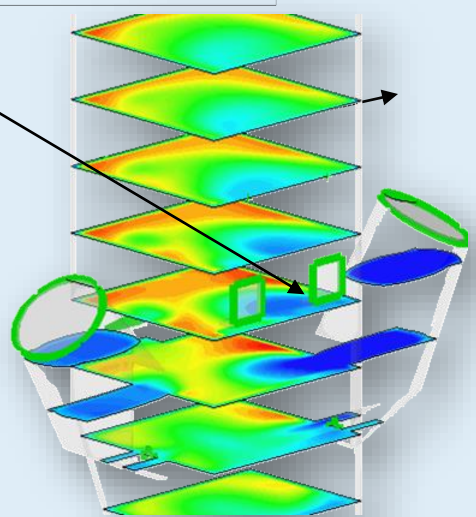
Opposed TA ducts



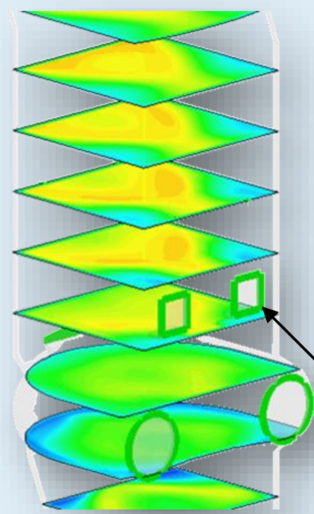


The downward momentum present in the base case is a result of the North side inlet of TA which is situated very close to the wall. Reduction of the mass flow from this TA duct improves results in meal not falling lower. The opposite change results in more particles fall in the hot combustion region and quench it.

25-75% (TA)



2 TA ducts manifold



When the TA ducts is moving away from the wall in the case of opposed TA ducts with a 50-50 distribution there is not an area of downward momentum and the meal particles are carried upwards. The same trend has been observed for the TA manifold.

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Calciner Exit CO Emissions

Base Case
731ppm

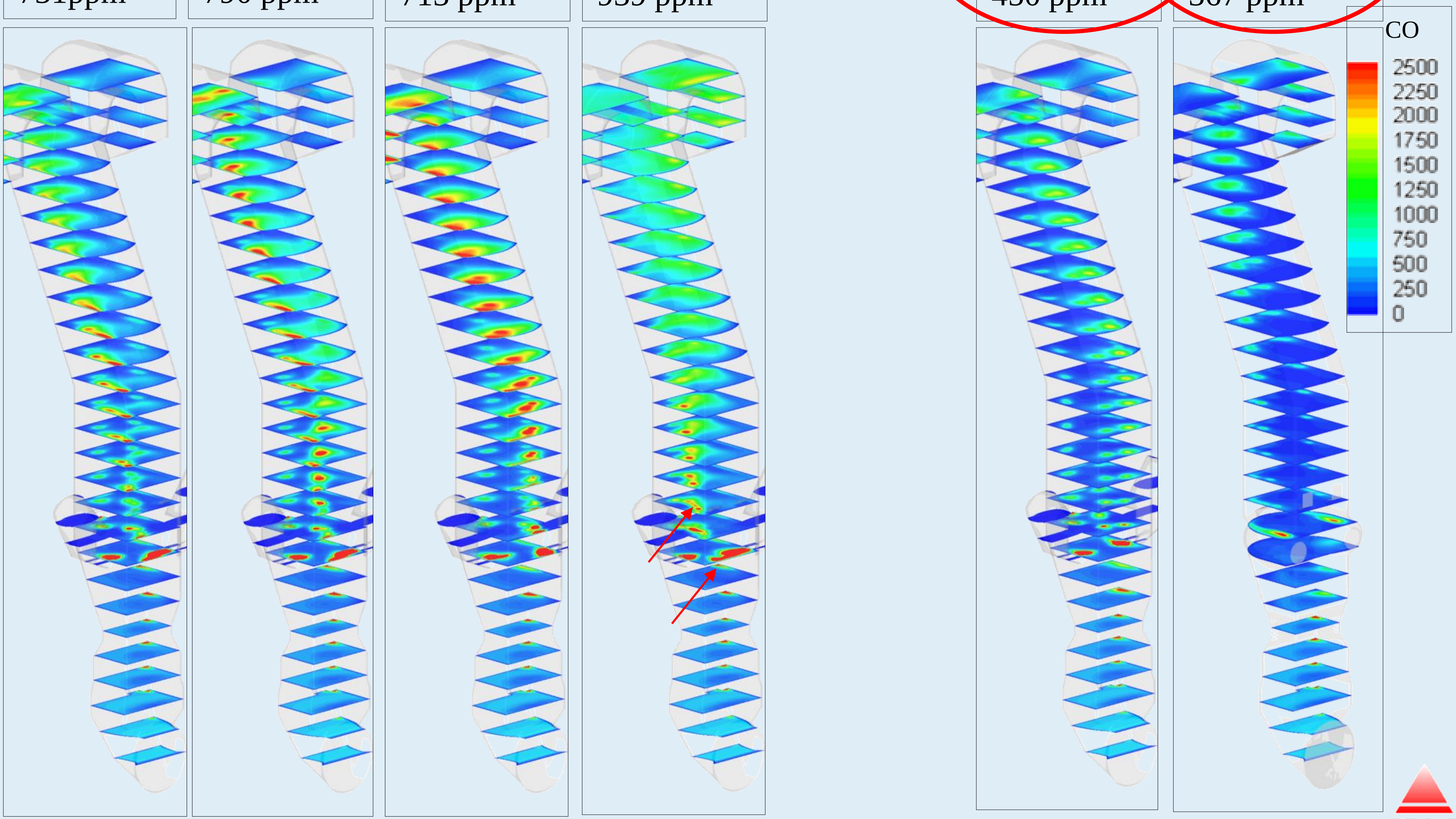
No plates
790 ppm

75-25% (TA)
713 ppm

25-75% (TA)
939 ppm

Opposed TA ducts
450 ppm

2 TA ducts manifold
367 ppm



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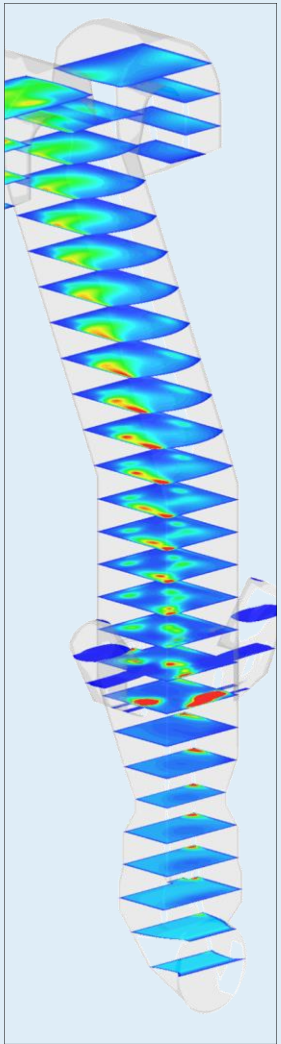
CO (ppmv)

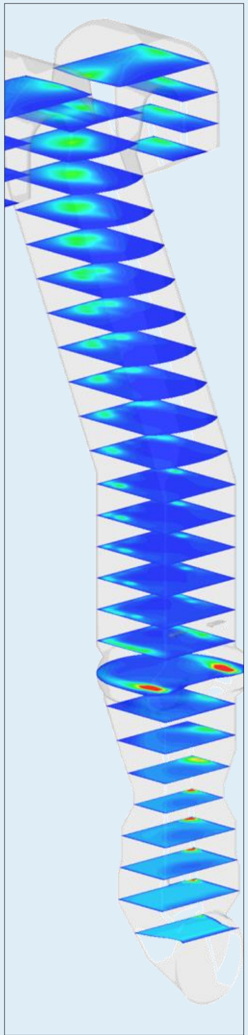
Base Case

731ppm



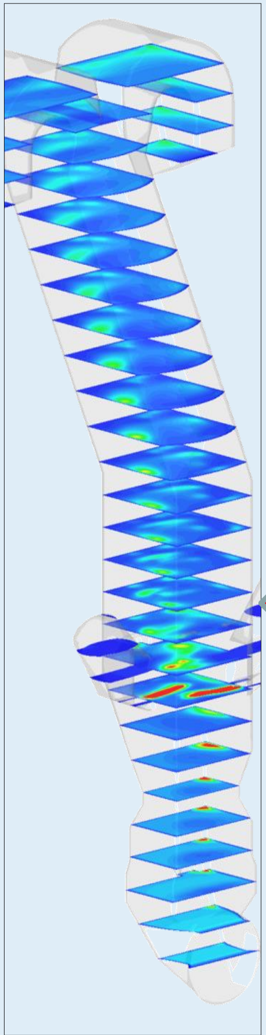
2 TA ducts manifold

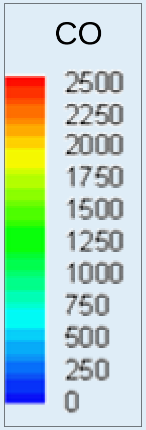
367 ppm



Increased Momentum

435 ppm





Burner with Axial Sleeve This was tried due to its lower cost of installation TA manifold €1.5 m

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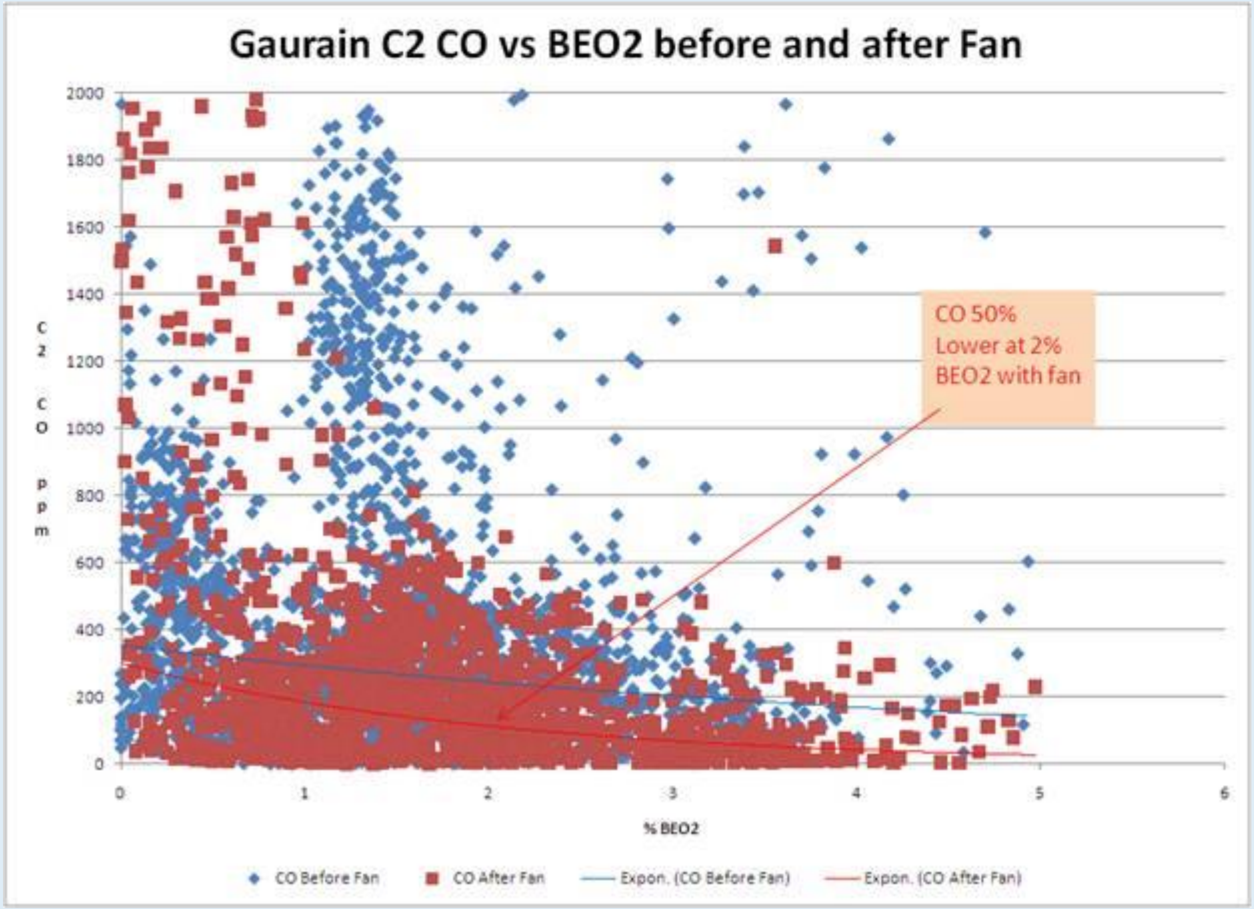
Plant Feed-back: Before and After



Plant Feed Back:

45% reduction in CO for the same O2 level

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Reduction of CO Emissions from an AT Precalciner

(fluff at 10% TSR via a flap valve has shown unacceptable levels of increase in CO)

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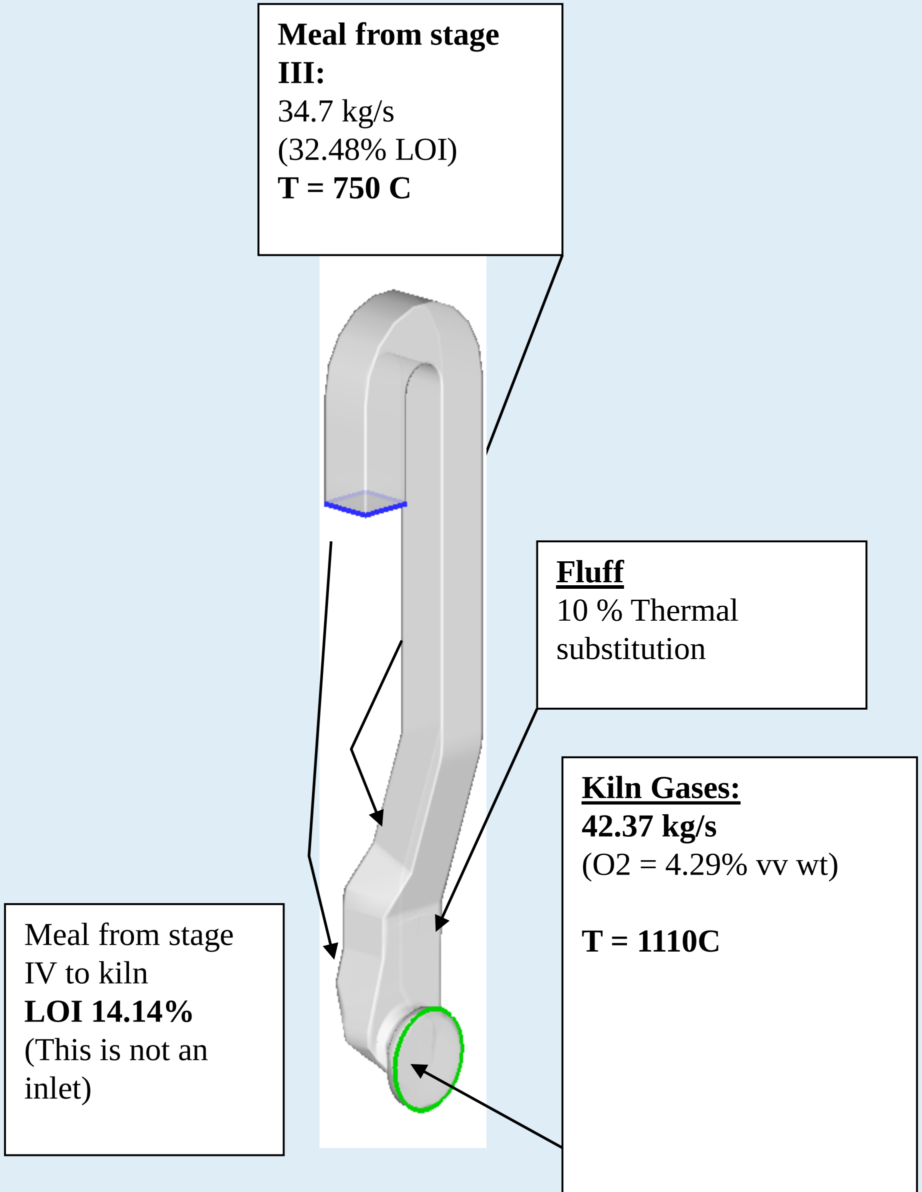
Background



- A cement plant of 2000 tpd was planning several modifications to increase AFR's co-firing with oil.
- One issue it faced, while burning fluff at **10% TSR** via a screw feeder was producing unacceptable levels of increase in CO.

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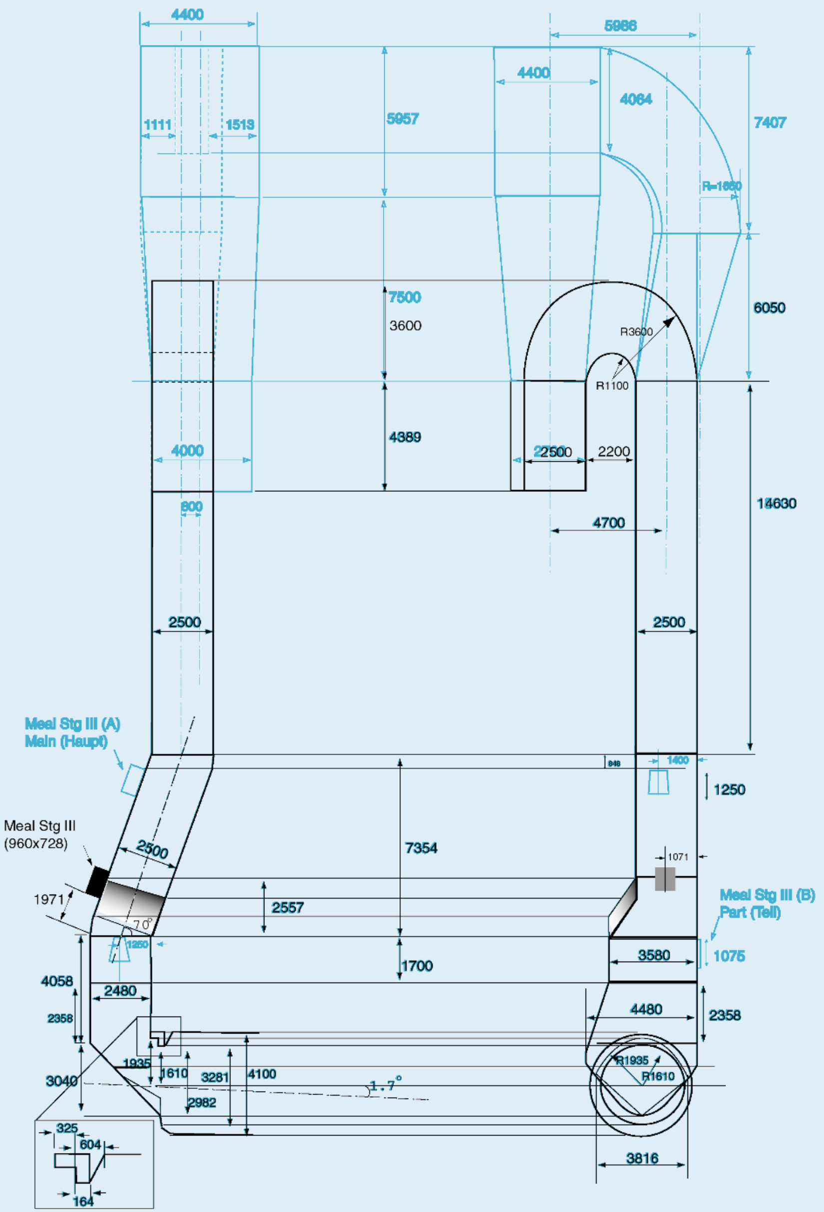
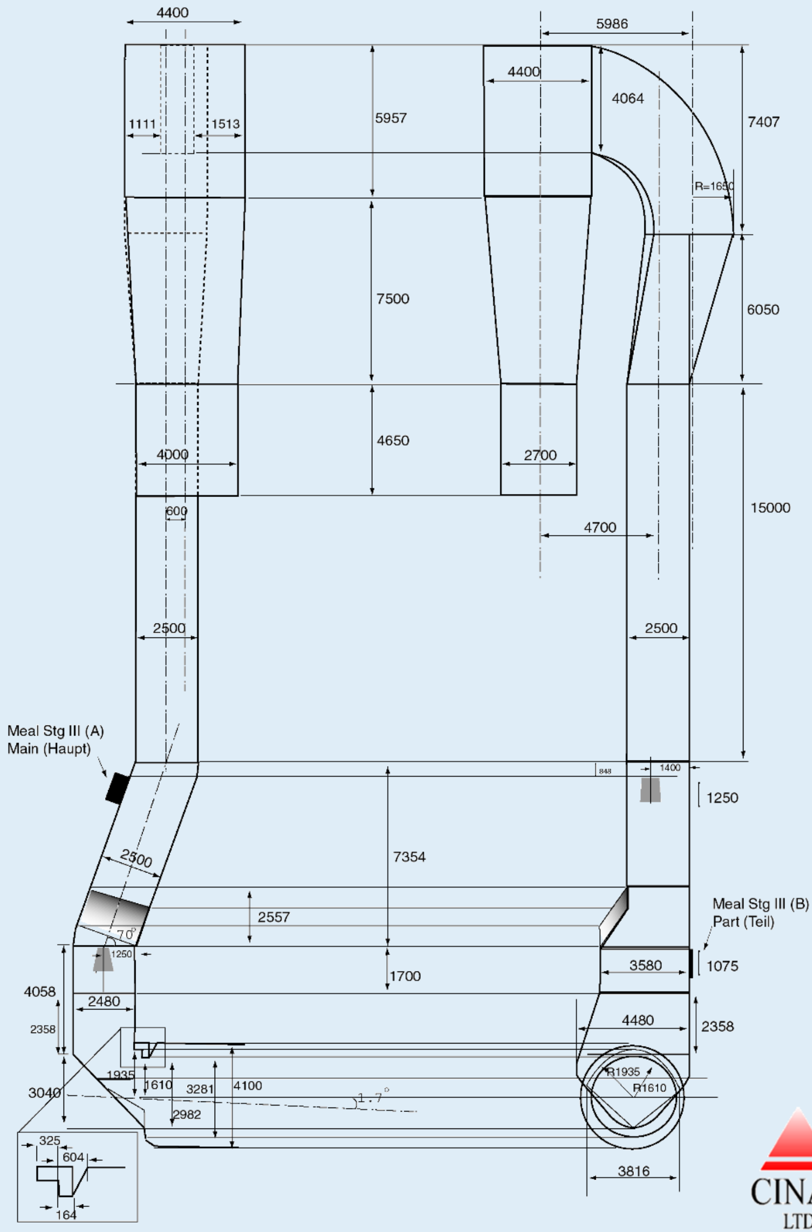
Geometry

Planned Extension



New Design



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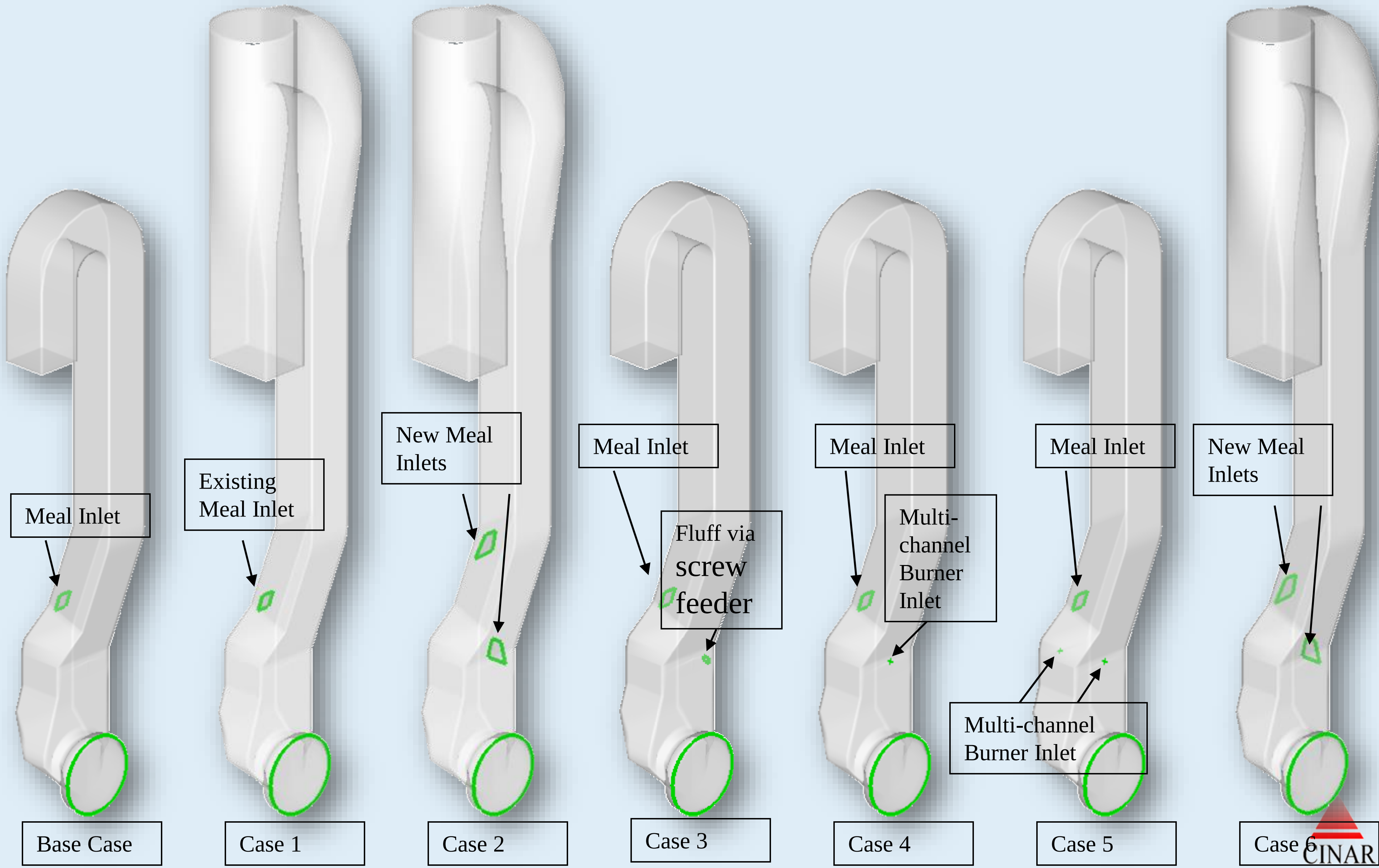
MI-CFD Simulated Cases



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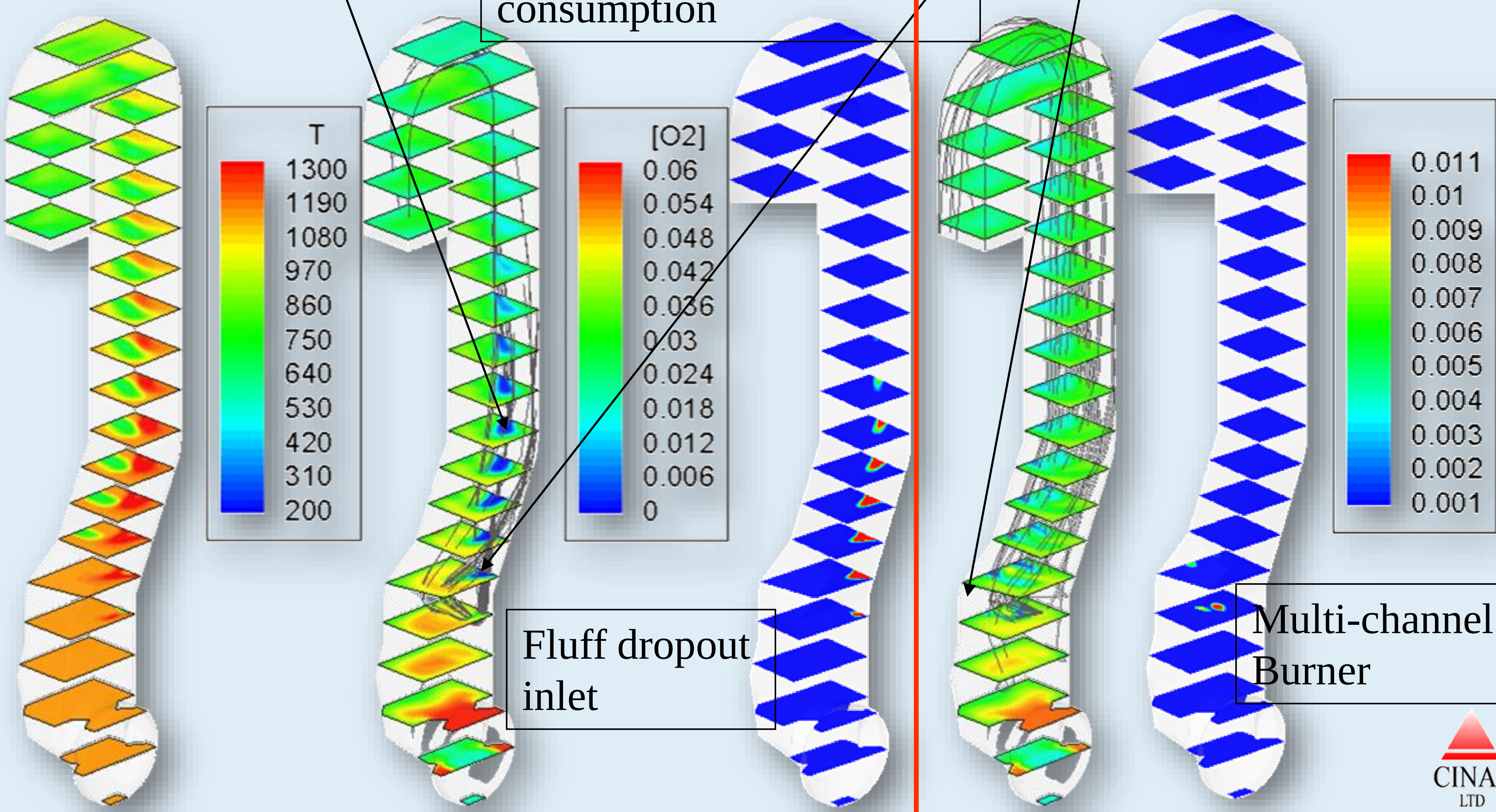
Inadequate mixing

Volatiles released and consumed with the available oxygen.

Inadequate mixing mechanism (via screw feeder) for volatile's consumption

Oxygen supplied with higher momentum burner



Fluff dropout inlet

Multi-channel Burner

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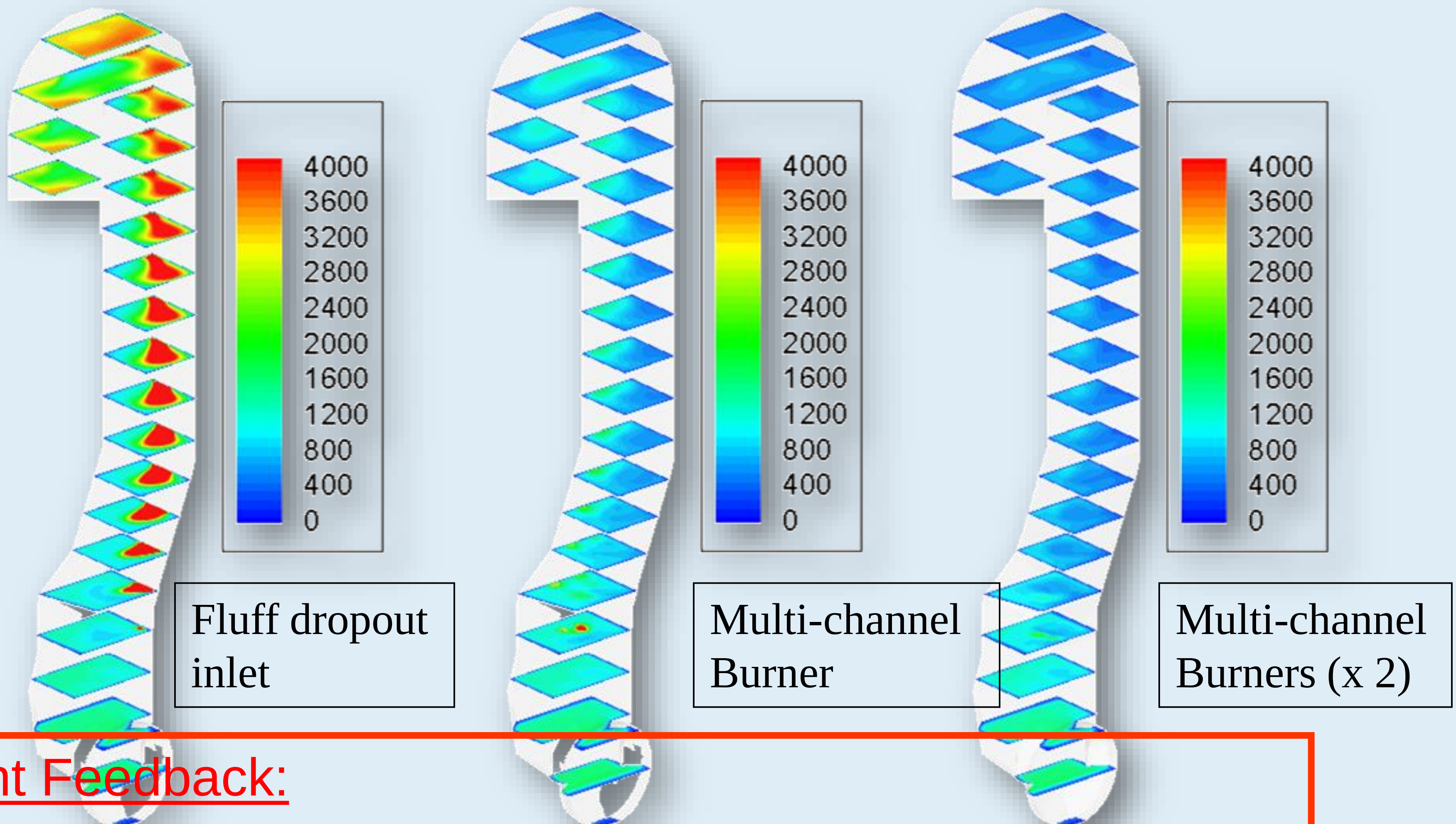
CO Predictions

CO Exit: 2563ppmv	CO Exit: 753ppmv	CO Exit: 567ppmv



Plant Feedback:

Installation of single M-Ch burner reduced CO by 70%

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Reducing CO-General Comments

Fuel-rich pockets enhance CO formation, more so if fuel volatiles are trapped in the flow recirculation zones;

Improved mixing in hot regions (temperatures above 1000 C), in the presence of OH radicals reduces CO at a faster rate;

Improving the residence time alone, away from the NBR (in lower temp. and OH regions; (below 950 C) is less efficient.

If mixing cannot be improved by a simple geometrical alteration, air jets or multi-channel burners or JEMS, having at least half of the momentum of the unmixed stream, may be considered.

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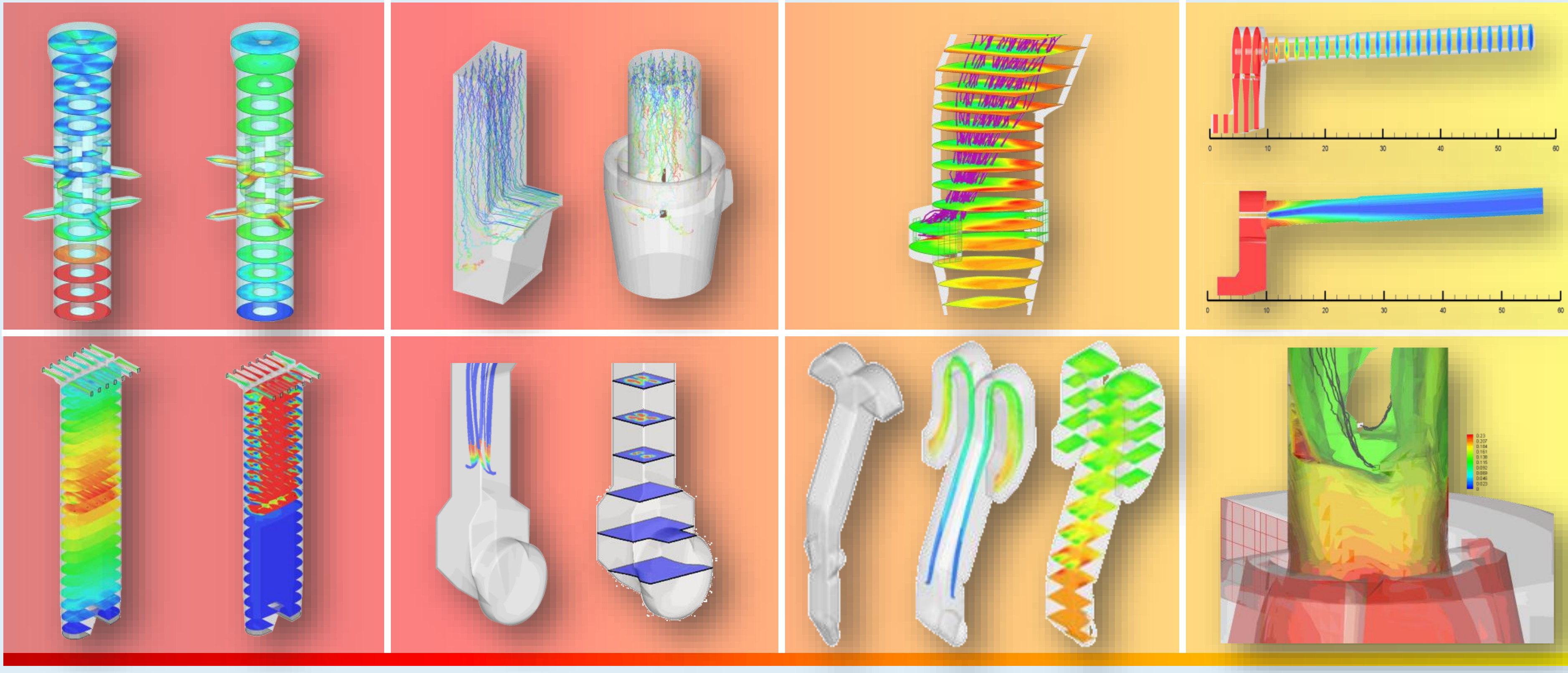

Reducing kiln NOx

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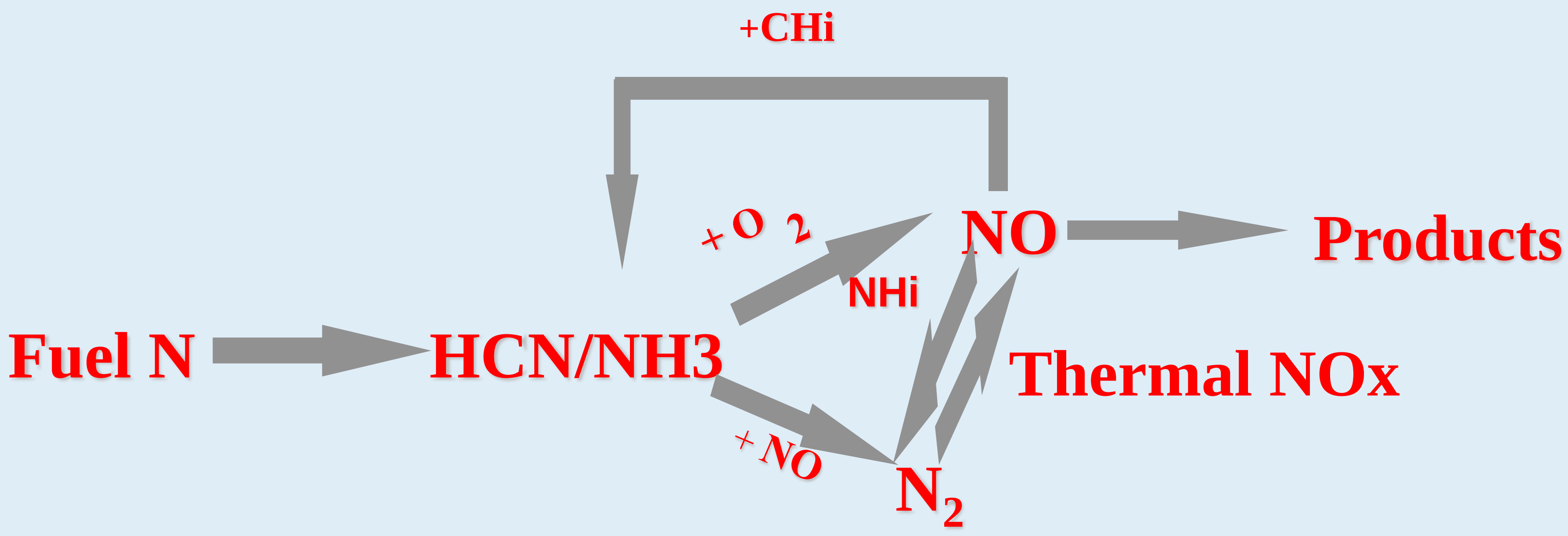
Post-Processing for Trace Species

- Proven global reactions are used for the nitrogenous species.



Reducing NOx in Calciner

- **Suppressing Air-Fuel mixing:**

  Low NOx burner, FGR, flameless oxidation;

  Lower potential for NOx (10-40%),
  But potential risk for higher CO

- **Fuel Reburning/Staging:**

  Creation of CHi and OH radicals which reduce both NO and CO (kiln generated);

  Higher potential for reducing both (10-80%)

- **SNCR/SCR:**

  Inject of NH_3 or NH_2CONH_2 @ (900-1100 C)

  Higher potential (10-80%)

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The Most Important Variables for Reducing NOx:

Temperature;

Residence time;

Fuel volatile/nitrogen content;

Stoichiometry conditions;

Volatiles/Riser Gas

&

Volatiles/TA mixing!

Reducing Kiln NOx

Producing a ‘lit-back’ flame with minimum air premixing of the kiln burner;

Creation of a ‘short-sharp kiln flame-reducing the higher-temperature flame envelop for lower thermal NOx formation;

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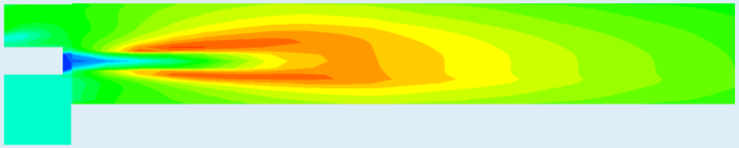
Reducing Kiln NOx

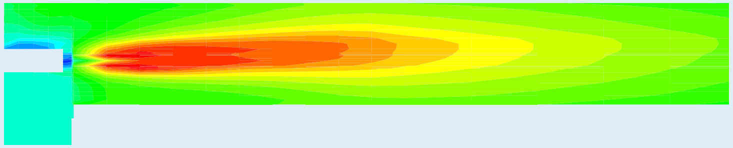
Mono-channel burner

Estimated Flame Length:	20-25 m
Ignition distance:	1.5-2 m
Exit NOx:	1049 ppm



Multi-channel burner

Reduction in Flame Length:	5 m
Reduction in Ign. distance:	1 m
Exit NOx:	634 ppm
	(40% reduction)



Plant Feed Back:

NOx emissions 620 ppm
(41% reduction)

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Reducing NOx Emissions in an AT Calciner

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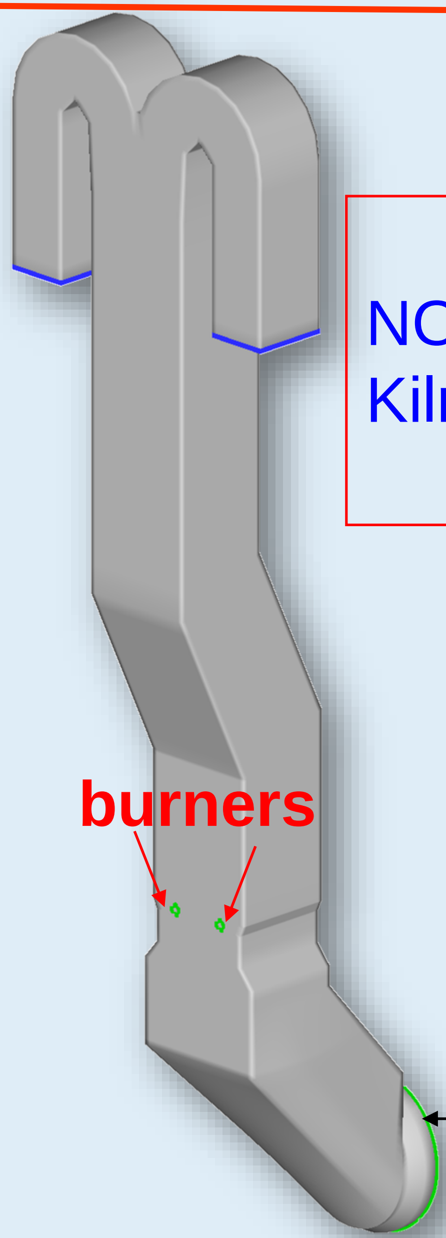
NOx Reduction in an AT Calciner

Further NOx reduction potential: 30-35%



Calciner Exit

NOx: 371

Kiln NOx reduction: 45 %

Kiln Inlet

KBE O2 :	9.9 %
NOx:	670 ppm

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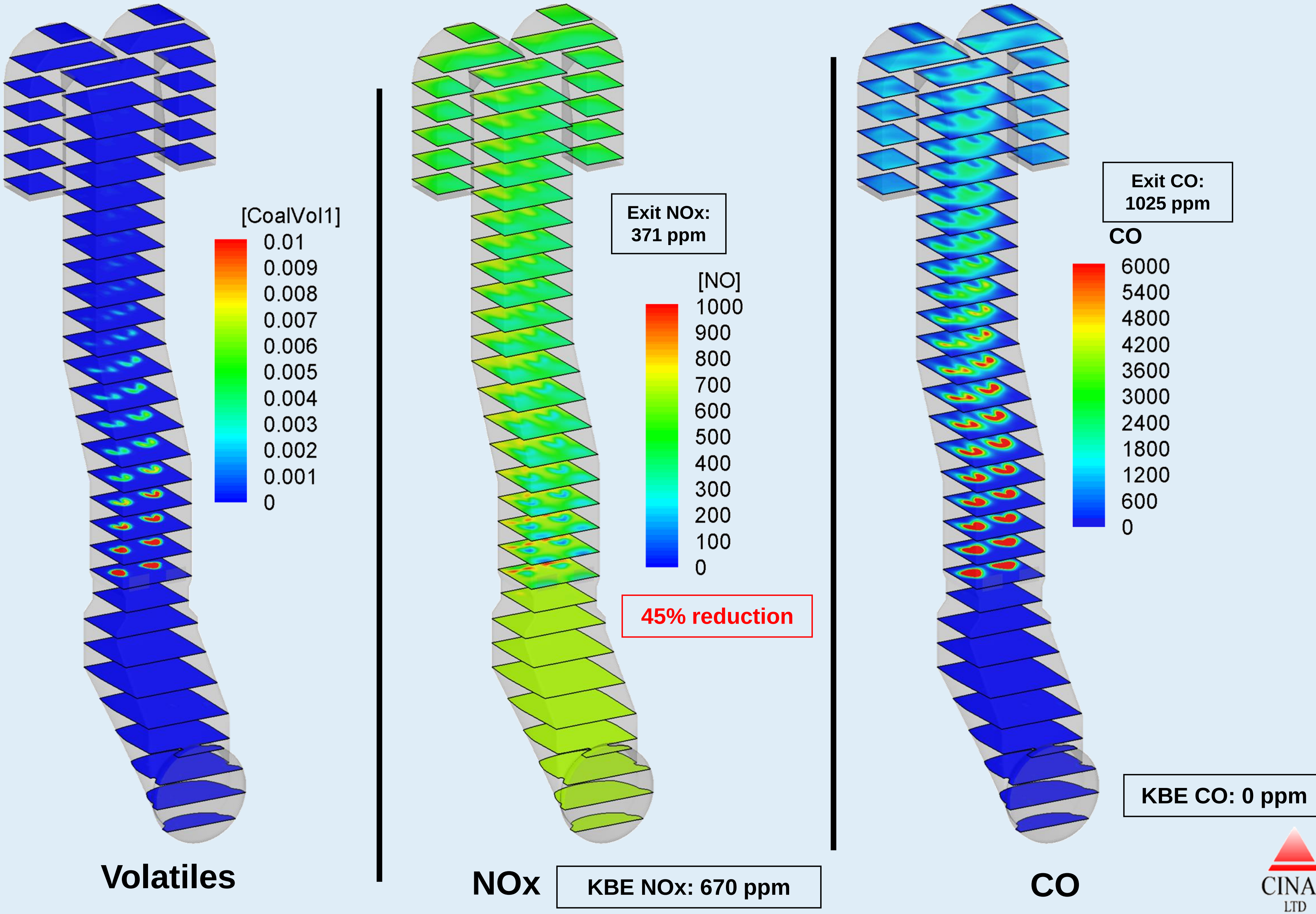
Fuel Volatiles – NOx (ppm) & CO (ppm)



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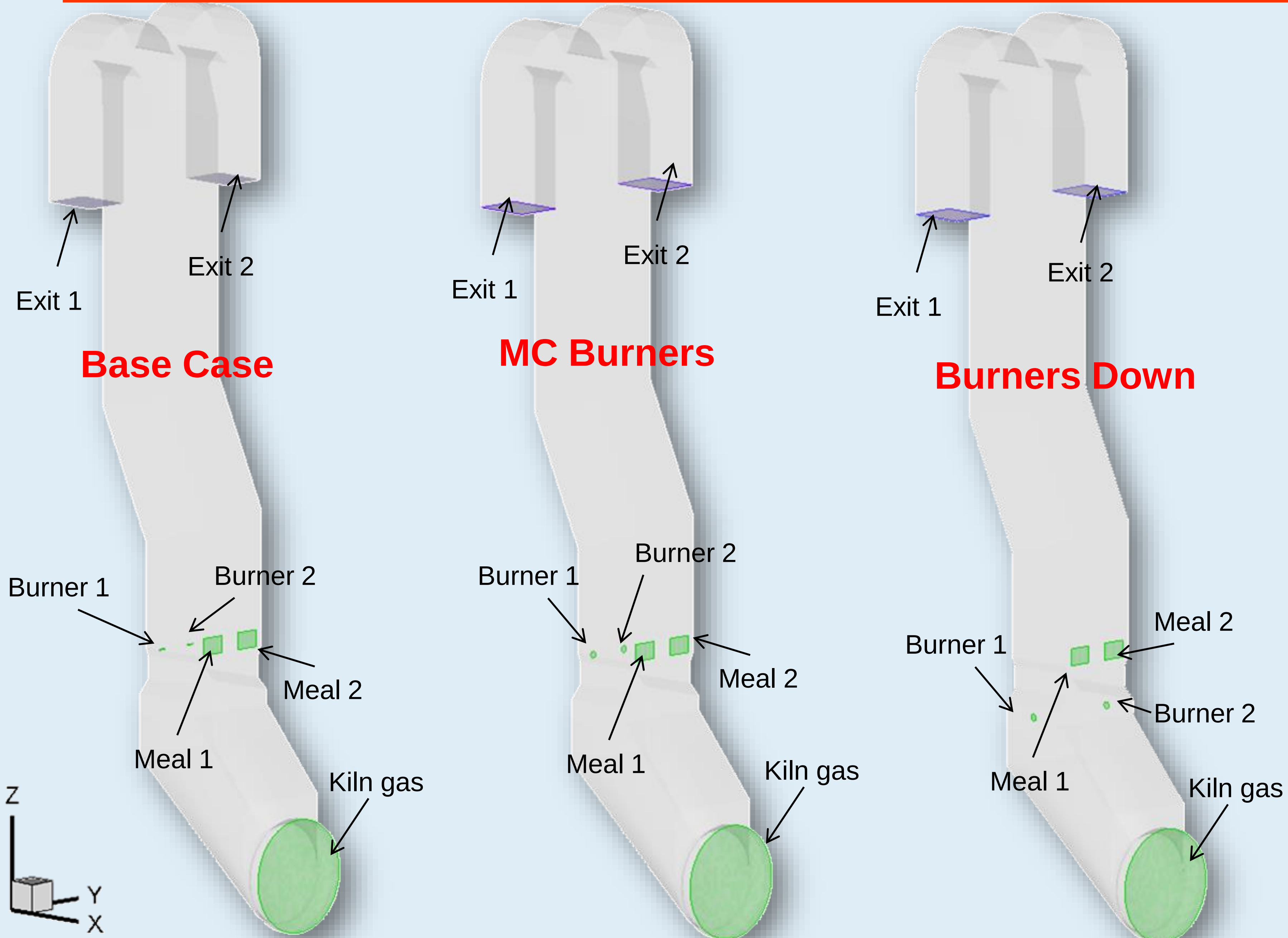
First Priority: Calcination & Combustion



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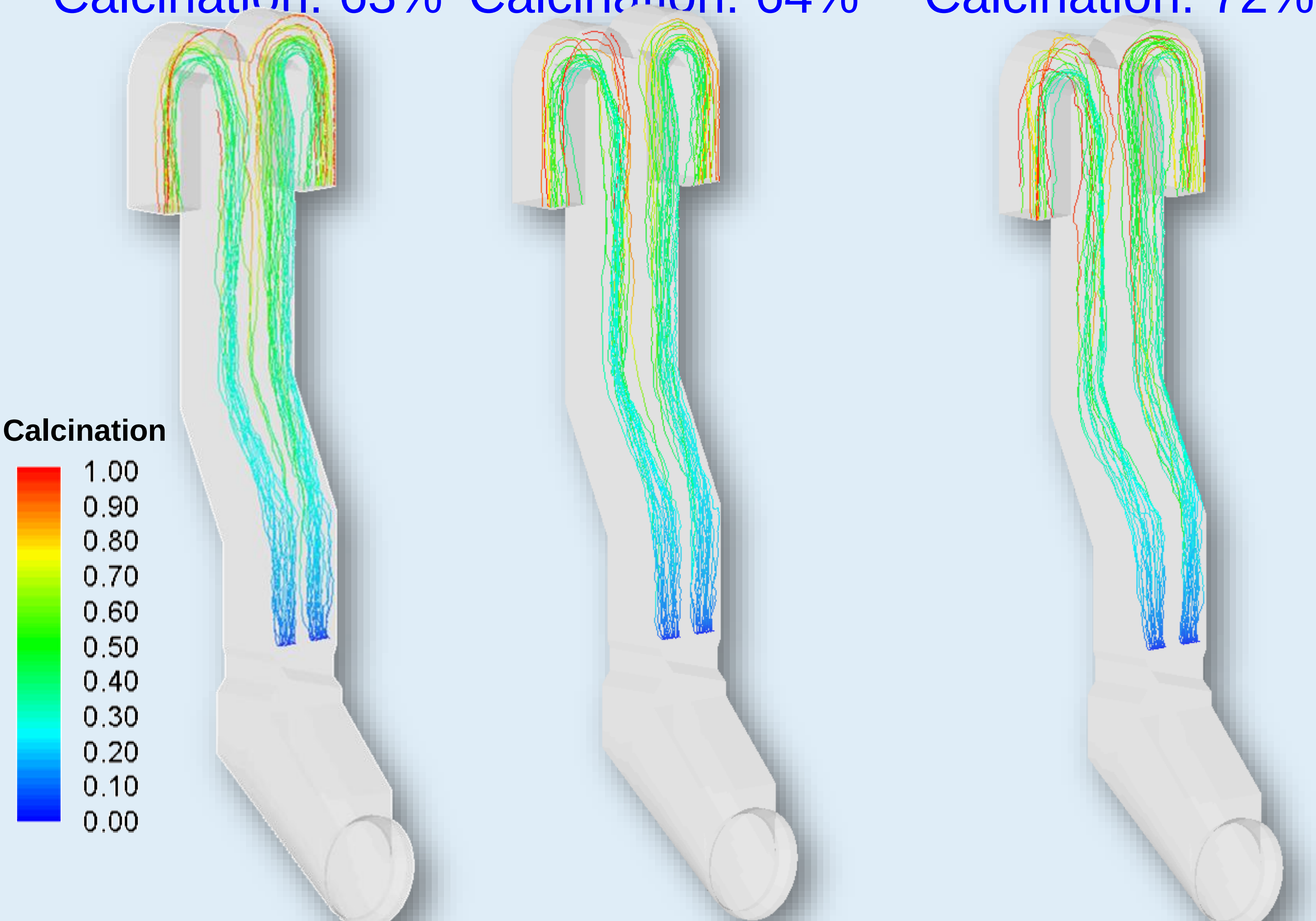
Meal Particles Tracking

Base Case — Calcination: 63%

MC Burners — Calcination: 64%

Burners Down — Calcination: 72%



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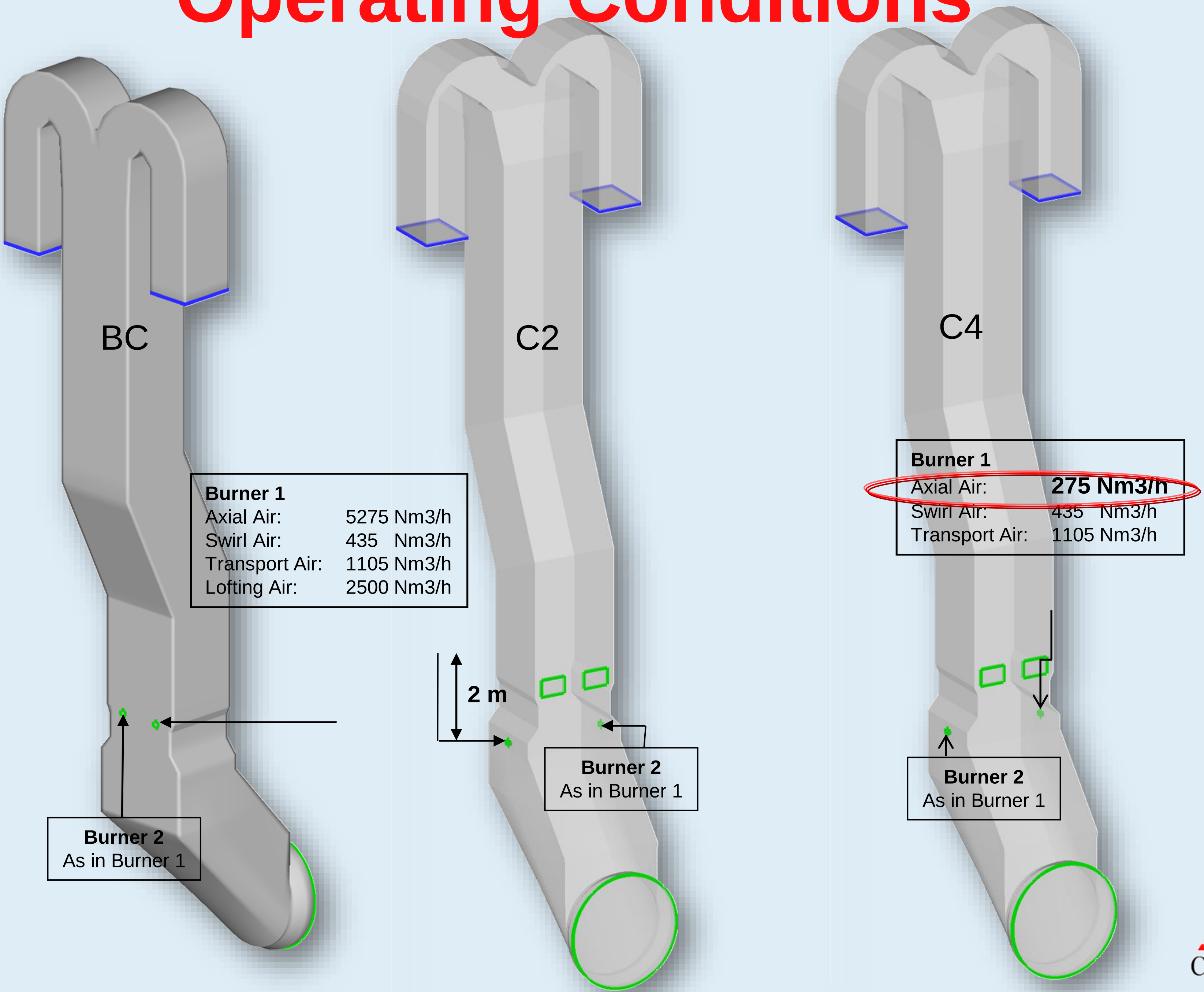
Operating Conditions



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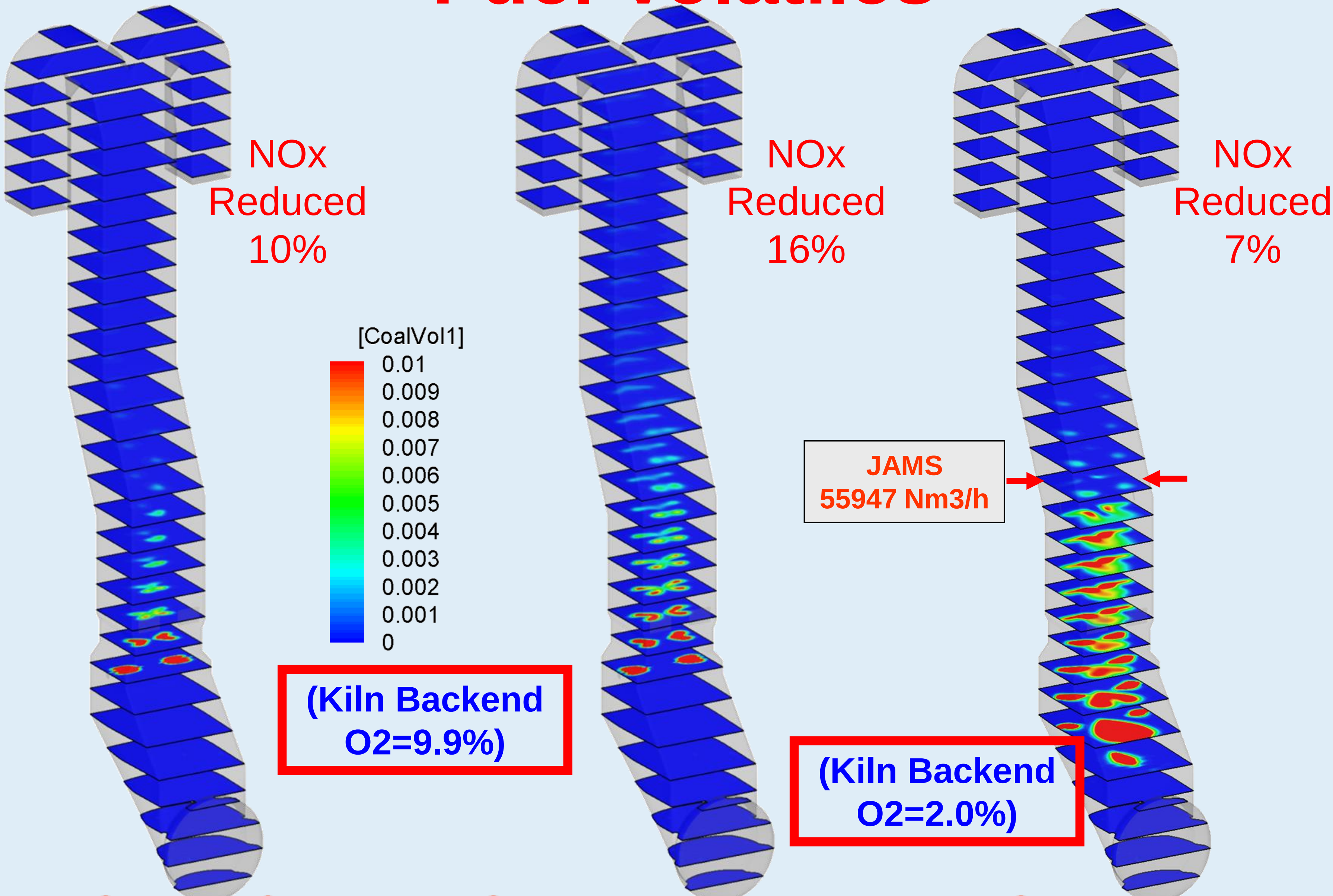
Implementation of JAMS

Two JAMS: (Jet Air Mixing System)

55947 Nm3/h at a distance of 5m above the original MC burners on the side walls with 150 m/s velocity.

Fuel Volatiles



Case 2: **Case 4** (Less Axial Air) **Case 5** (JAMS)

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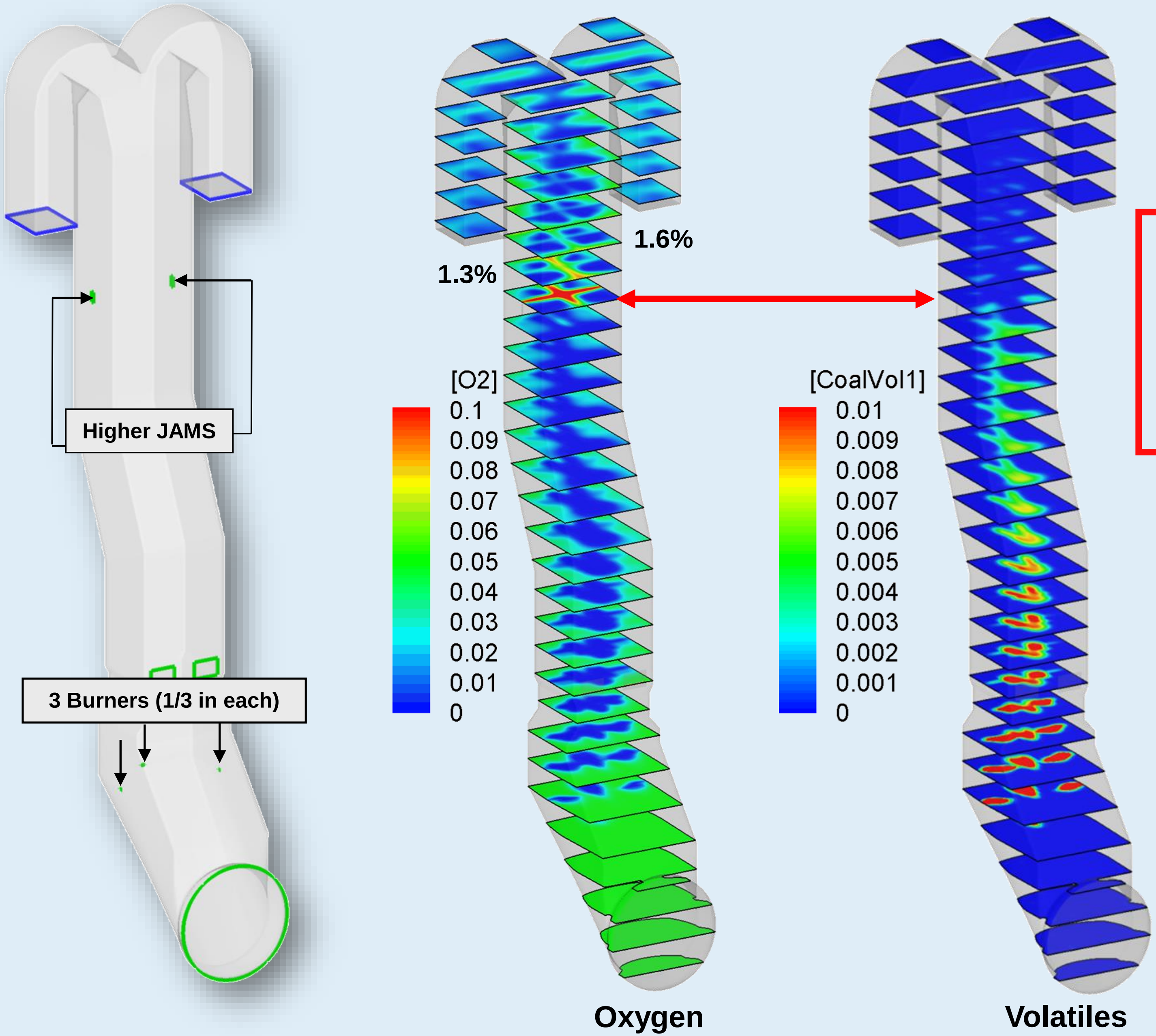
JAMS Moved Up (From 5 to 19m above)



NOx Reduced 28%

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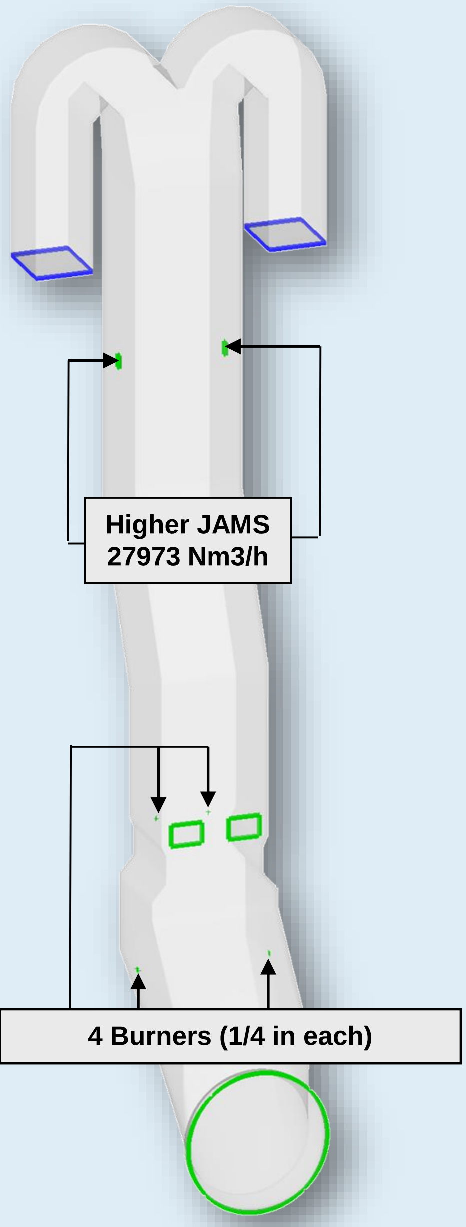
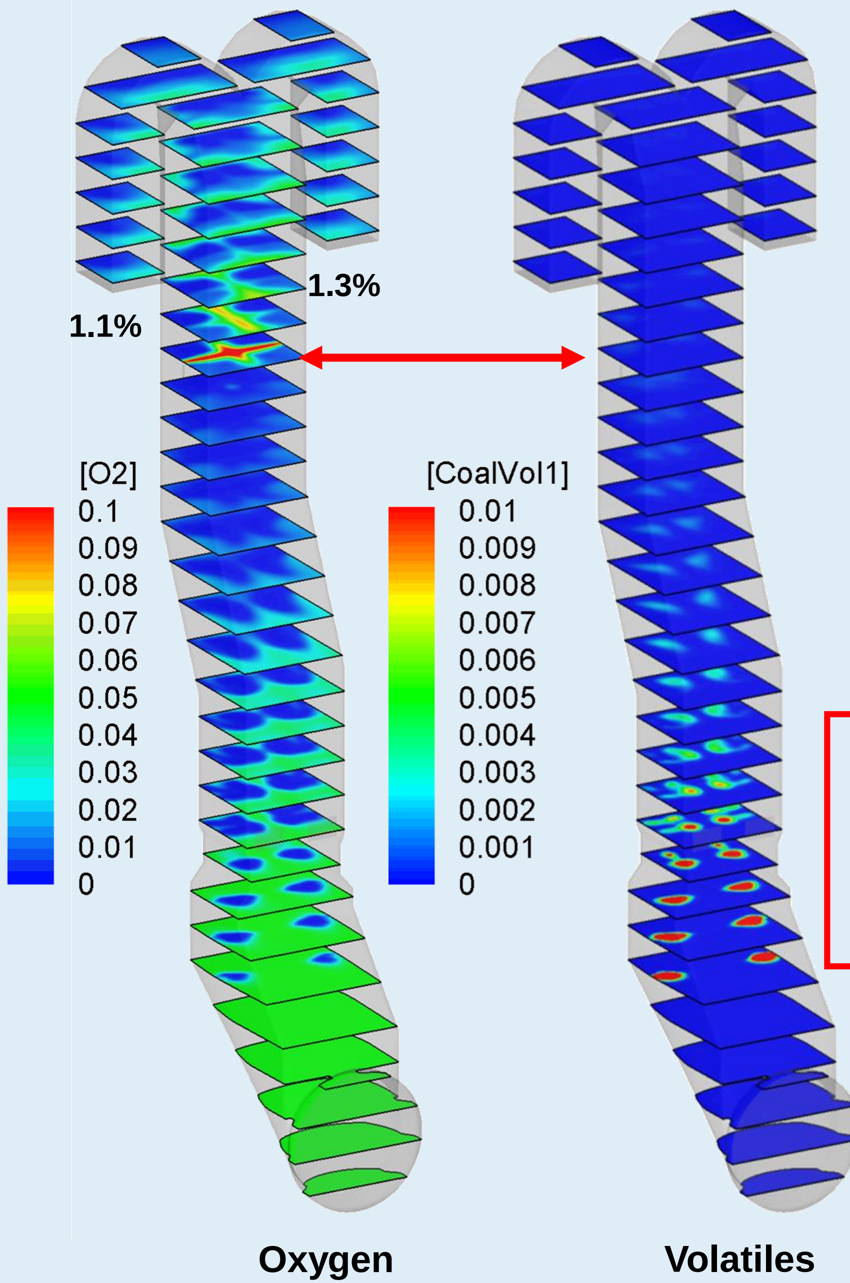
Upper JAMS (4 burners)





NOx Reduces by 33%

CO Increases! correspondingly due to lower RT!

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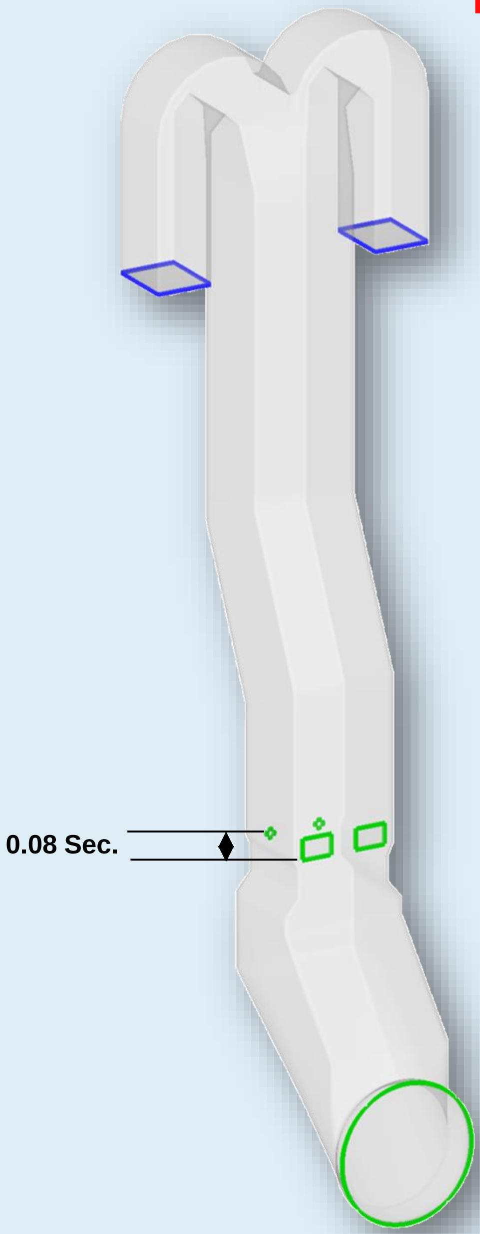
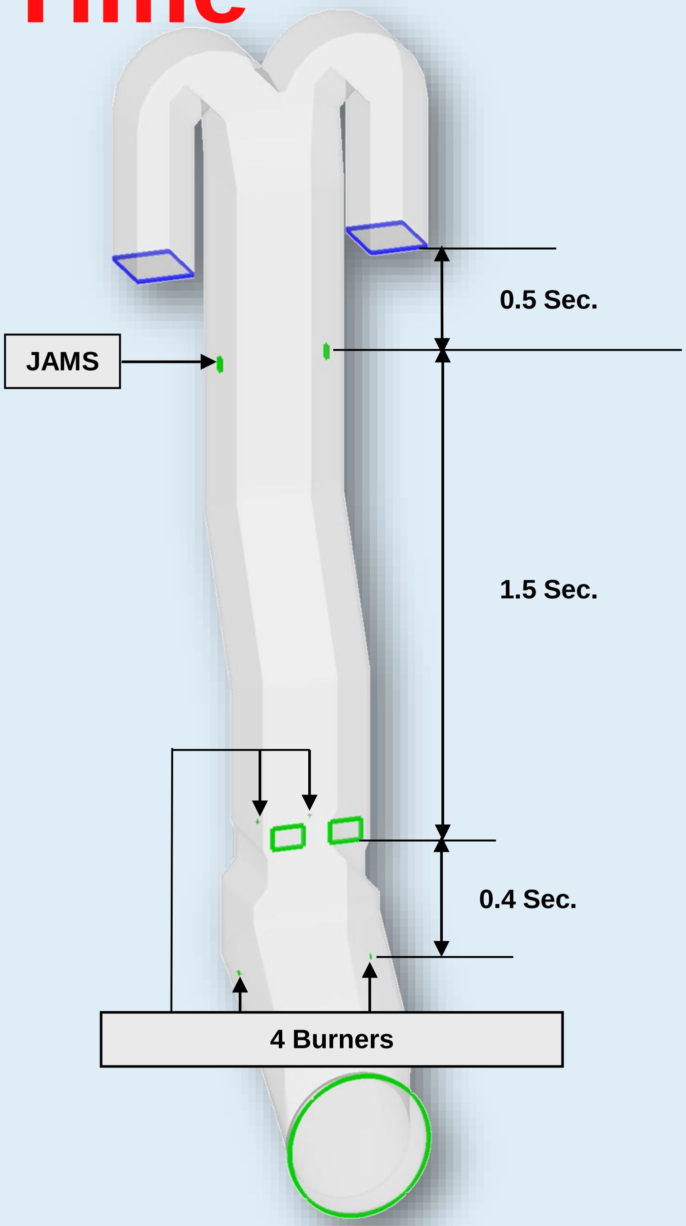
Residence Time



Base Case



Upper JAMS (4 burners)

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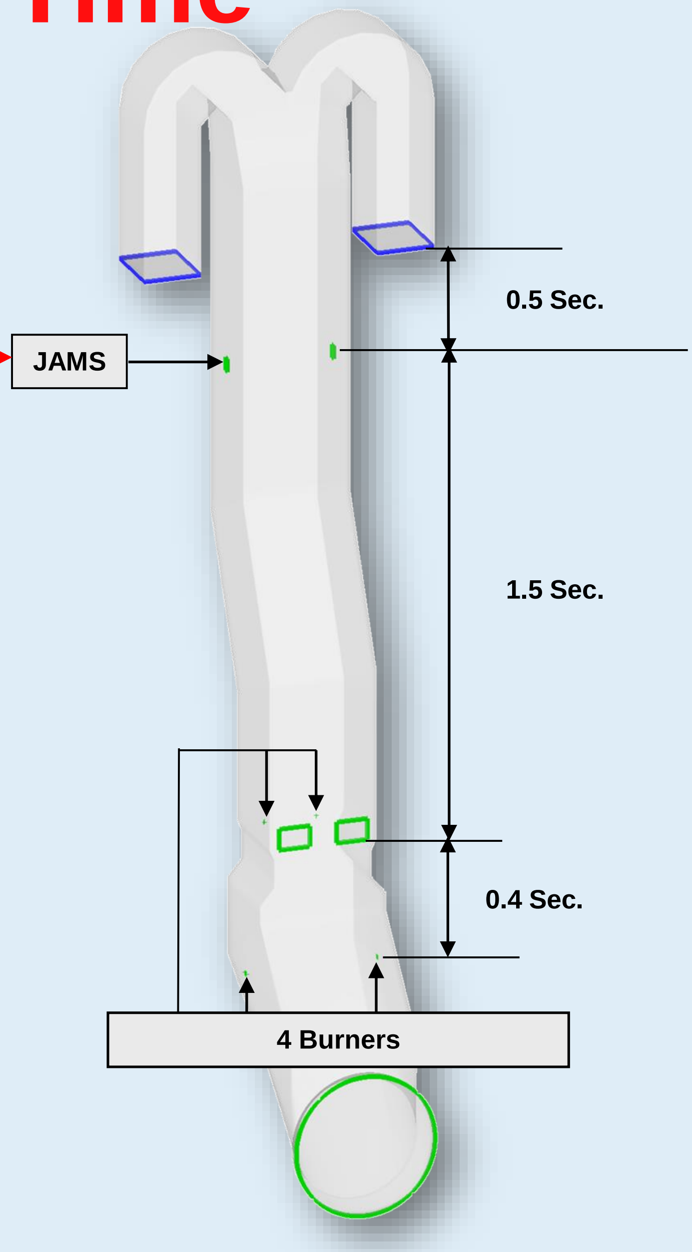
Residence Time

Additional 12,000 Nm3 of air for the JAMS over the 18,000 Nm3/hr already being supplied to the system from the multi-channel burners, will add an estimated fuel penalty of < 10 kcals/kg



Important Variables:

- Num. of burners,
- Location of burners with respect to JAMS
- Volatile release/composition

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Reducing NOx Emissions

in a RSP Calciner

(RT = 5 s)

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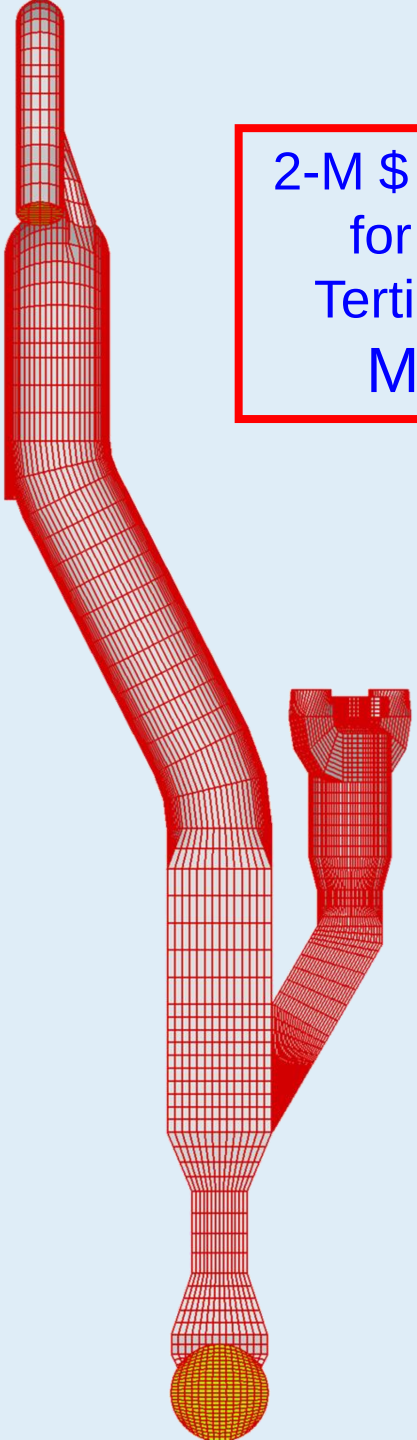
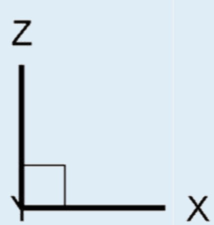
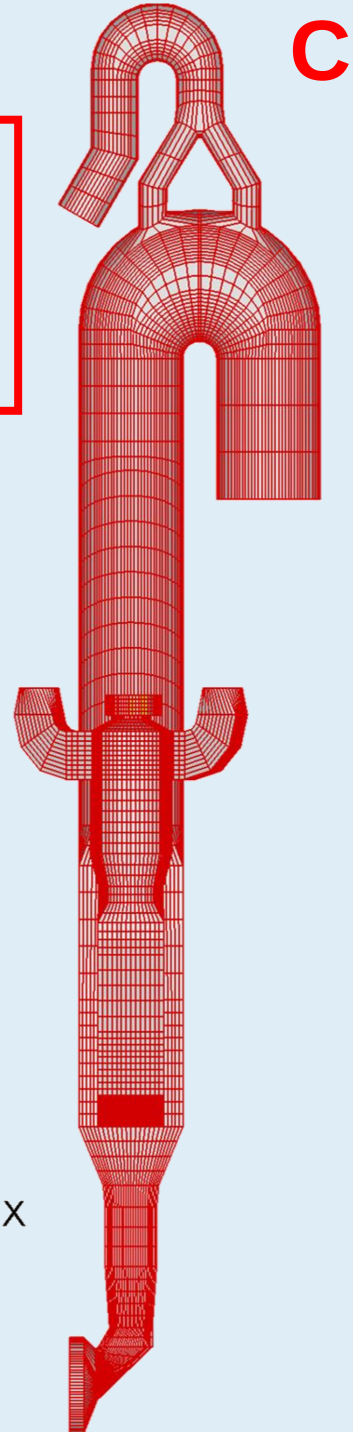
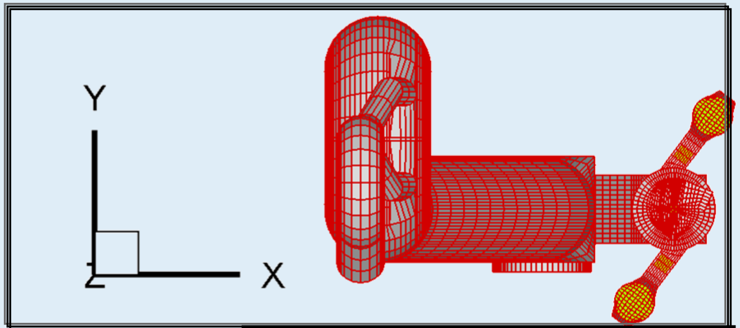
Computational Grid

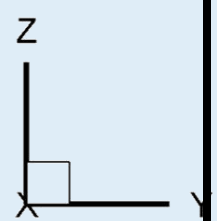
2-M $ Investment for Staging Tertiary Air for MINOX!

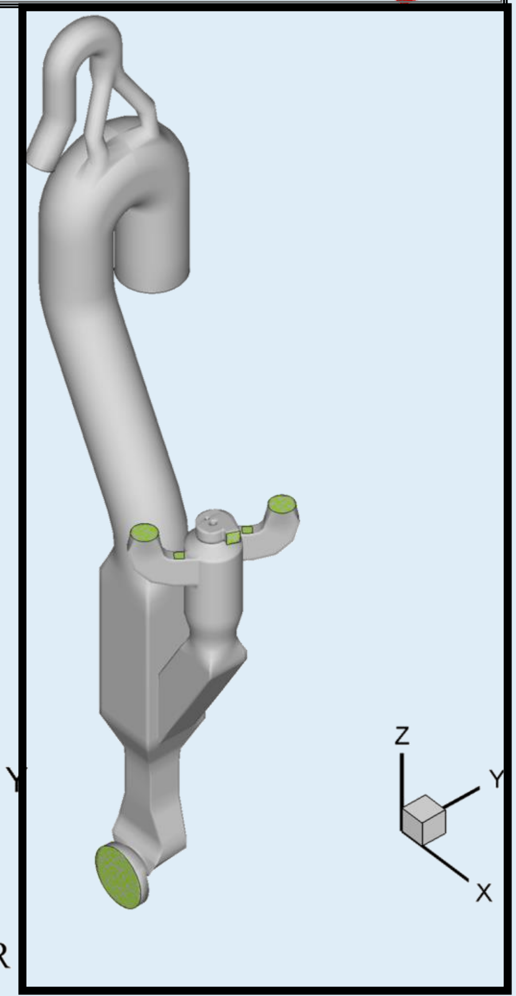












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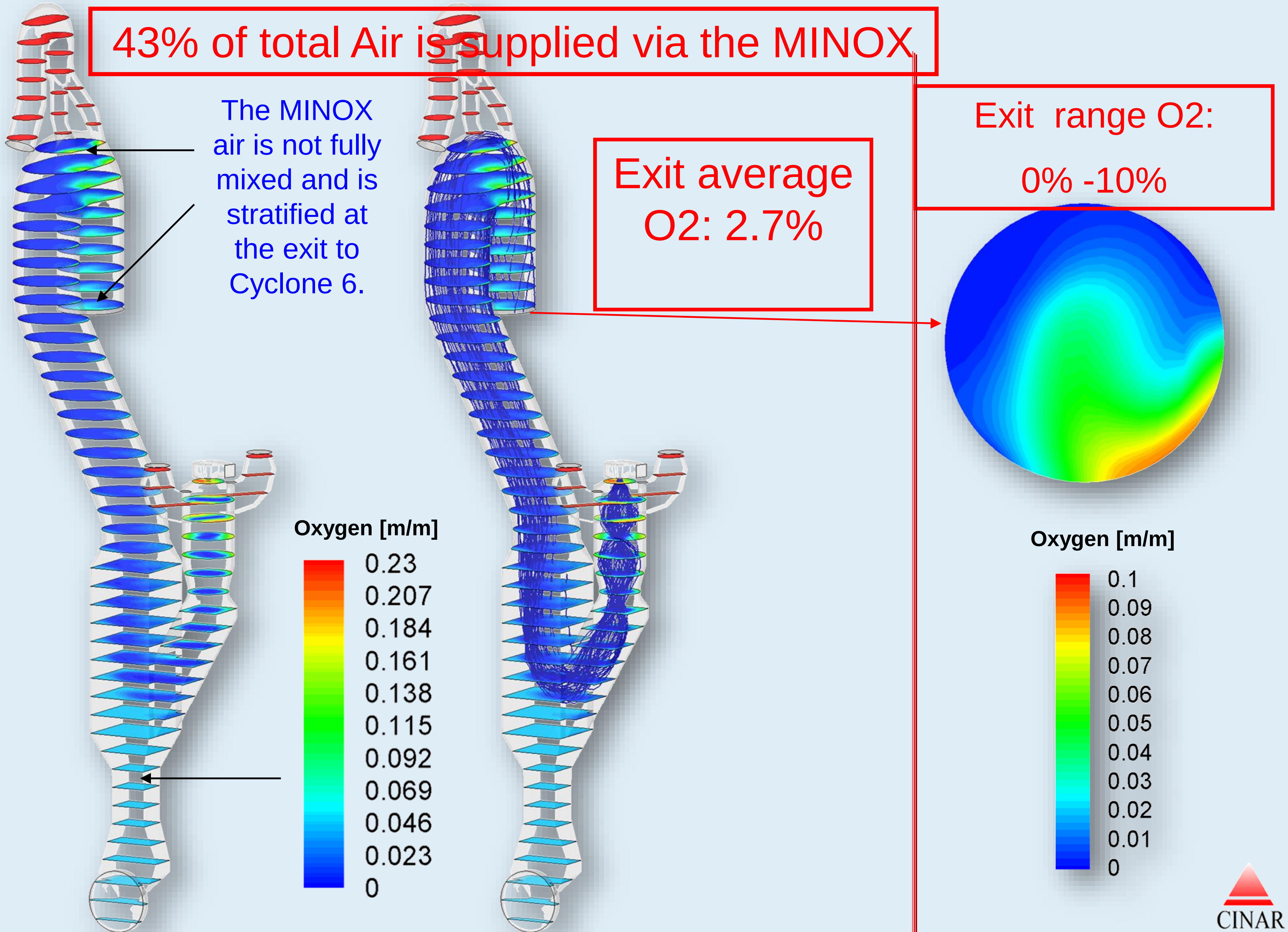
43% of total Air is supplied via the MINOX



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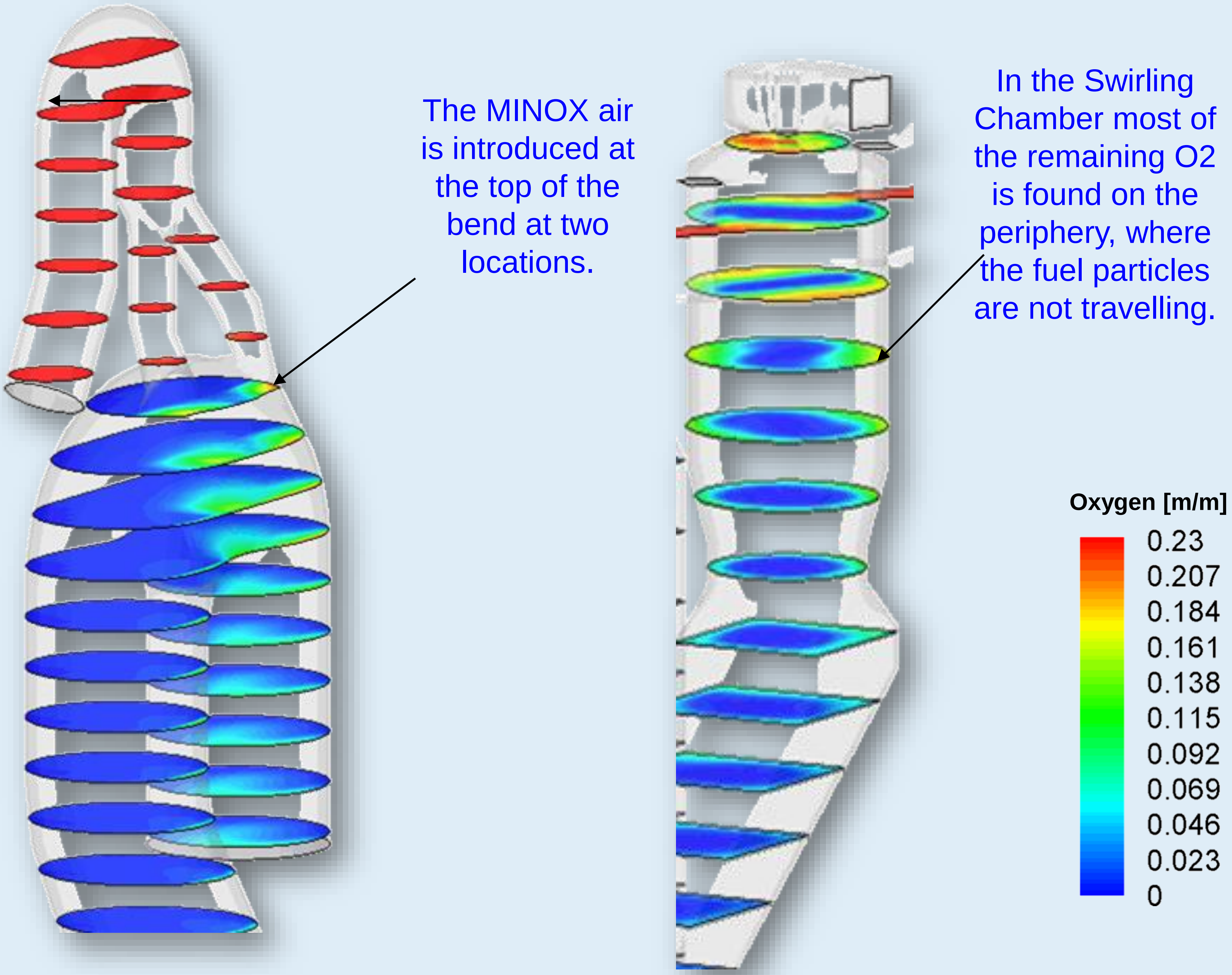
Oxygen Profile

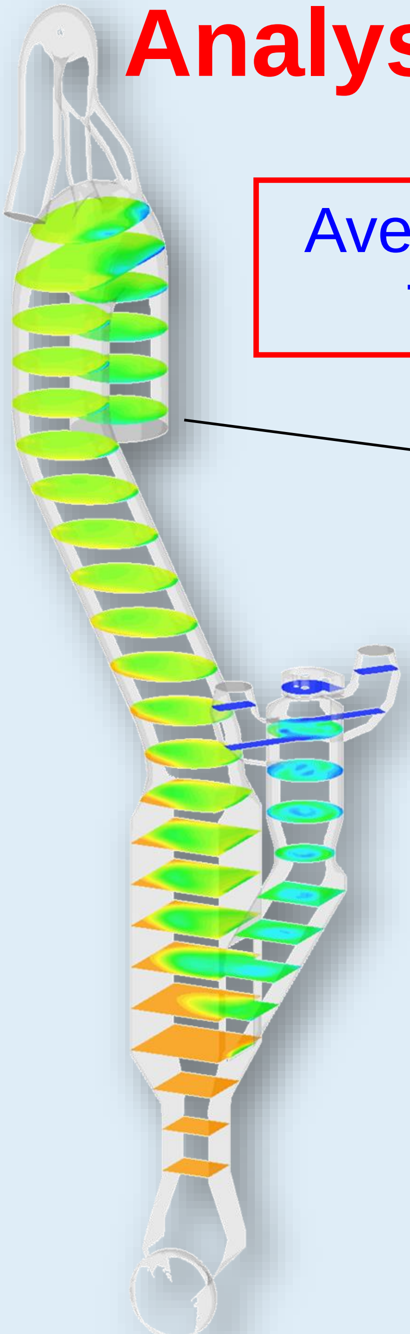


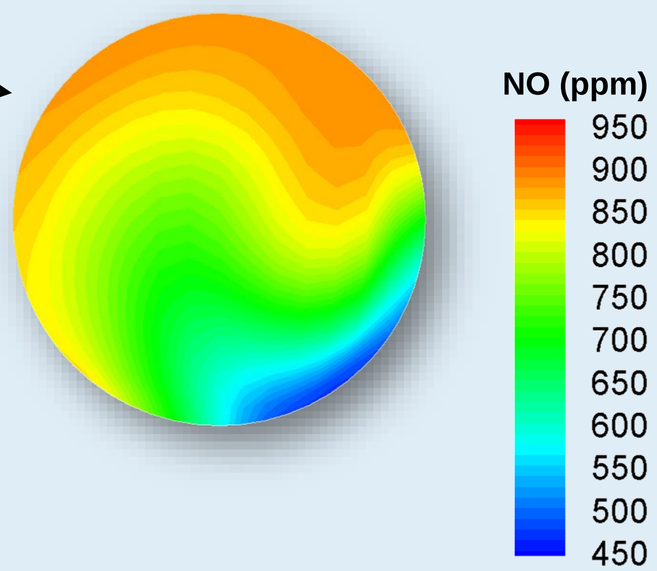
CINAR LTD

Analysis of Base Case Results – NOx

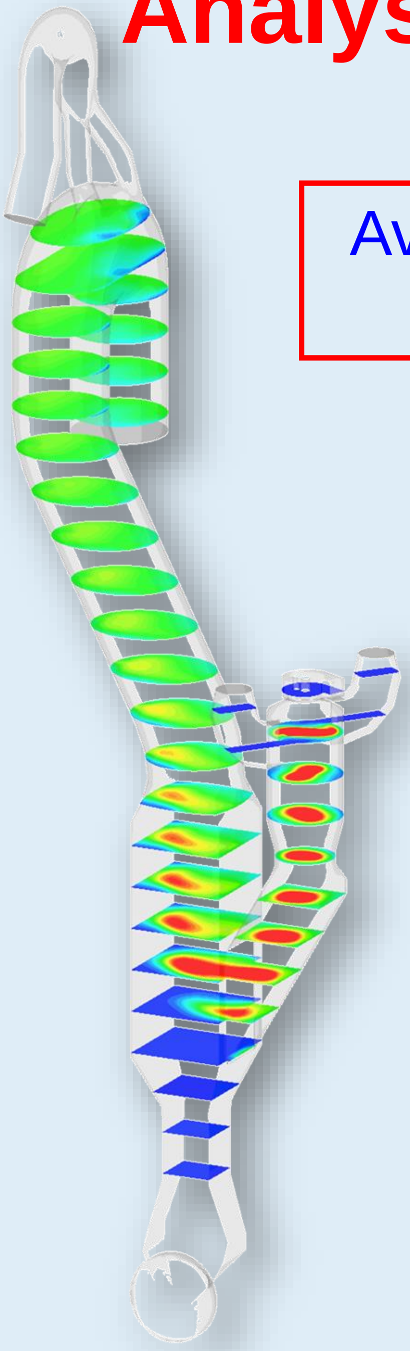
Average Value:
770ppm

Exit range NOx :
500-900 ppm



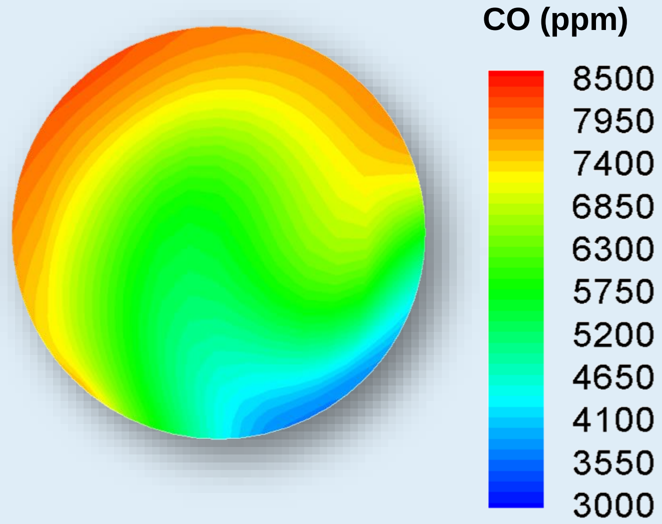


Analysis of Base Case Results – CO



Average Value:
6048ppm

Exit range CO :
3000-8500 ppm



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Another example of RSP

RT: 5 seconds

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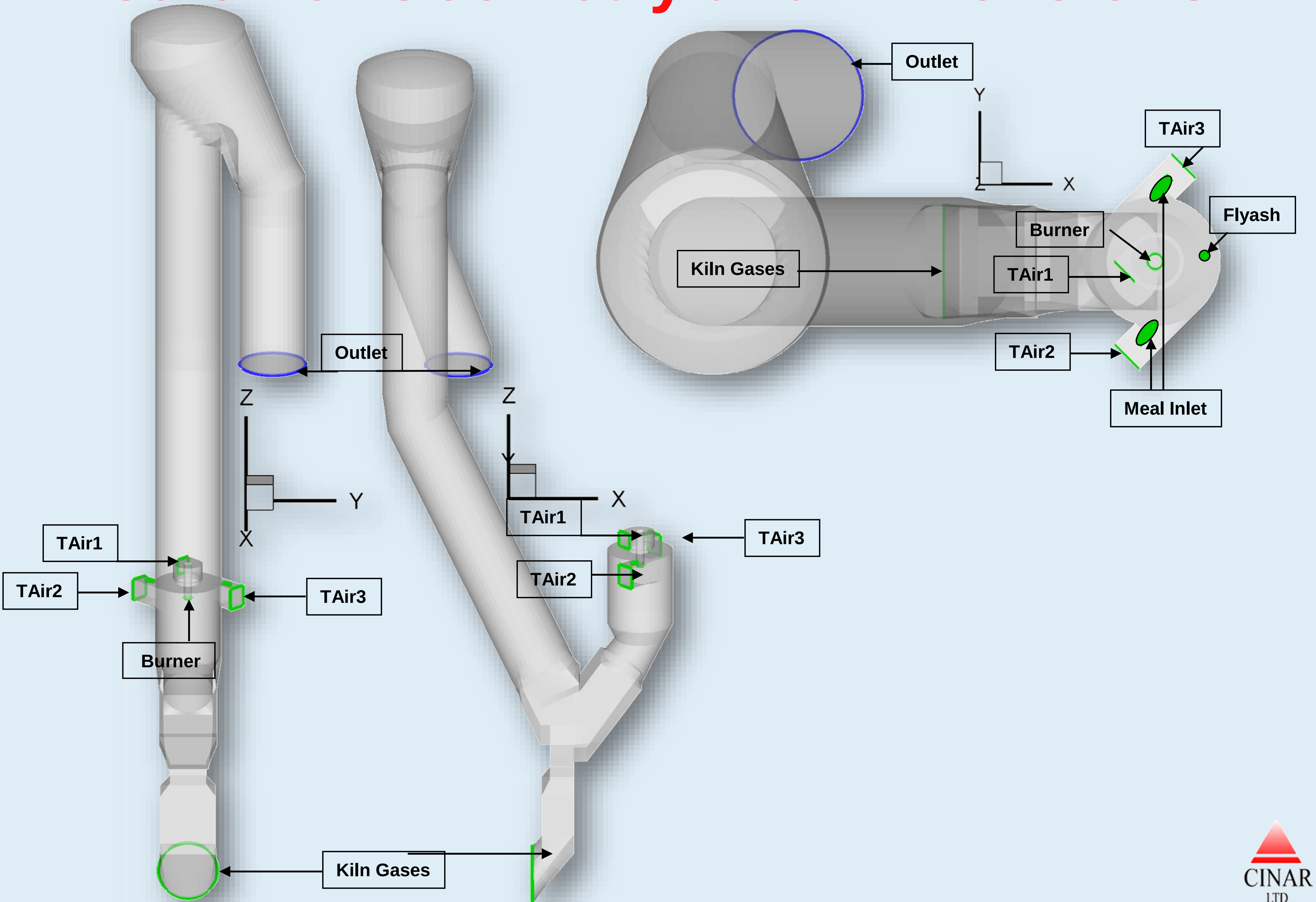
Calciner Geometry and Dimensions



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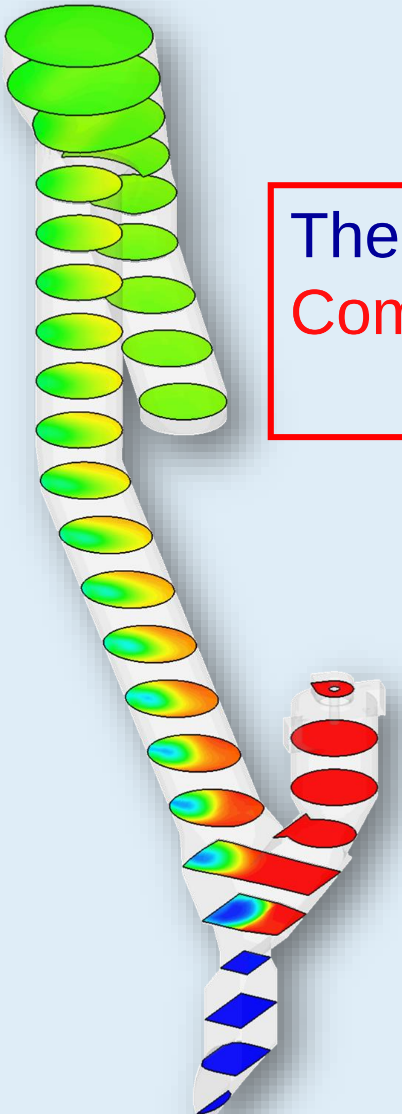
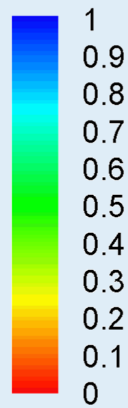
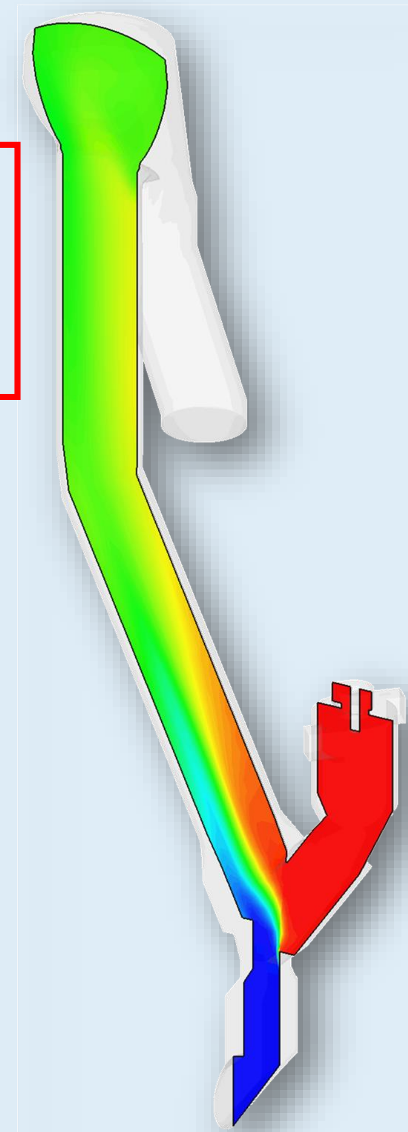
Analysis of Base Case Results – Mixing of KRG with Combustion Chamber Flow



The Kiln Riser Gas is in blue and Combustion Chamber Flow is in red (Fully mixed is Green)





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The Original Concept of Air staging was Modified to fuel staging (Reburn)!

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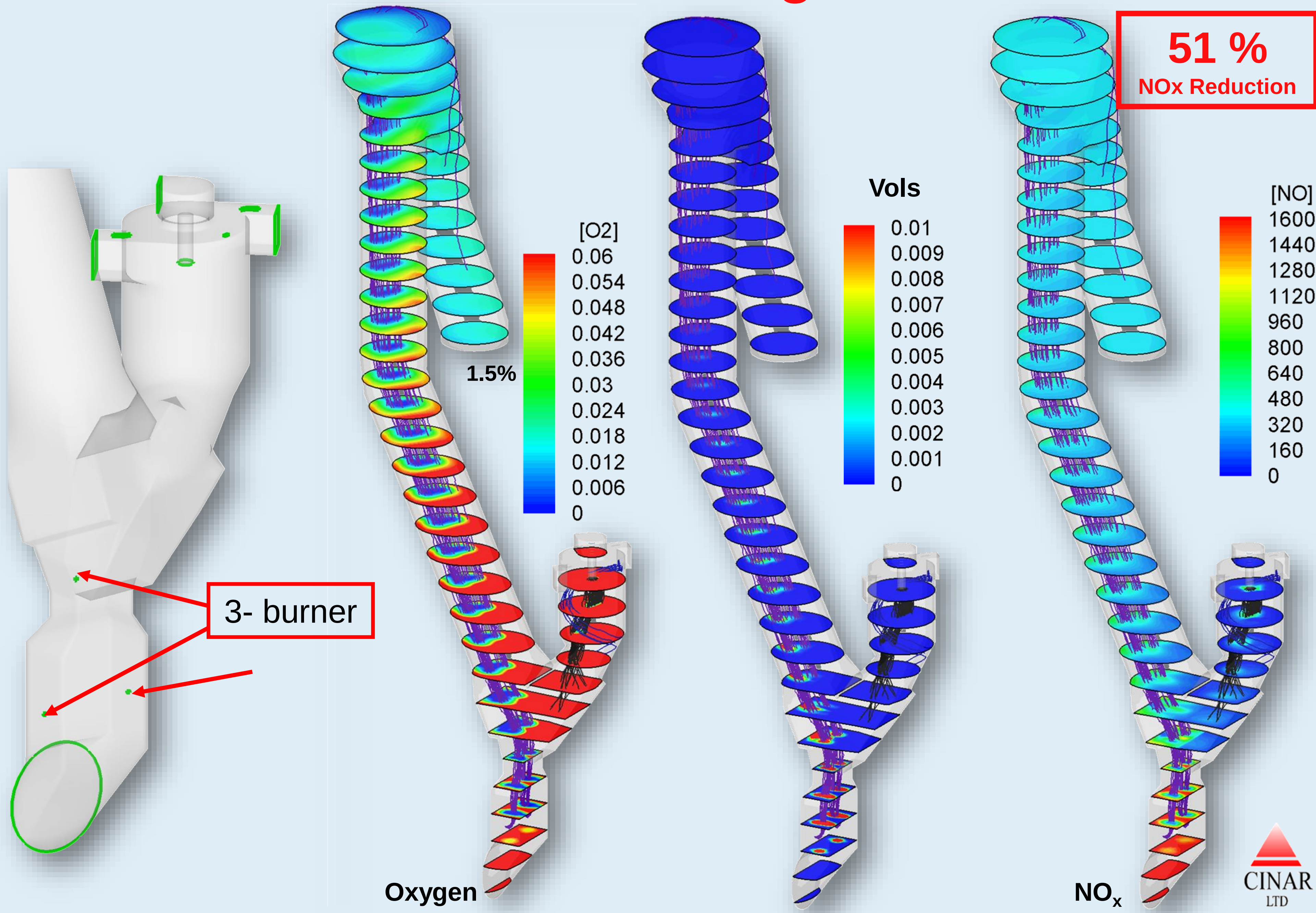
51% NOx reduction via firing 80% of fuel in RD



NOx reduction in In-line Calciners

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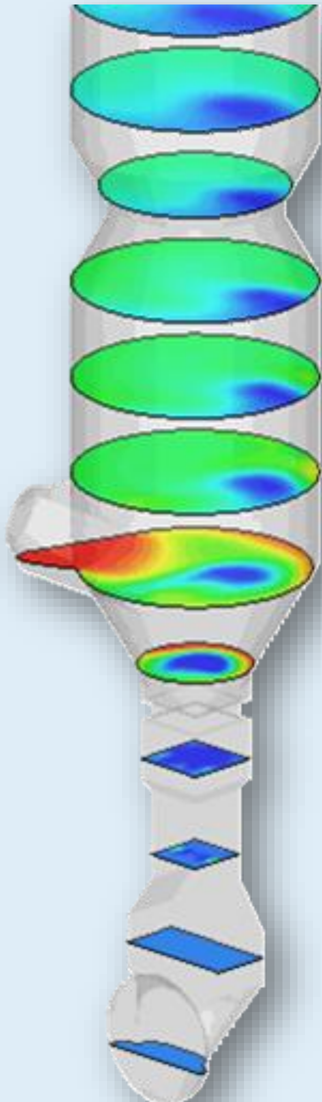
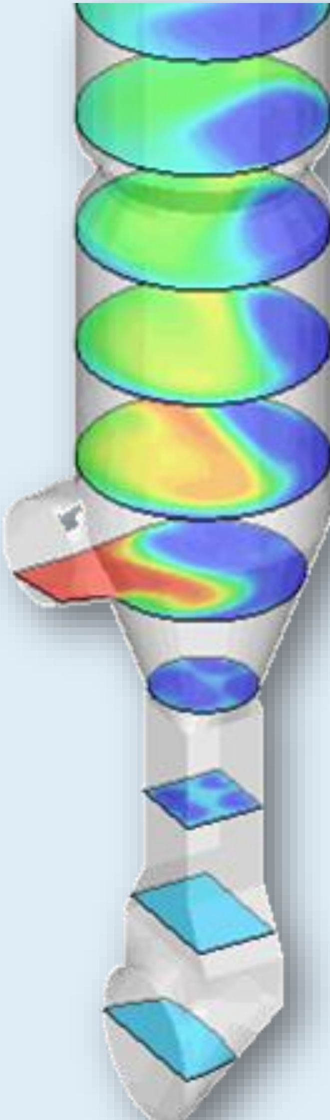
Geometry -I

O2 (fr)



Geometry -II

O2 (fr)



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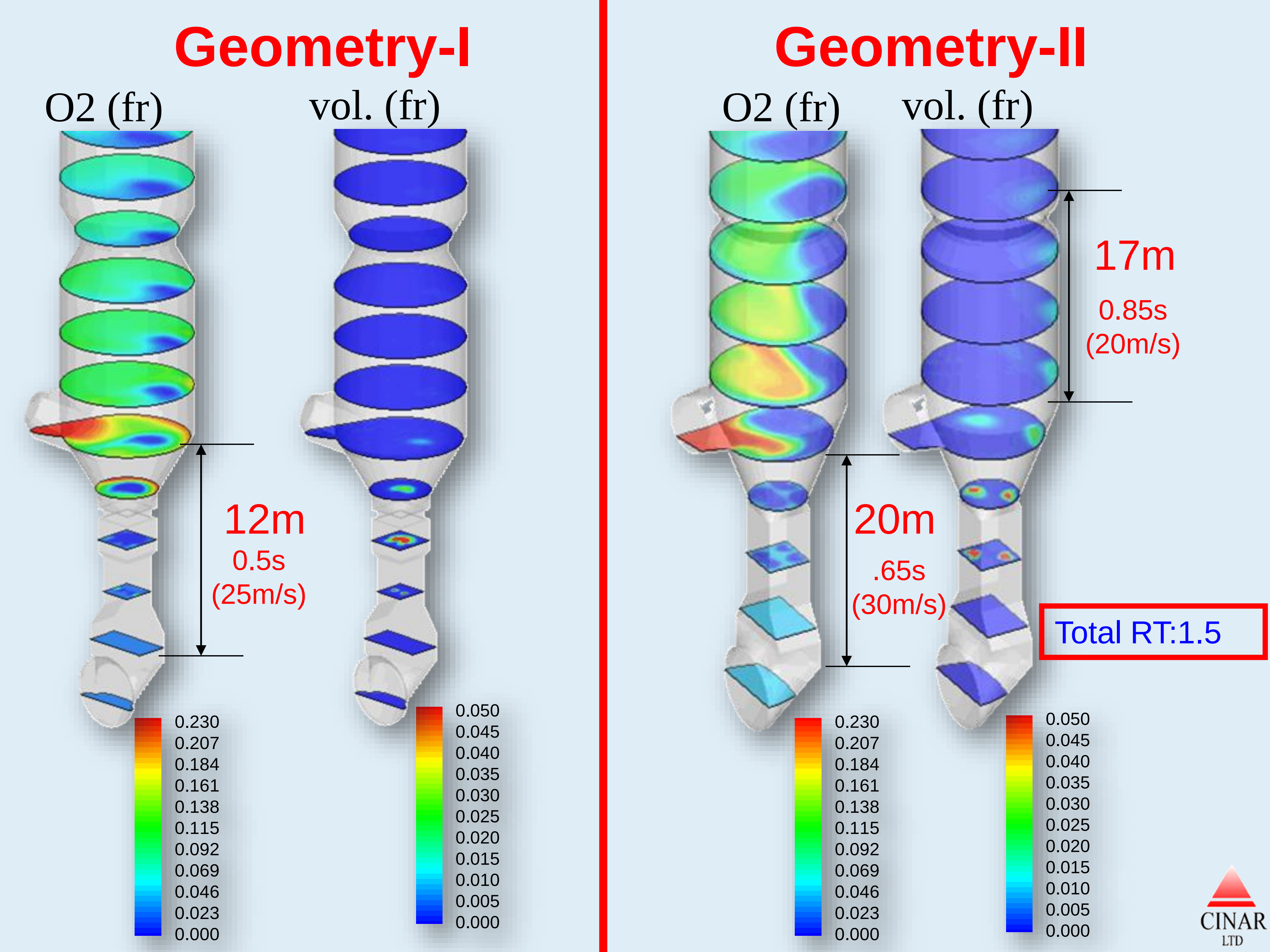
Reduction of both NOx and CO

Data: Geometry-I	
CO:	830 ppmv
NOx:	848 ppmv
O2:	2.2%

Data: Geometry -II	
CO:	50 ppmv
NOx:	300 ppmv
O2:	2.3%



Geometry-I
O2 (fr)
vol. (fr)
12m
0.5s
(25m/s)
0.230
0.207
0.184
0.161
0.138
0.115
0.092
0.069
0.046
0.023
0.000
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Geometry-II
O2 (fr)
vol. (fr)
17m
0.85s
(20m/s)
20m
.65s
(30m/s)
Total RT:1.5
0.230
0.207
0.184
0.161
0.138
0.115
0.092
0.069
0.046
0.023
0.000
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
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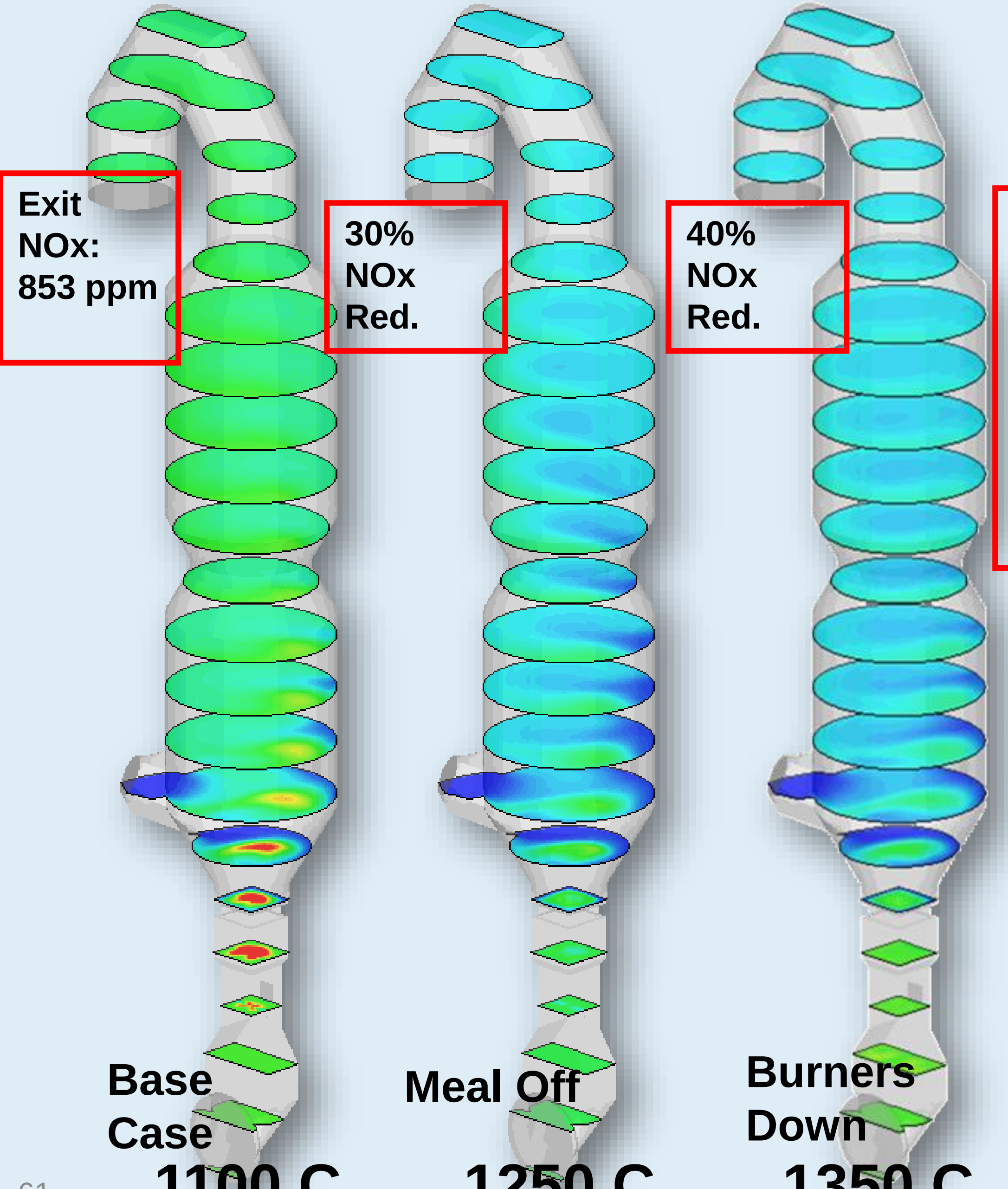
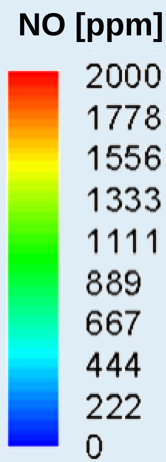
NO Concentration Profile: Geometry- I



As a general guide: for every 100 C increase about 15-20% reduction in the NOx is observed (with High Momentum burner, otherwise about 10%!



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Case Study: NOx emissions remained high even with SNCR!!

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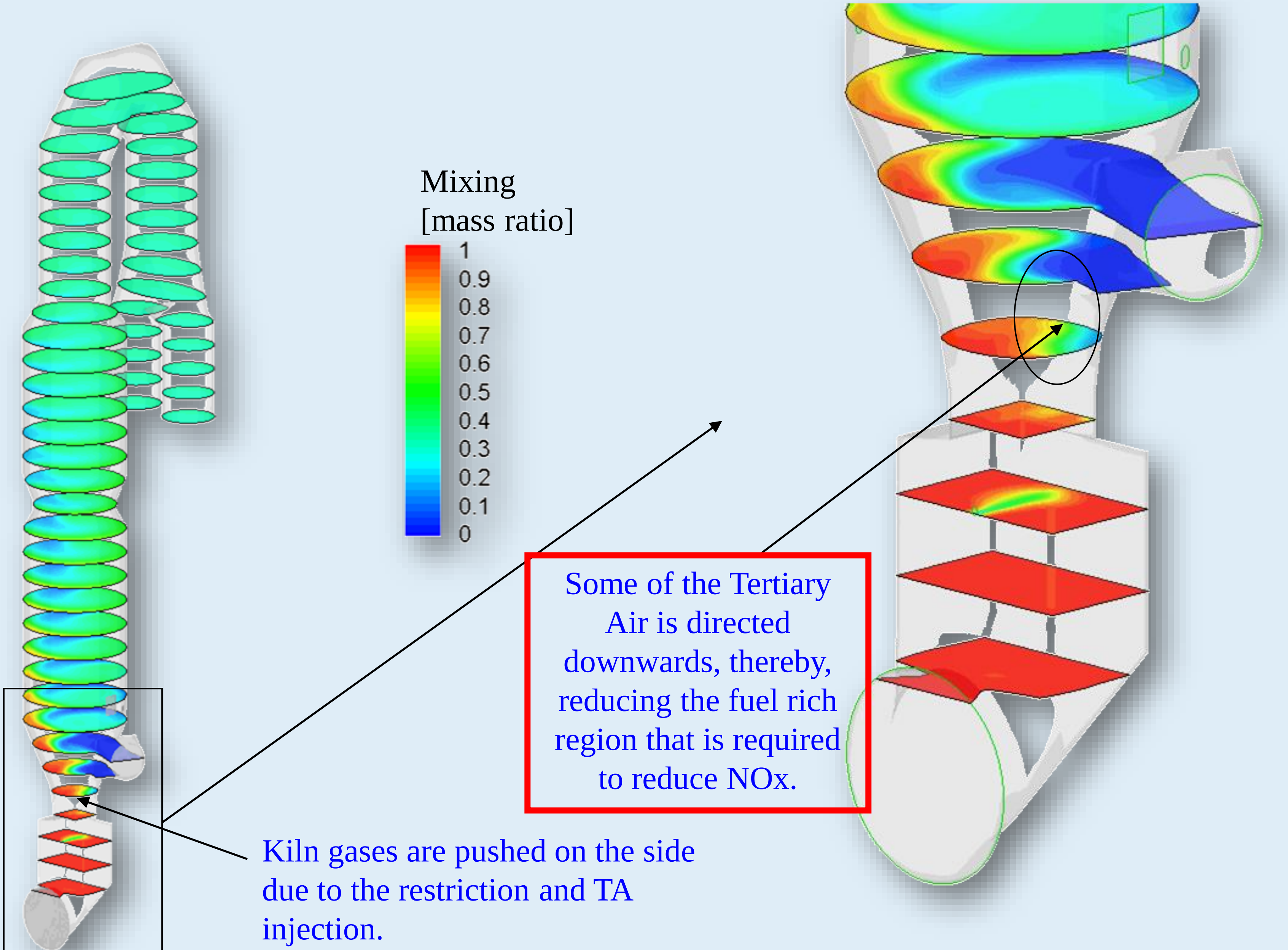
1. Base Case **Mixing**



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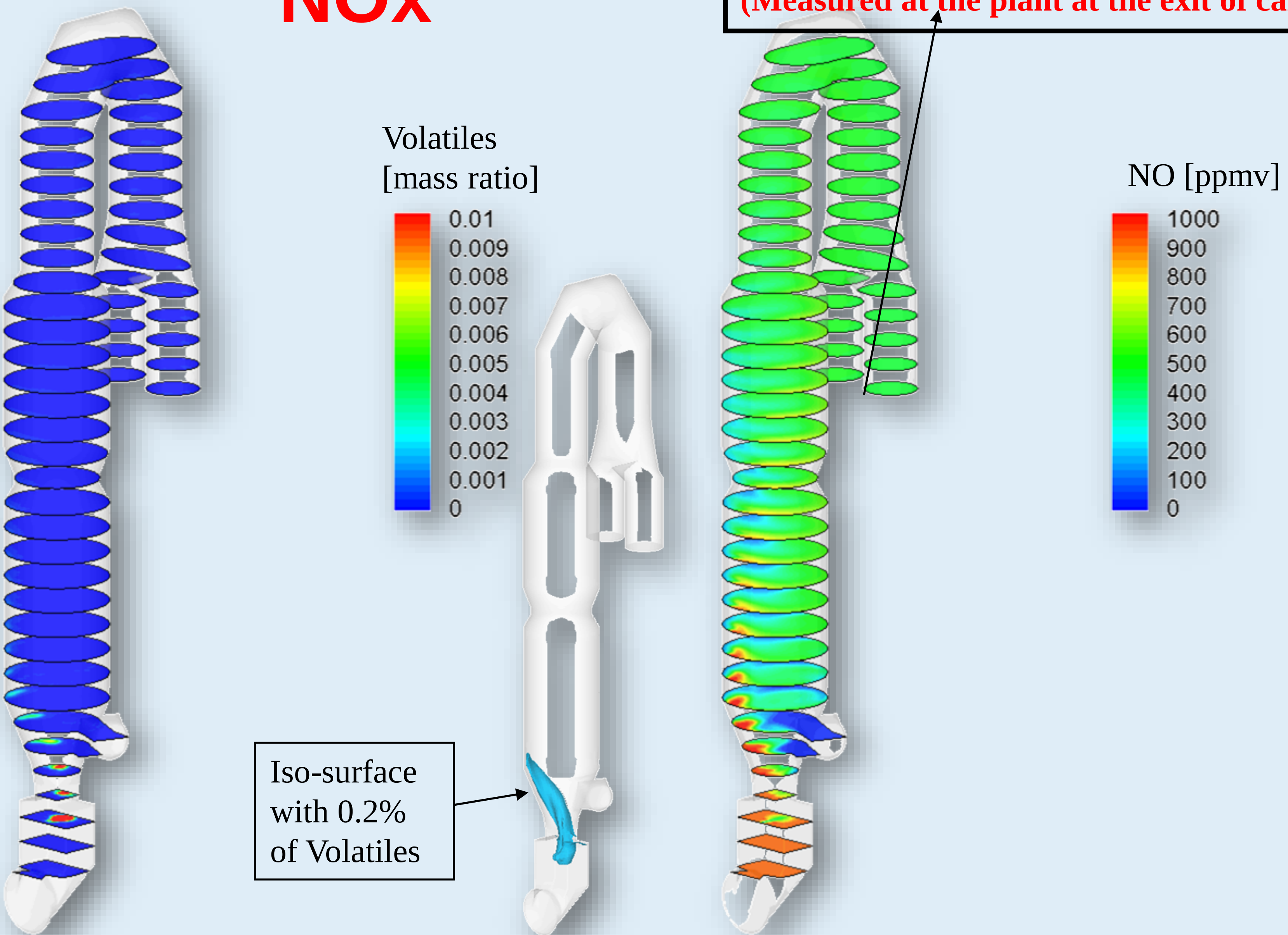
Base Case Volatiles and NOx

Exit NO ppmv @ 5.3% O2 = 561 (Predicted)

530-560 ppmv

(Measured at the plant at the exit of calciner)



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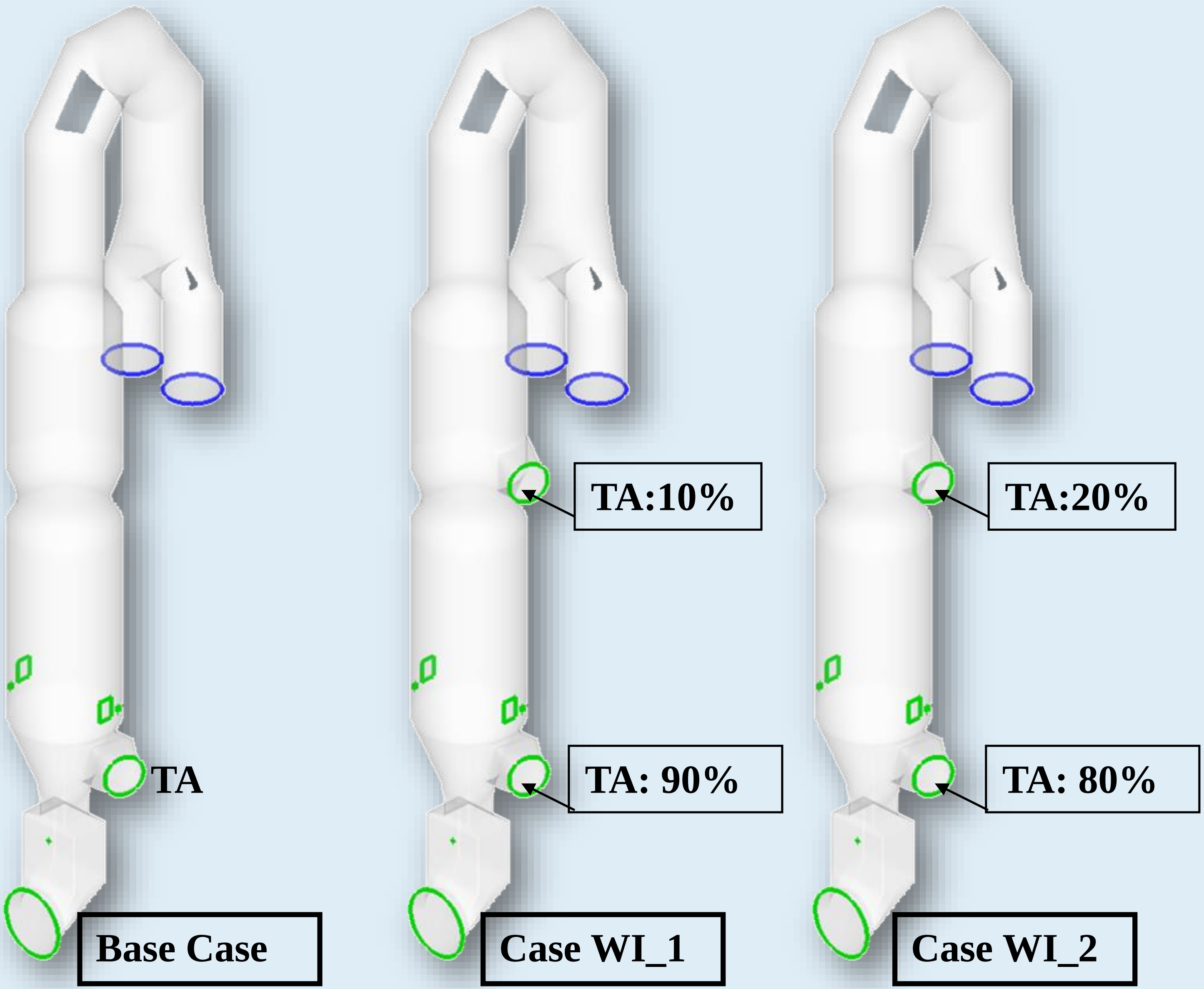
Staging of the Tertiary Air (Sinoma high Capex Solution)



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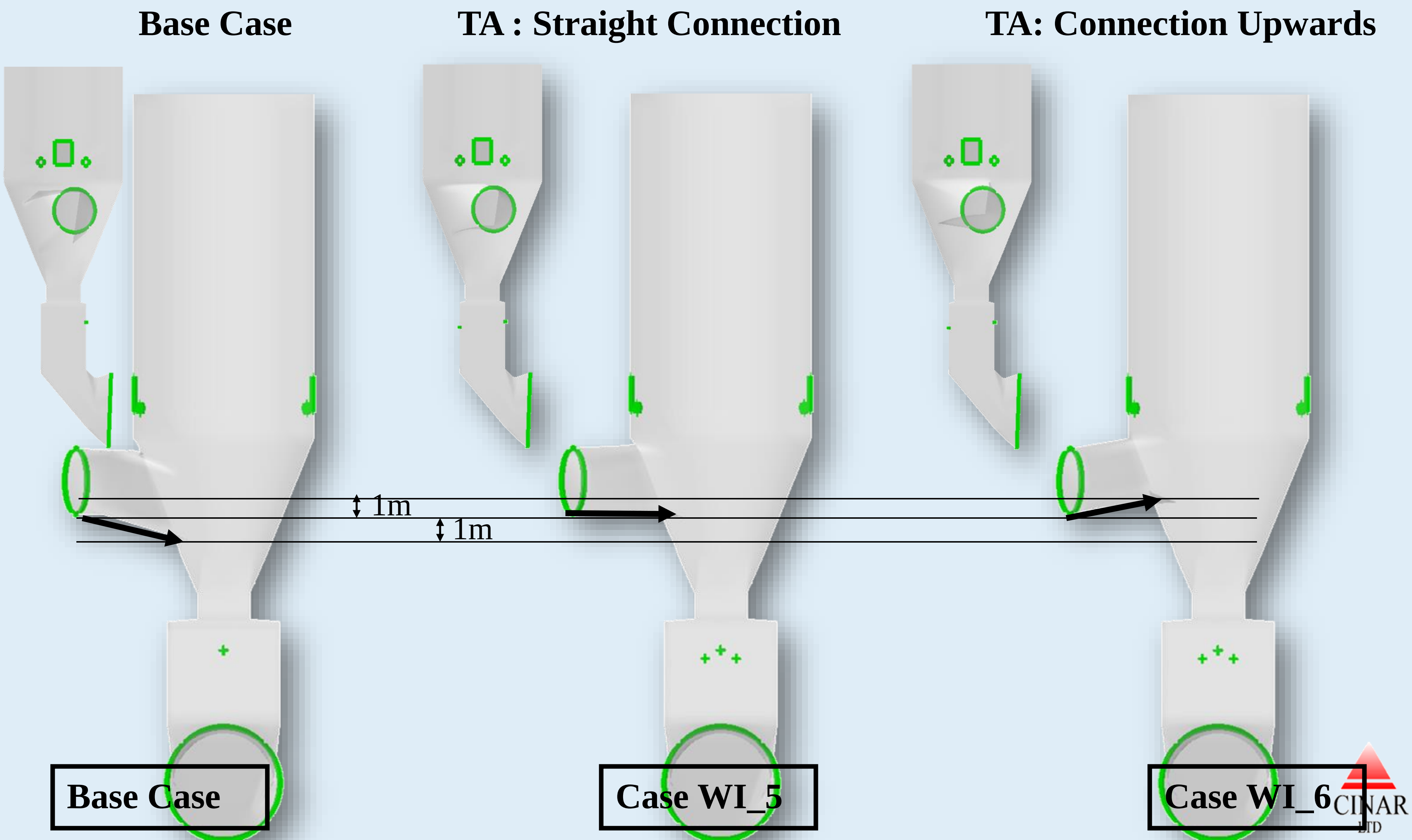
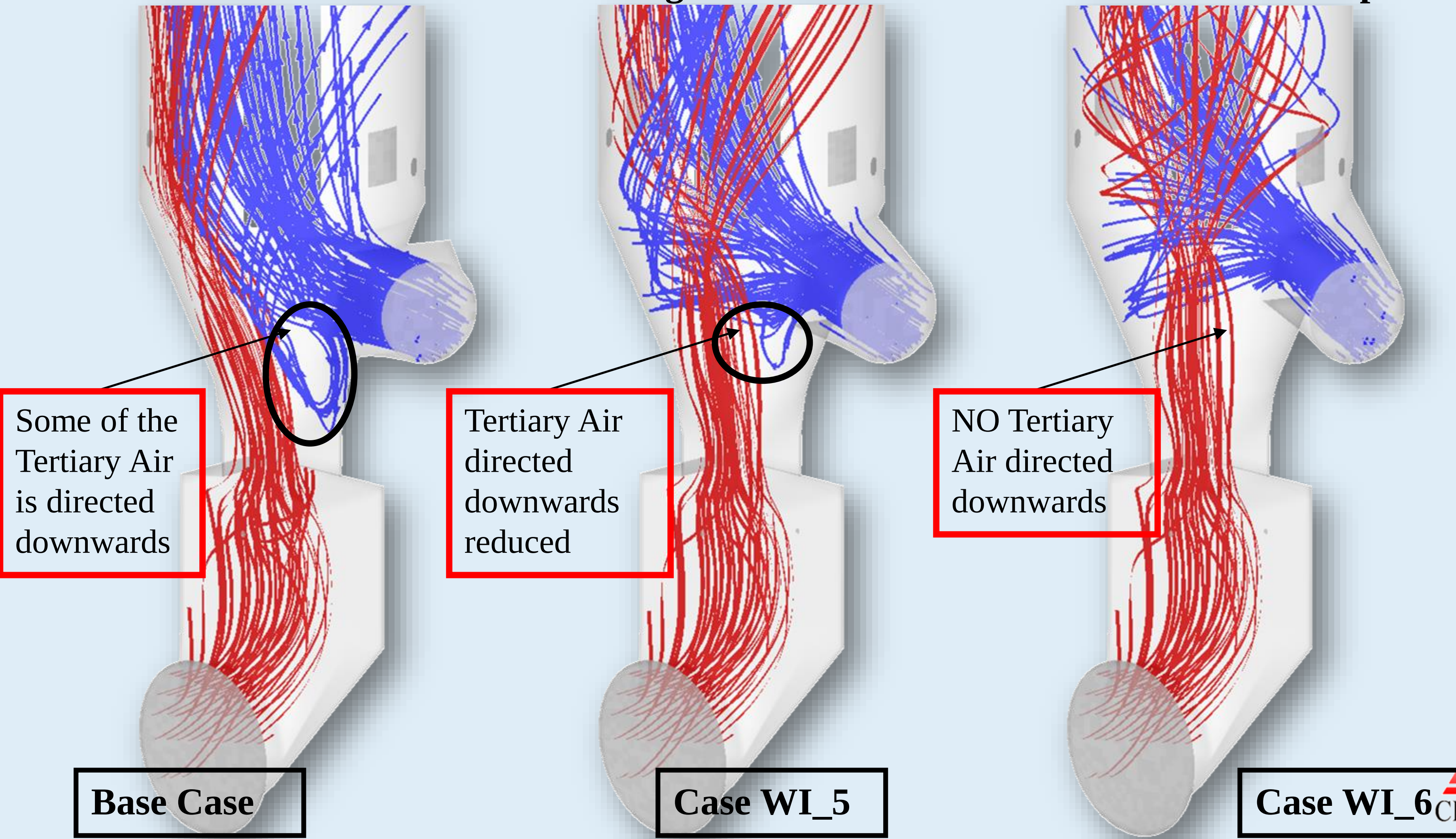
Proposed TA modifications



TA and KRD Mixing

Base Case | **TA : Straight Connection** | **TA: Connection Upwards**



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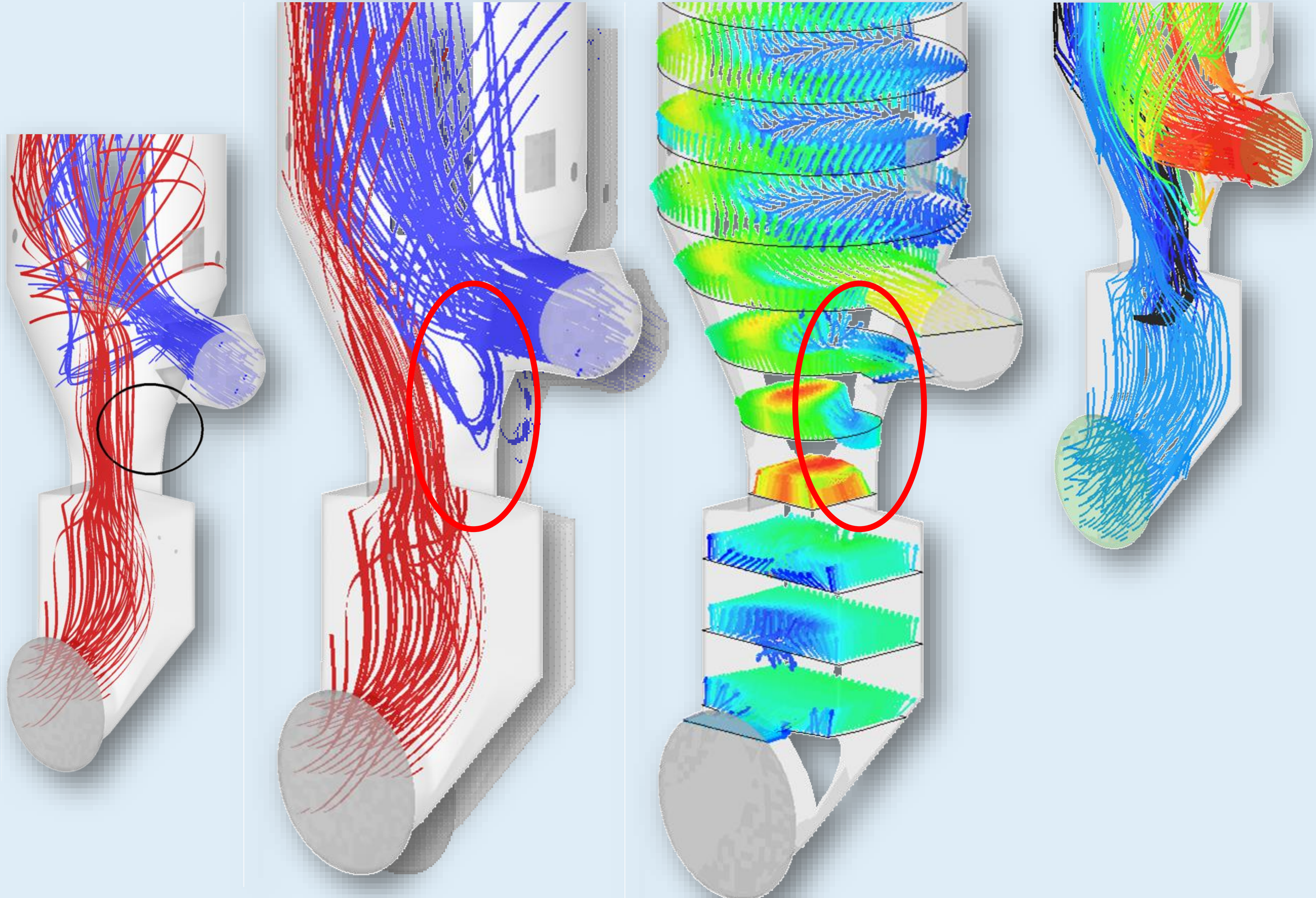
Kiln gases and TA Mixing



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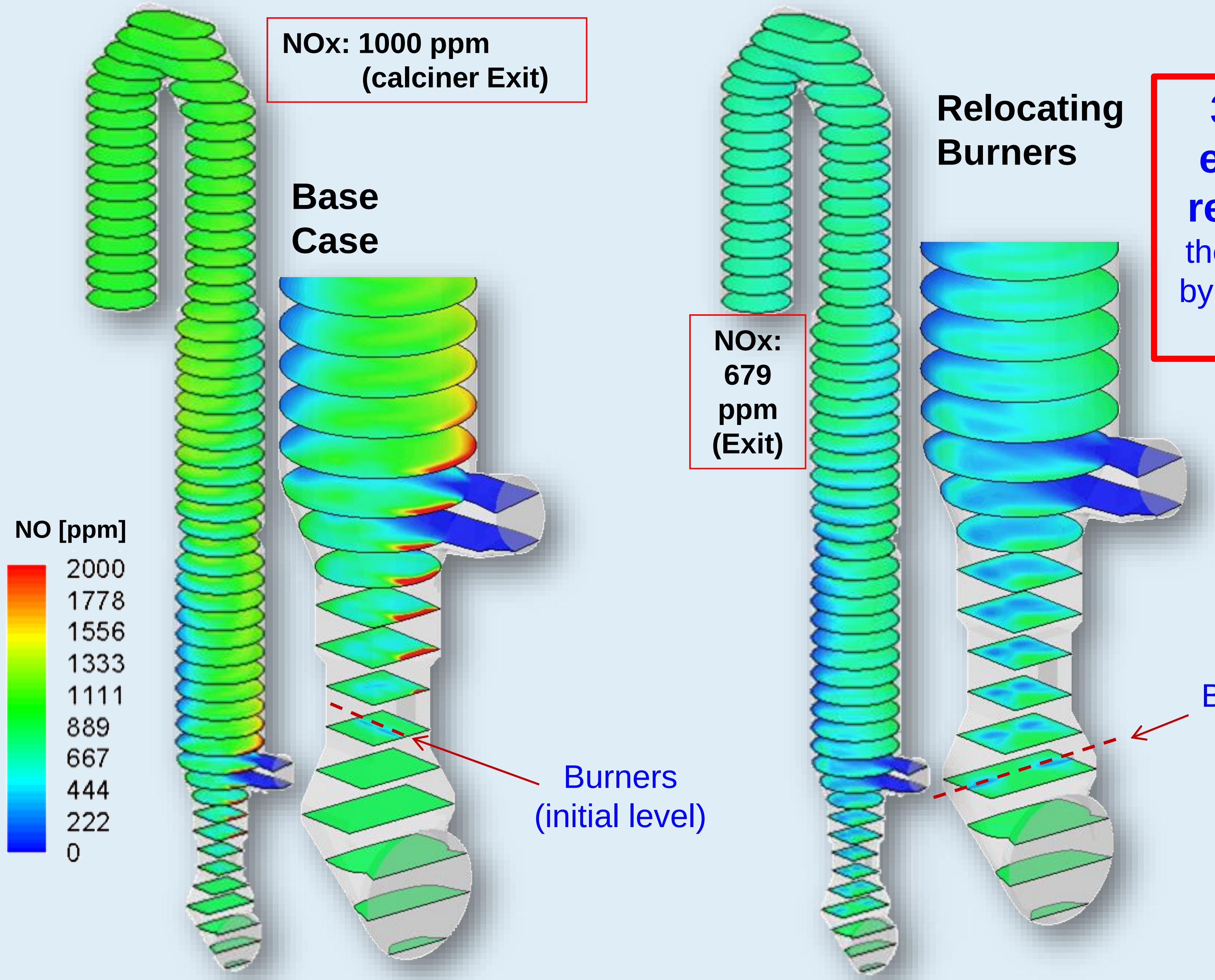
NOx Emissions Reduction



32% NOx emissions reduction in the calciner exit by relocating the burners

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Plant new configuration Feedback

- On February there was contact with the plant:
  - Fuel split in 4 burners installed
  - TA duct was slightly modified
- The values of NO_2 at the exit of the stack are reported to be at around 40% reduced.

Before Modifications ~800 mg/Nm3	
Date	**Stack Value (NOx mg/Nm3)**
16-Feb-2013	637
17-Feb-2013	595
18-Feb-2013	650
19-Feb-2013	
20-Feb-2013	776
21-Feb-2013	739
22-Feb-2013	470
23-Feb-2013	484
24-Feb-2013	474

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NOx emissions from Separate line Calciners

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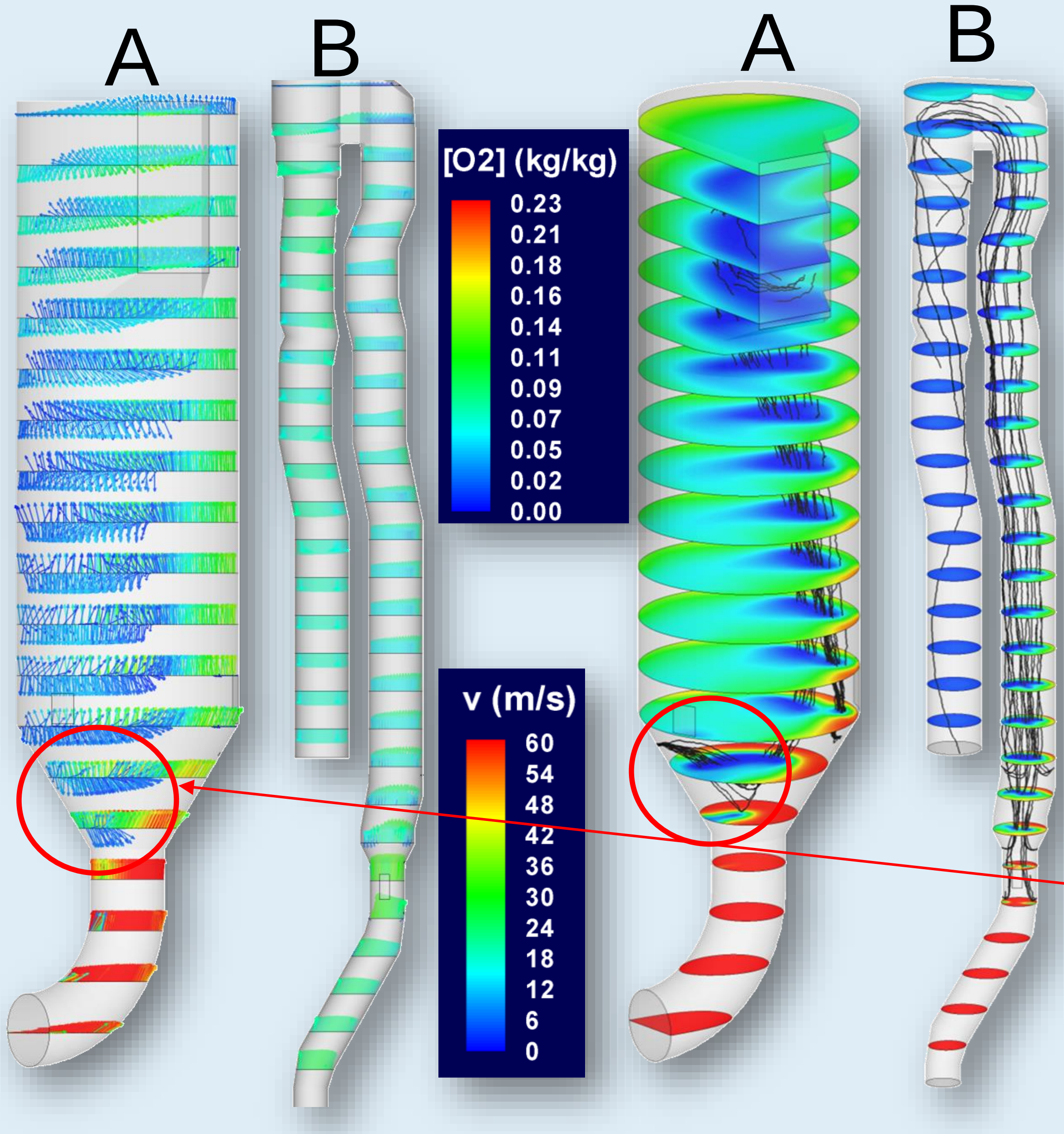
SLC NOx: Aerodynamics Effect



	SL-A	SL-B
O_2 at exit (%)	@4	@1.5
NO_x at exit (ppm)	387	1355
CO at exit (ppm)	620	110
SO_x at exit (ppm)	80	44

Duct expansion creates re-circulations zones

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Reducing NO/CO In Calciners

- Kiln generated NOx can be reduced from 50-85% in a calciner, depending on calciner configuration as well as several non-linear parameters;
- The conditions which are more favourable to reducing NOx/CO in a calciner are those which promote the destruction of NO via CHi and CO via OH radicals (reburn);

General Comments:

- Temperatures of up to 1200C, kiln backend oxygen of 3-6% with a good mixing of 'reburn fuel volatiles' over a residence time of about 0.5 second, followed by the gradual TA/JAMS mixing over a residence time of about 1.5 second are found to be the most important parameters, among others, i.e., volatile content, fuel nitrogen content, kiln NOx, burner momentum.

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Reducing NOx Beyond Combustion Modifications

(Reburn plus SNCR)

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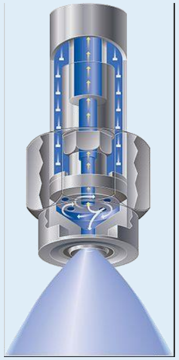
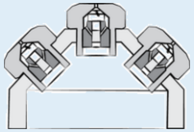
SNCR (Selective Non-Catalytic Reduction)

A post-combustion technology 'End of Pipe'.

Reduction of NO via NH_3 or NH_2CONH_2 (Urea) takes place at a 'narrow' temperature Window :

- For NH_3-(870-980 C)
- For Urea (980-1150 C)
- Spray patterns and dispersion rates;
- Retractable multiple port lances (with cooling jackets) are used to mix reagent with calciner gases;





$$NH_2CONH_2 \rightarrow 2NH_3 + CO_2$$

$$NO + 4\ NH_3 \rightarrow 4\ N_2 + 6\ H_2O$$

SNCR: Even more expensive!

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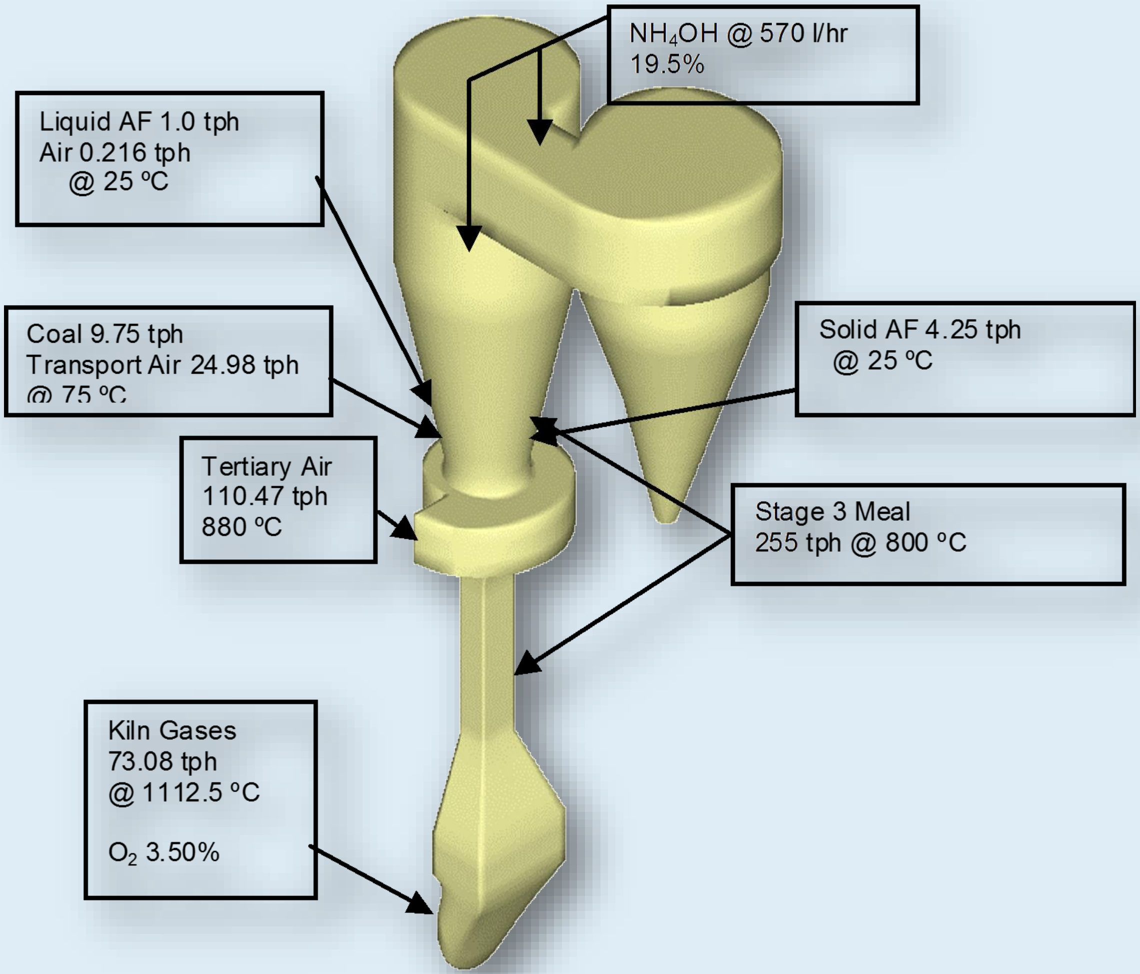
SNCR In-Line Precalciner: RT=1.5 s



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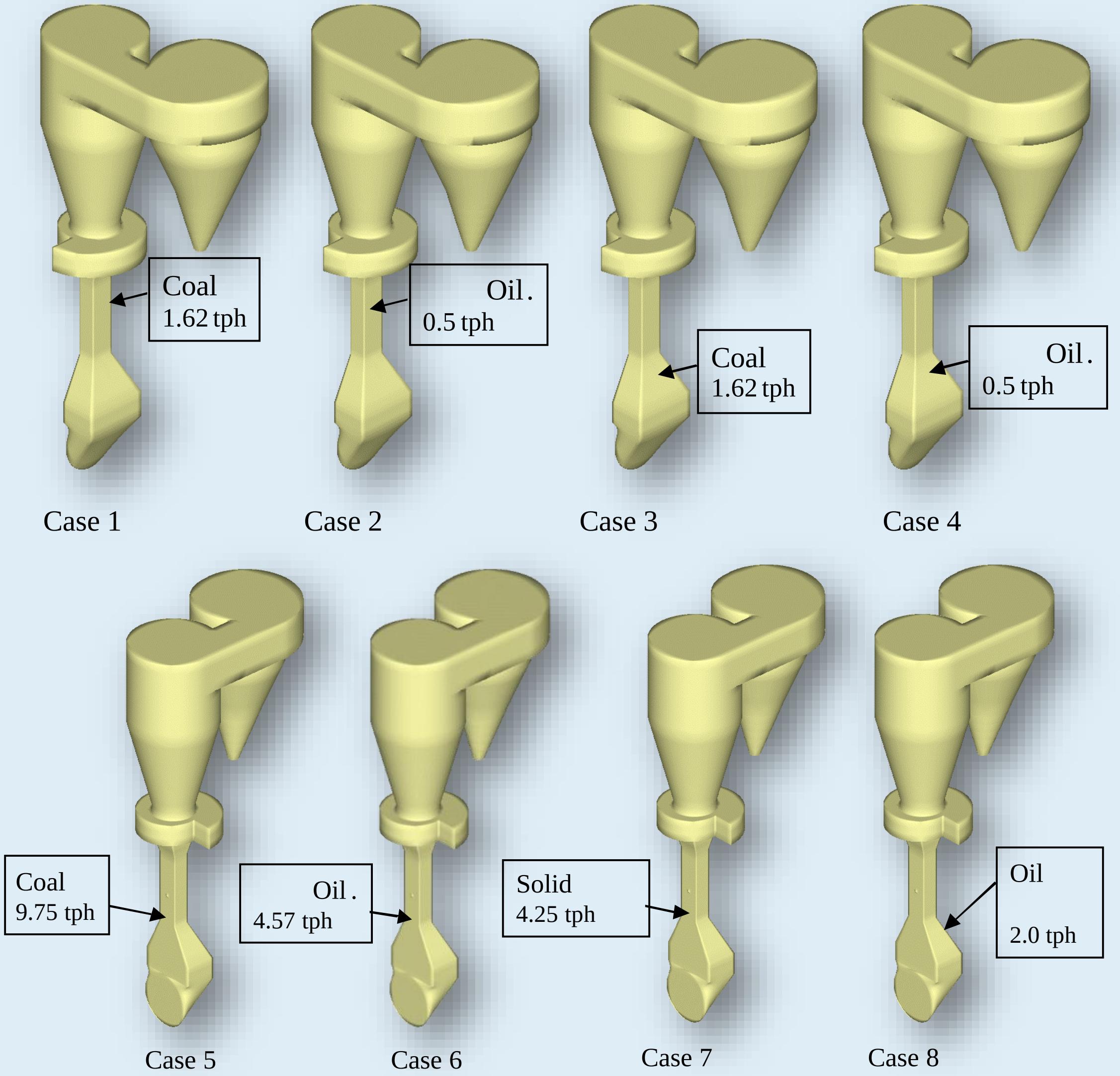
NOx Reduction In-Line Precalciner



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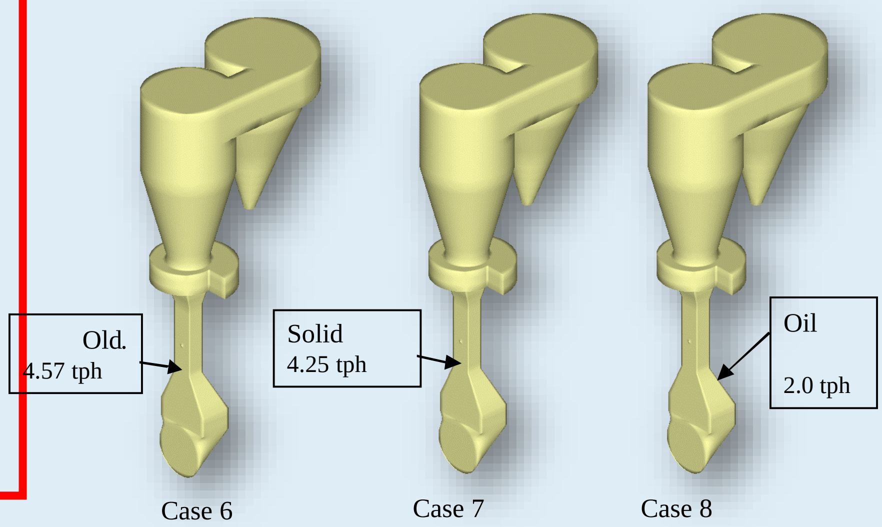
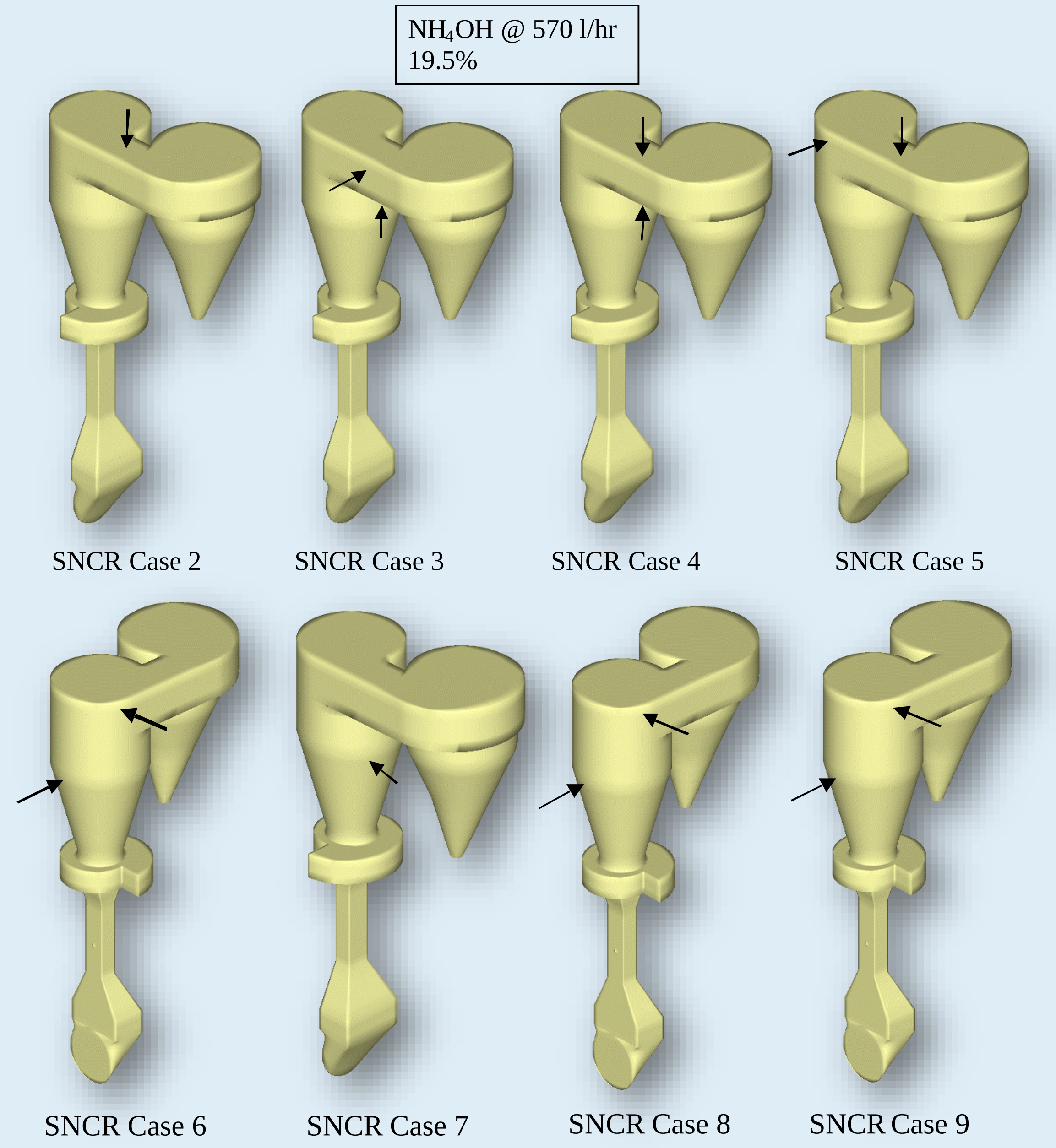
Reburn Optimisation

Cases	Fuels			NO[ppm]
[tph]	Coal	AFR(S)	AFR(Oil)	
B Case	9.75	4.25	1.00	652
Case 1	9.75	4.25	1.00	648
Case 2	9.75	4.25	1.00	651
Case 3	9.75	4.25	1.00	607
Case 4	9.75	4.25	1.00	649
Case 5	9.75	4.25	1.00	604
Case 6	5.00	4.25	4.57	393
Case 7	6.22	9.50	1.00	472
Case 8	8.40	4.25	2.00	581

Max. NOx reduction: 40%



CINAR LTD


NH4OH @ 570 l/hr
19.5%
SNCR Case 2
SNCR Case 3
SNCR Case 4
SNCR Case 5
SNCR Case 6
SNCR Case 7
SNCR Case 8
SNCR Case 9

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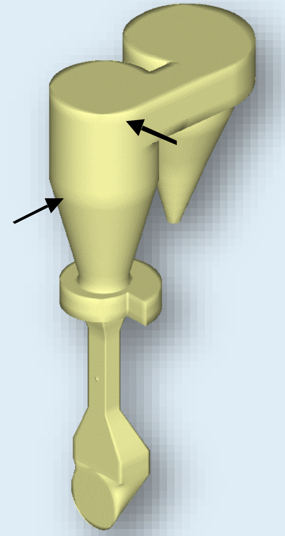
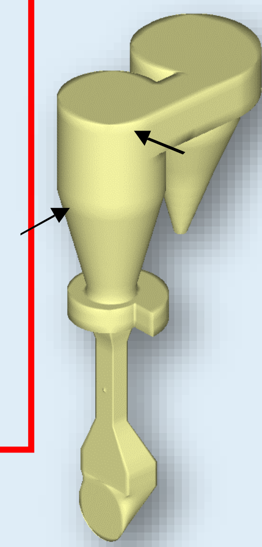
SNCR plus Reburn Optimisation

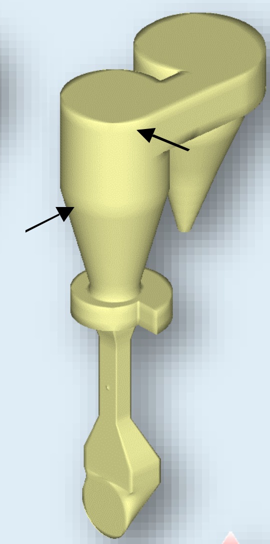
Cases	Fuels (tph) Coal	AFR (S)	(Oil)	NO (ppmv)	NH3] (ppmv)
SNCR Case 1	9.75	4.25	1.00	350	212
SNCR Case 2	9.75	4.25	1.00	404	132
SNCR Case 3	9.75	4.25	1.00	367	103
SNCR Case 4	9.75	4.25	1.00	334	169
SNCR Case 5	9.75	4.25	1.00	338	218
SNCR Case 6	9.75	4.25	1.00	320	118
SNCR Case 7	9.75	4.25	1.00	574	14
SNCR Case 8	5.00	4.25	4.57	223	152
SNCR Case 9	6.22	9.50	1.00	224	81



SNCR Case 6



SNCR Case 8



SNCR Case

Max. NOx reduction: 12%

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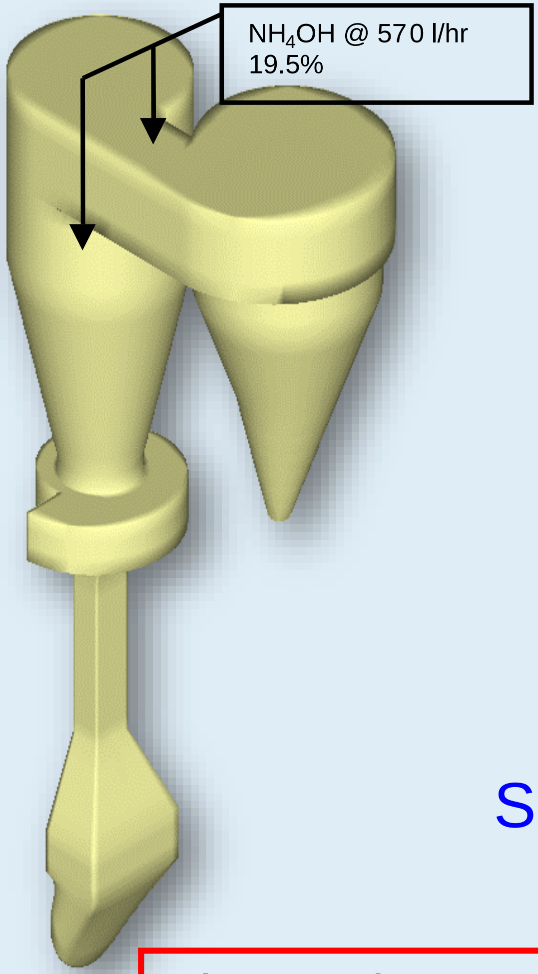
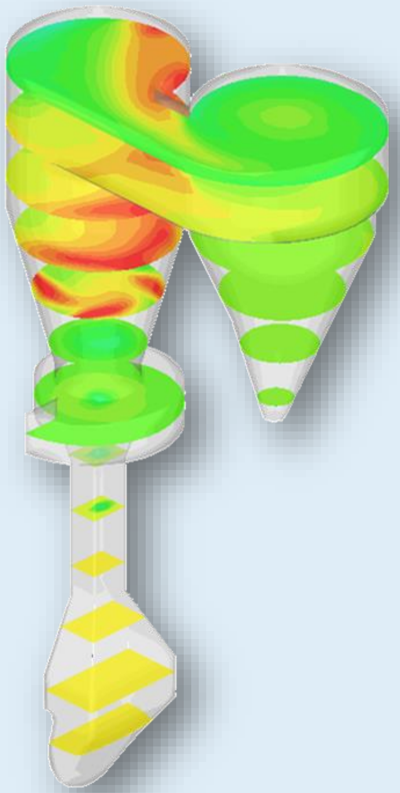
Temperature [ºC]





SNCR (Exit Temperature 860 ºC)

Flow and temperature stratification plus not enough residence time!

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SNCR/SCR

- SNCR is well established in the boiler sector and on some Plants can get down to 200 mg/NM3
- However both CO and NH3 compete for OH radicals and a higher concentration of CO temperature window also shifts by 50-100 C, due to several reasons:
  - Temperature and flow is stratified;
  - Insufficient mixing (injectors) + need 1-1.5 s residence time
- A plant which operates at 200 mg/Nm3 has 16 injectors and it took them 2 years to get there
- With MI-CFD it can be much quicker!!

- SCR, at much lower temperatures (300-450 C), NH_3 to NO molar ratio 1:1 in the presence of catalyst, for typically 80-90 % NO_x reduction efficiency. Can be installed after PM control devices, Solnhofer, Germany

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