



Implementation of Oxygen Enhanced NO_x Reduction (OENR) Technology on Container Glass Furnace

2026 Glass Problems Conference
September 14-17, 2026

Carson Chu, Arthur Francis, Jim Murphy, Kelly Tian (Linde)
Miroslav Simcik, Marketa Polachova (Glass Service)
Jeff Remson (REMSCO Glass Furnace Consulting)

Making our world more productive



Acknowledgements



- Michael Yack, Director of Application Engineering, Linde
- Jesse Cates, Senior Application Design Engineer, Linde
- Shrikar Chakravarti, Business Development Director, Global Glass, Linde
- Kevin Cloutier, Manager – Construction Service, Linde
- Sho Kobayashi, Senior Fellow, Linde
- Gerardo Vallejo Rivero, Senior Application Engineer, Linde
- Sarah Torkamani, Business Development Manager, Glass Service North America
- Glenn Neff, Glass Service North America

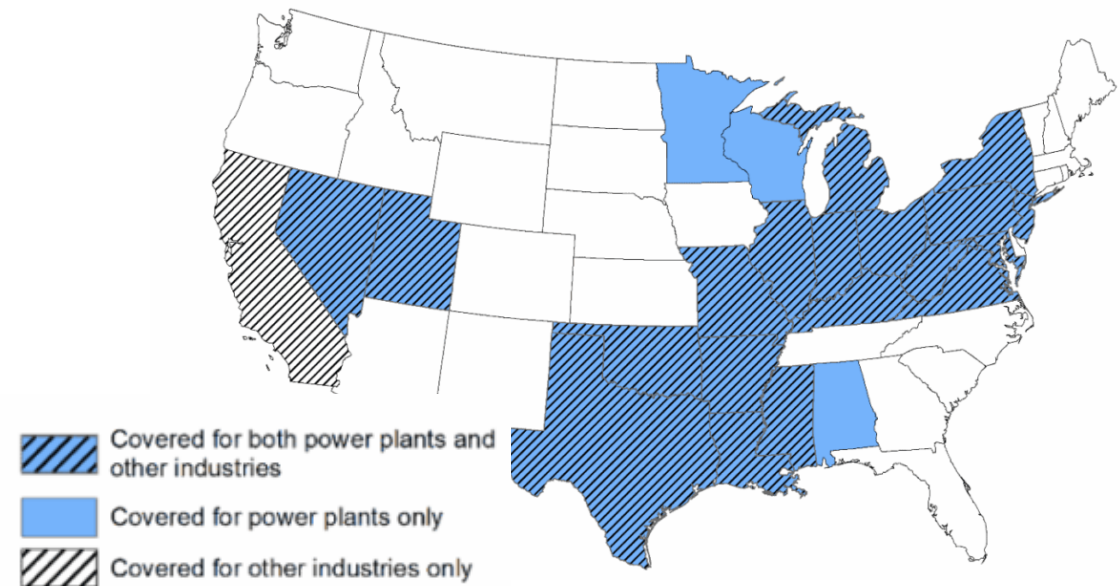
Motivation – Stringent NO_x Emission Limits in US



- High temperature (>1600C), high N₂%, and over-stoichiometric conditions promote NO_x formation in glass furnaces
- Present regulations require new or existing furnaces to adopt **Best Available Control Technology (BACT)** and comply with local emission limit.
 - e.g. **0.75 lb NO_x/ton** in the South Coast Air Quality Management District (California)
- EPA's "Good Neighbor Plan" for cross-state pollutions
 - NO_x emission limit is **<4 lb/ton**
 - For container, pressed/blown, and fiberglass glass furnaces in 23 upwind states
 - Applies to new and existing emission sources
 - **Latest status:** on hold by EPA due to judicial challenges

Industries under pressure to reduce NO_x

Map of States Covered by the Final Good Neighbor Plan



[1] <https://www.epa.gov/Cross-State-Air-Pollution/interstate-transport-2015-ozone-naaqs#proposedsipapproval>

Project Background



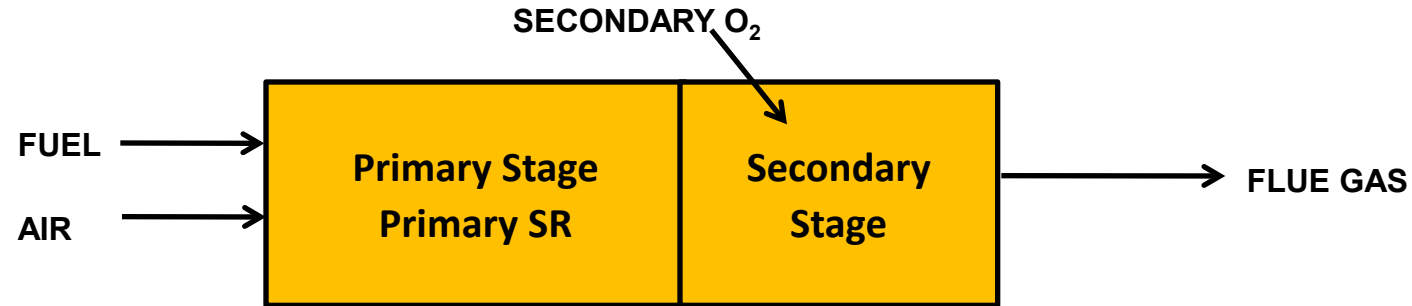
- Installation of **Oxygen Enhanced NOx Reduction (OENR)** technology on an end-port container glass furnace
 - Existing furnace: Air-regen – 320 tpd pull rate
 - Regenerator switches every 20 mins
 - Target: >25% below the current NOx level
- Short timeline: must be completed within 6 months

LINDE's OENR Deployment History

- Deployed on multiple furnaces in Europe for short term demonstration as well as on permanent basis

Case	Country	Pull rate (mtpd)	Year	Furnace Type	Glass Type	NOx reduction
1	France	600	1997	Side-fired	Float	~20%
2	Italy	80	2013	End-port	Tableware	~18%
3	Italy	190	2014	End-port	Container	Target met
4	Italy	150	2014	End-port	Container	~18%
5	Italy	410	2018	End-port	Container	~24%
6	Italy	380	2018	End-port	Container	~18%

Presented project is first permanent installation in US



(Data from Rue/Abbasi. IGT 1997)

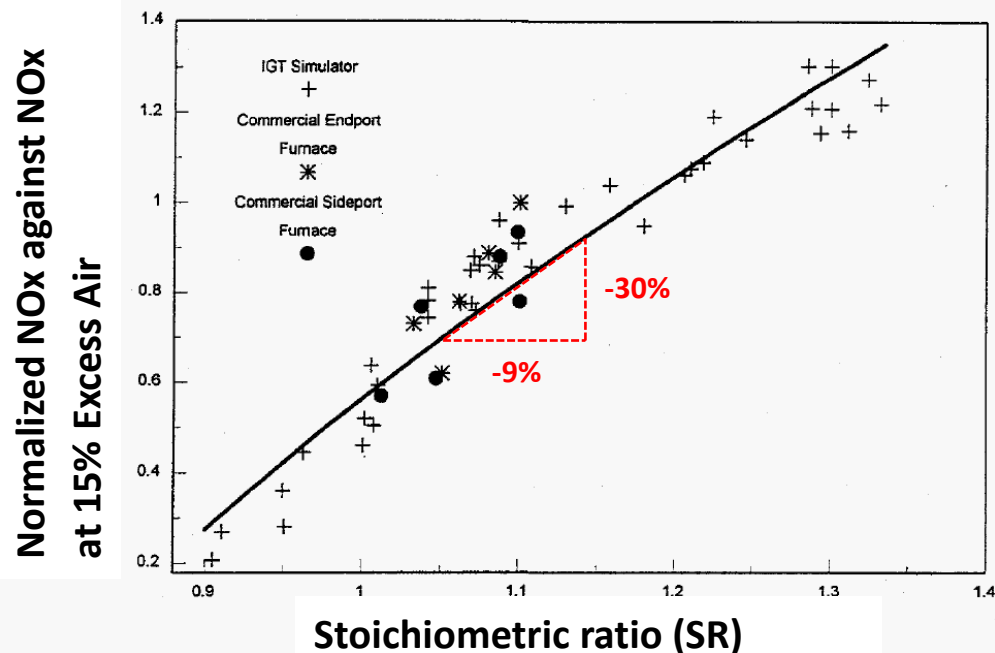


Figure 1. Effect of First-Stage Stoichiometric Ratio on NO_x Production

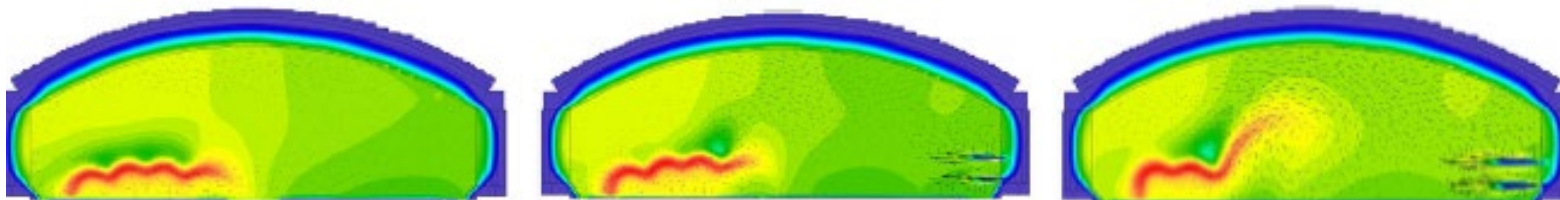
- Stoichiometric ratio (SR) reduction of primary air flame is the key factor in NO_x reduction
- About 30% NO_x reduction could be achieved by 9% reduction in primary SR (PSR)
- CO emission becomes the limiting factor for further NO_x reduction
 - High CO may damage refractory integrity
- Secondary O₂ injection burns off excessive CO
 - O₂ Injection alternates according to furnace reversal

Options for Combustion Staging: Air vs Oxygen



Four secondary oxidant options work equally well in theory

	Pros	Cons
Cold air	• Simple setup	• Large air volume disturbs main flame • Higher fuel consumption
Hot air	• N/A	• Complex system, involving heater and insulation • Large air volume disturbs main flame
O2 enriched air (OEAS)	• Additional flexibility (adjusting between O2 and air) for staging jet penetration and mixing	• Complex system, involving both air and O2. • Large air volume disturbs main flame • Higher fuel consumption • Require O2
Pure O2 (OENR)	• Simple setup • Easy to adjust CO burn out on site • Reduced fuel consumption	• Require O2



Baseline

OENR

OEAS

- Flame profile could change with different staging method
- OENR: minimal flame interference
- OEAS: large flame disturbance



- **Glass Service (GS)** provided support for CFD simulations:
 - Construction of a 3D furnace model
 - Simulation of the base cases
 - Technical support for additional simulations

- **Linde** also supplied O₂ and OENR equipment
 - Oxygen lances
 - Flow control skid
 - O₂ storage tank and vaporization
 - Associated civil and mechanical works

- **Linde** continued to study the effects of different parameters
 - Oxygen flowrate
 - Oxygen velocity
 - Injection angle and location
 - Number of lances
- Selected configurations were tested during field trials.

- **Remsco Glass Furnace Consulting** provided support during commissioning on:
 - Furnace operation
 - OENR performance and optimization
 - Emission measurements



➤ Factors that may affect OENR performance:

- Oxygen flow rate
 - More oxygen => lower Primary SR => lower NOx
- Oxygen jet velocity
 - Gas entrainment
 - Gas flow pattern
- Injection angle and locations
 - Flame impingement
 - Gas flow pattern
- Number of lances per side
 - Changes in jet momentum
 - Gas flow pattern

CFD tool used to identify

- Best configuration
 - Lowest NOx
 - Lowest CO
- Operation limits
 - Flame shape
 - Potential hot spot
 - Inputs to HAZOP review

➤ A fully coupled GFM model predicts:

- Temperatures (furnace, gas, and glass)
- NOx and CO emissions
- Gas flow patterns

Model Inputs and Assumptions



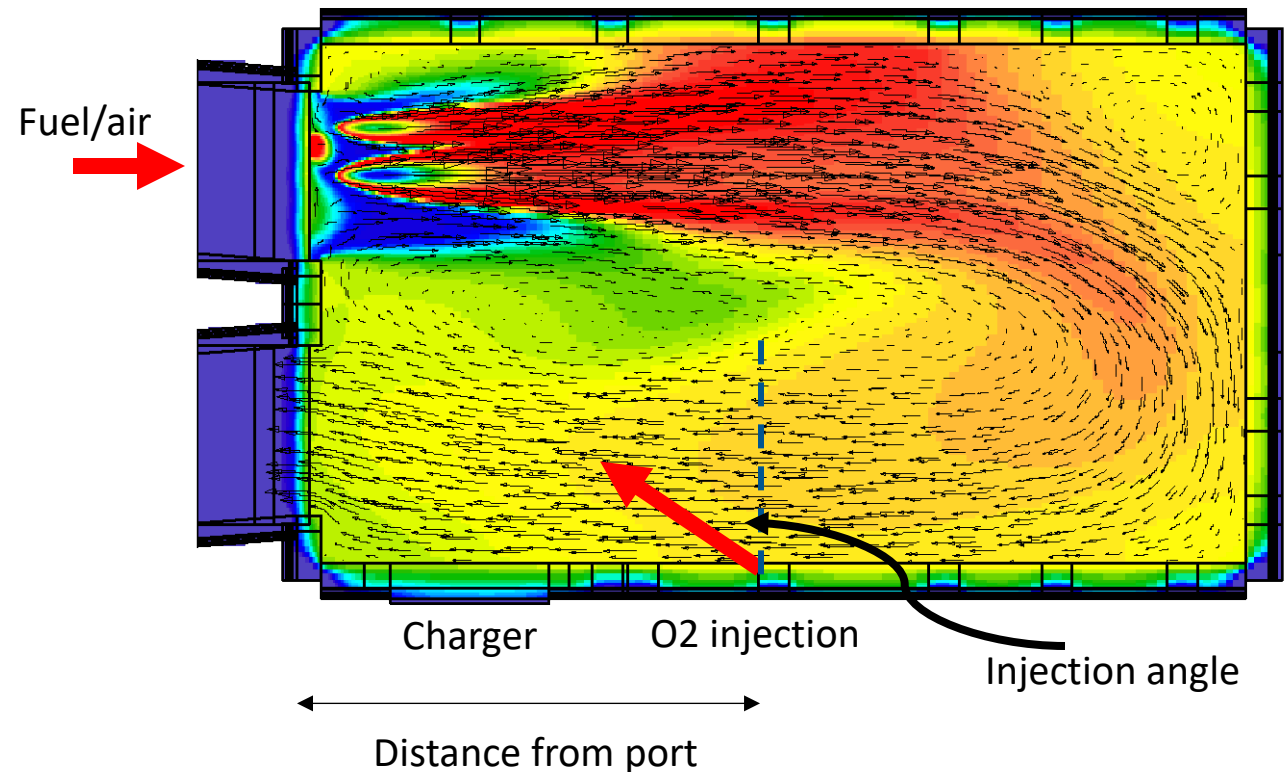
Inputs	Range
Gas flow	44,600 - 45,500 SCFH
Oxygen flow	7,000-10,000 SCFH
Primary SR (PSR)	0.99 – 1.15
Injection angle	15-45 degrees
Injection velocity	149 - 630 ft/s
Number of lances	1 or 2 lances

Assumptions:

- Pull rate: 276 STPD
- The regenerators are not included in the model.
- Assumed air temperature = 1100C (2012 F)
- Overall SR (OSR) = 1.15
- Air infiltration = 1059 SCFH
- NOx: thermal NOx only (Post-process method)

$$OSR = \frac{\text{Actual total O2 input}}{\text{Stoichiometric O2 for complete combustion}}$$

$$PSR = \frac{\text{Actual O2 input in the main flame}}{\text{Stoichiometric O2 for complete combustion}}$$



Impacts of O2 Staging on NOx Reduction



Baseline

PSR=OSR = 1.15

CO at exhaust port = 286 mg/Nm³

NOx at exhaust port = 4.45 lb/ton

OENR (Reduced PSR with O2 staging)

PSR = 1.07

OSR=1.15

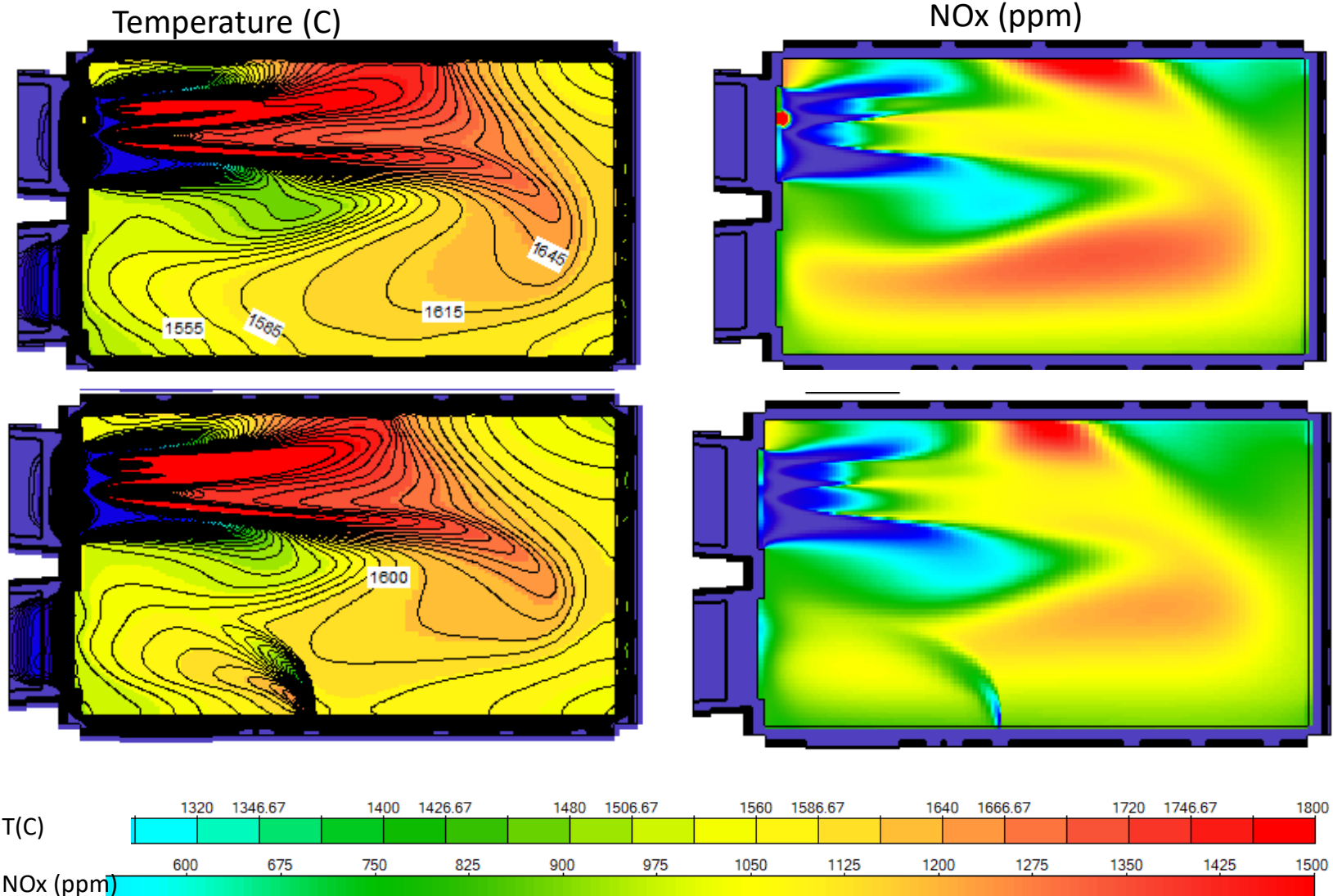
CO at exhaust port = 415 mg/Nm³

NOx at exhaust port = 3.84 lb/ton

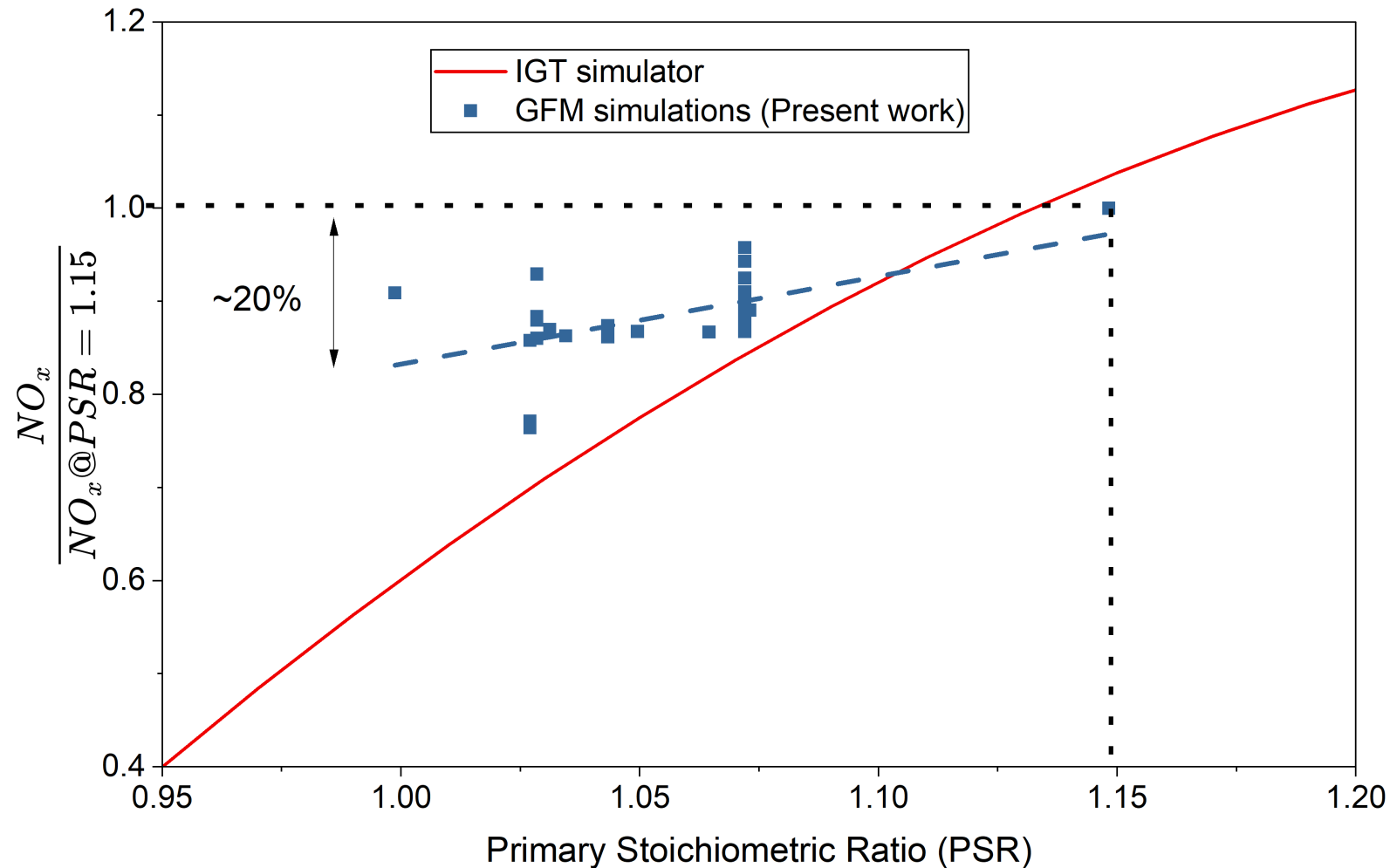
(14% reduction)

With OENR,

- Lower thermal NOx
 - Reduced hot region.
- CO slightly increases.
 - But still **well below** an allowable limit.



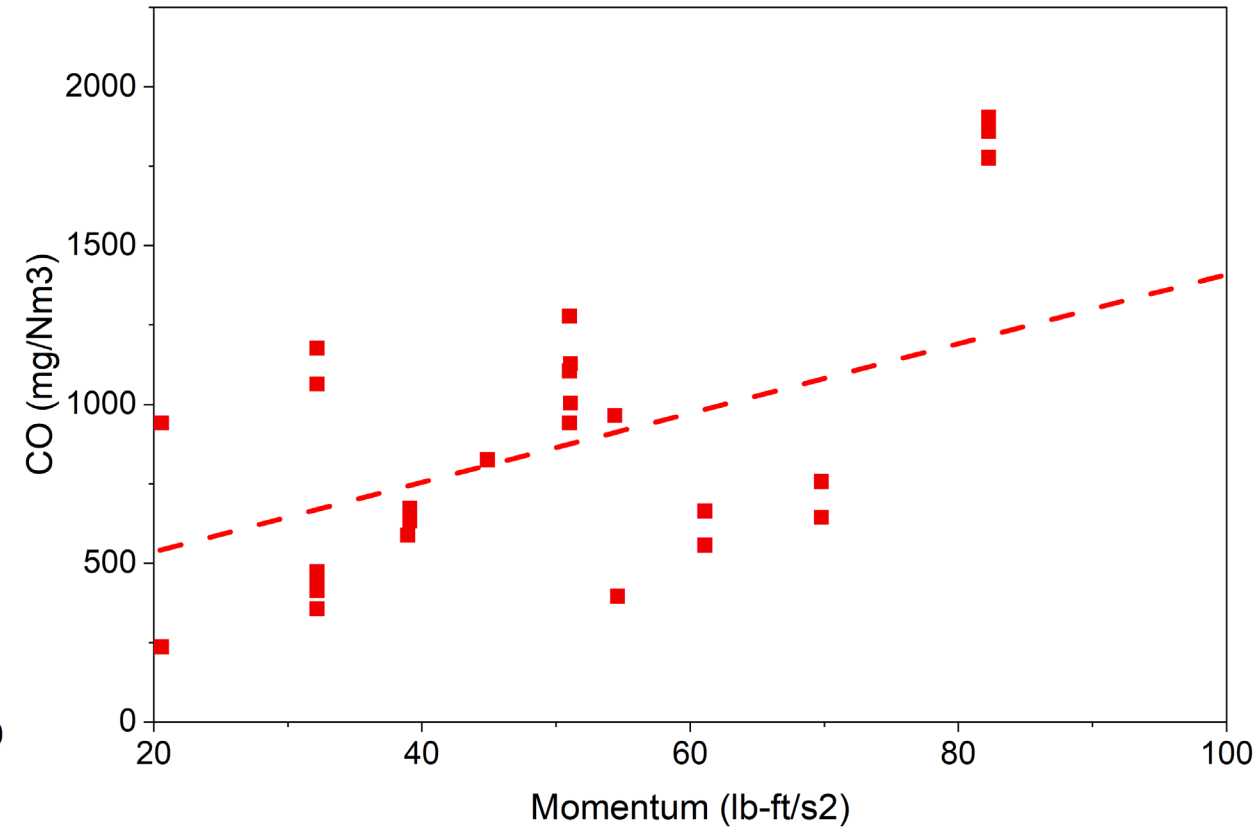
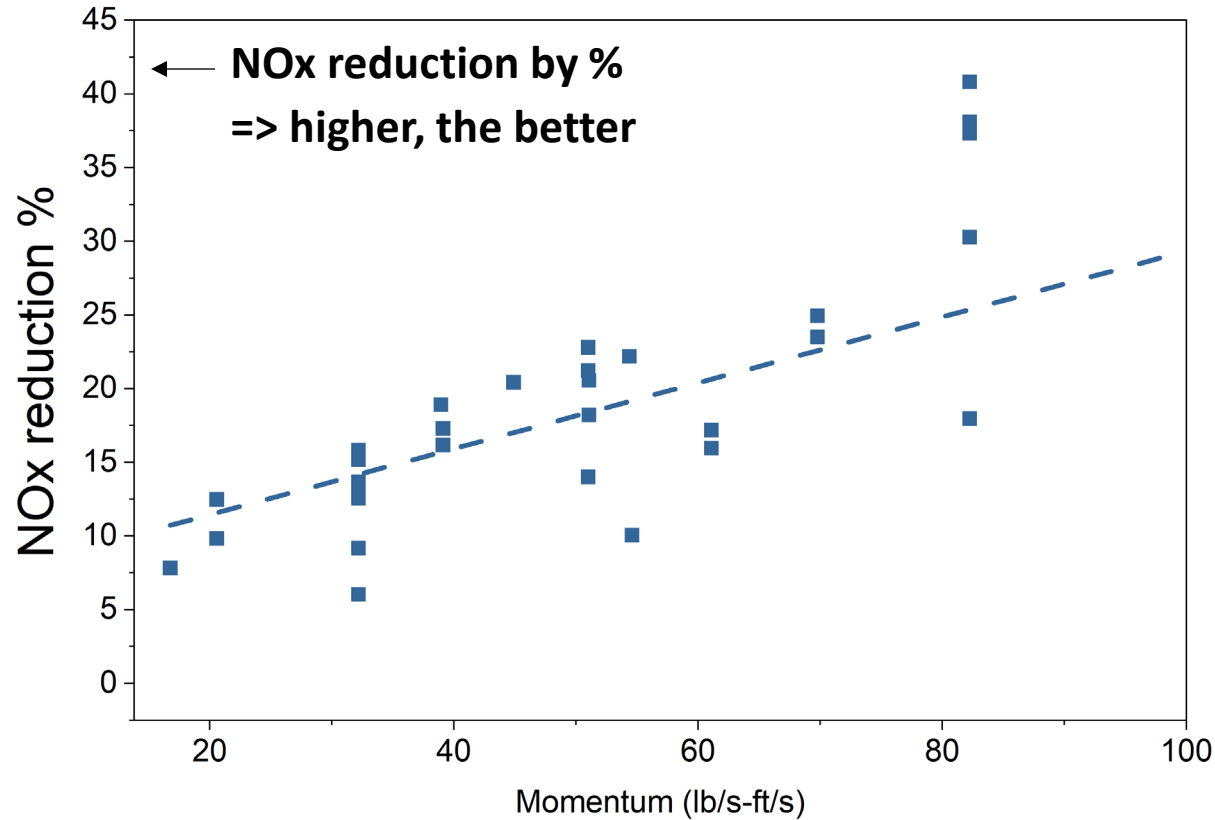
Effect of Reducing Primary SR on NOx reduction



- CFD Predicted NOx reduction < Previous IGT measurements
- At PSR=1.0, predicted NOx reduction is ~20%, which is less than the IGT simulator (~40%)
- **Reasons for model underprediction:**
 - Over-simplified NOx model
 - Only thermal NOx
 - Grid size
 - Highly affects accuracy in NOx prediction

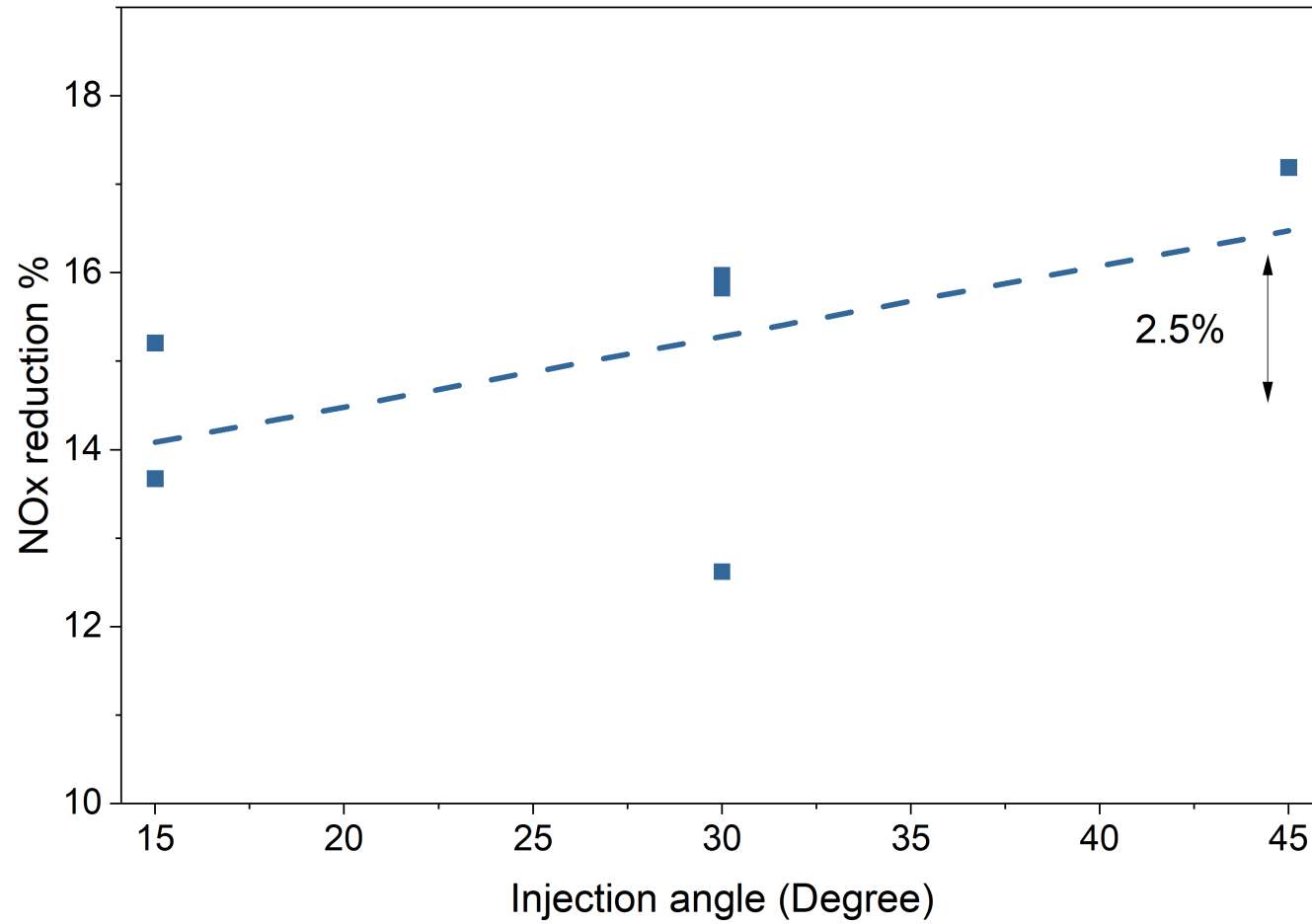
Linde expects to achieve higher levels of NOx reduction than model predictions

Effect of O₂ Injection Momentum on NO_x Reduction and CO Emission

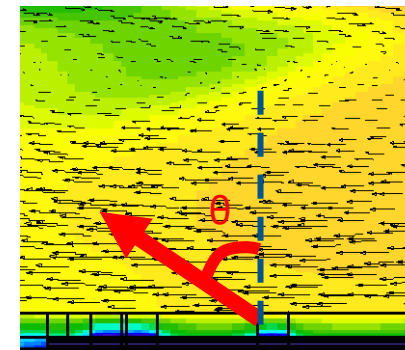


- As momentum increases, NO_x reduces but CO also increases:
 - Jet momentum promotes gas recirculation in furnace leading to reduced flame temperature and hence lower NO_x.
 - However, higher momentum also affects mixing and promotes CO.
- Need to identify the optimum O₂ injection momentum for reduced NO_x and minimize CO.

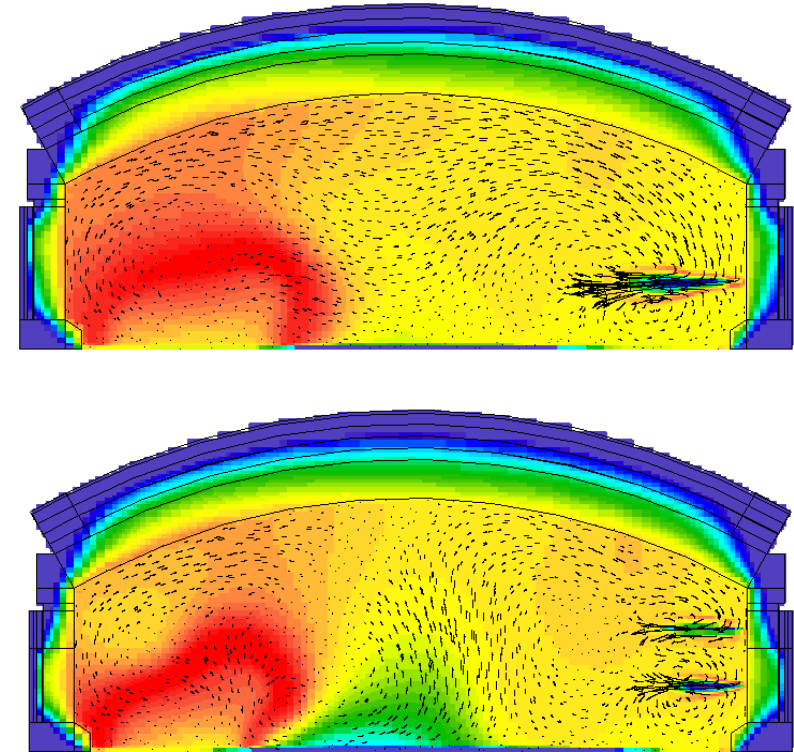
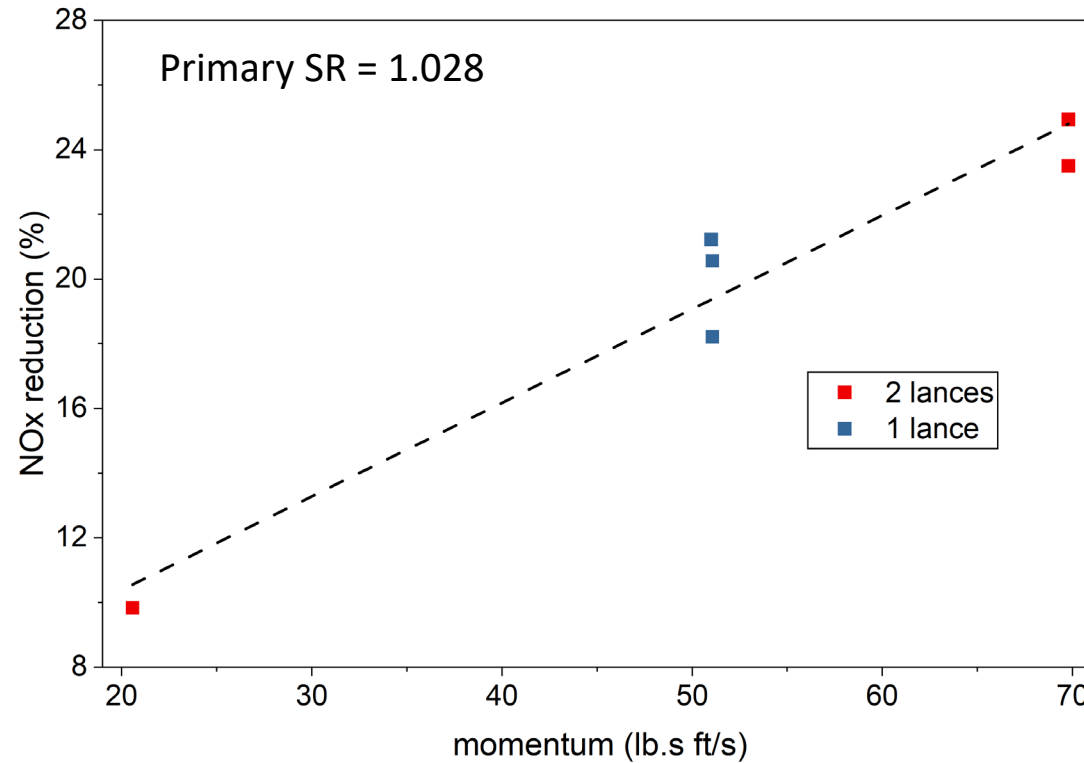
Marginal Impact of Injection Angle on NOx Reduction



- The improvement in NOx reduction is insignificant with increasing injection angles.



Number of Lances Per Furnace Side



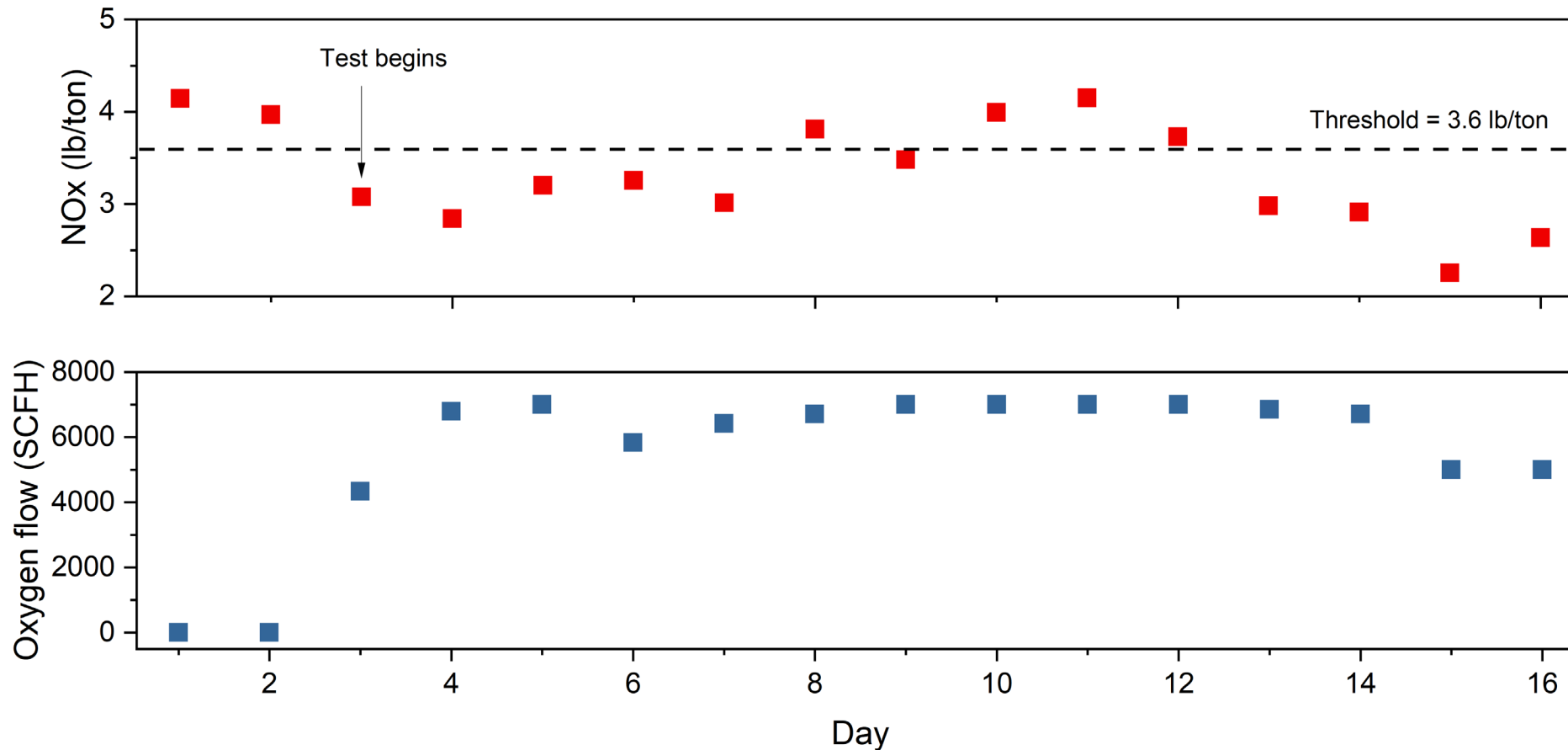
- Both 2- and 1-lance configurations follow the same linear relationship between NOx reduction and momentum.
- Suggesting that, at a given PSR, momentum is an influential factor for NOx reduction.
 - However, multiple lances offer additional flexibility for controlling jet momentum.



- Key findings
 - Lowering primary SR, i.e. richer conditions in the main burner, lowers NO_x
 - Higher momentum promotes NO_x reduction
 - However, excessive momentum yields higher CO due to disturbances to the main burner flame
 - Varying injection angle between 15 to 45 degrees has minimal impact on NO_x
- **Based on the above findings, a test plan was in place prior to commissioning that accounted for varying O₂ flow rates, nozzle sizes, and injection angles**

Field Trial Results:

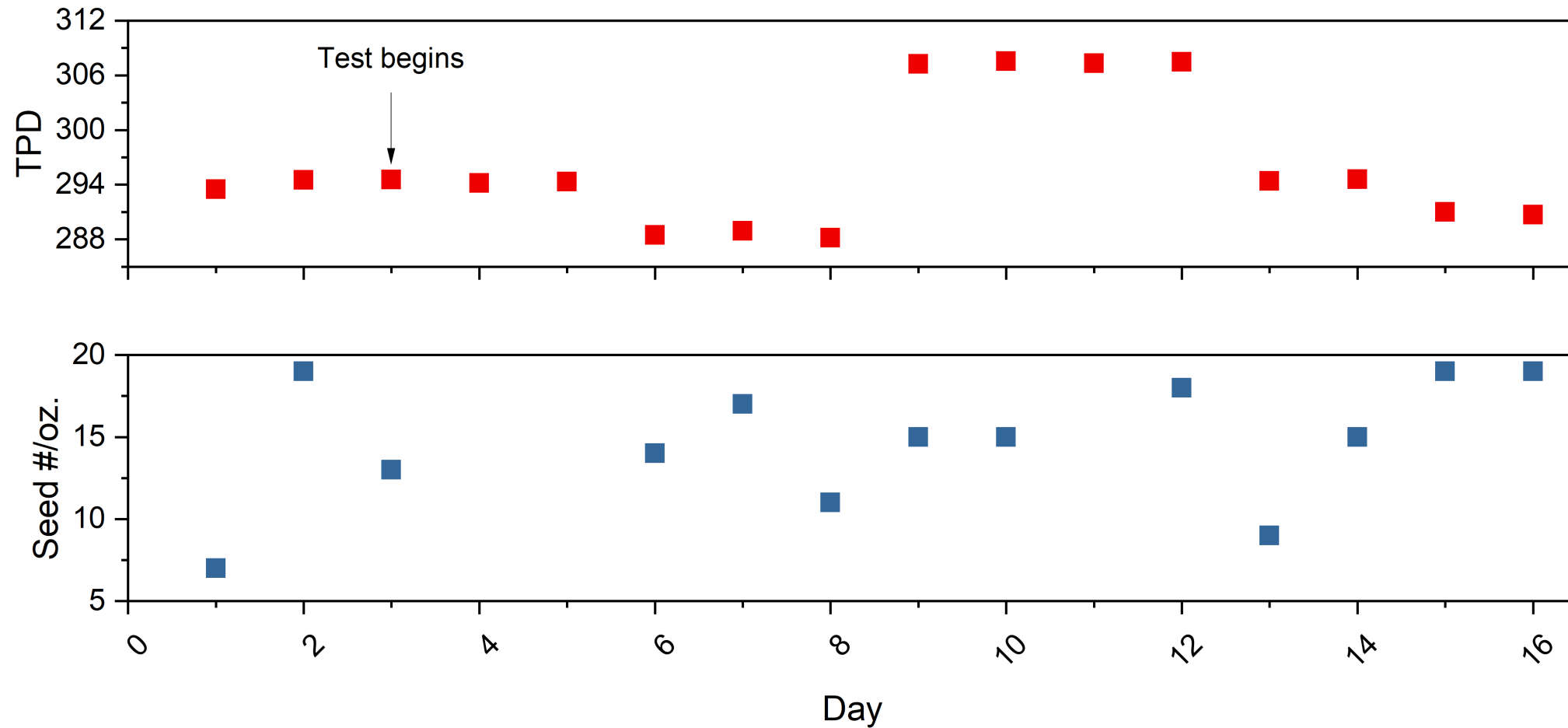
-- Exceeded NOx Reduction Target with Less than Expected Oxygen Flow



- During the trial, various configurations were tested.
- NOx reduction target was achieved with many tested configuration, final configuration selected based on factors including:
 - **CO, NG and O2 consumptions, crown and front wall temperatures, and batch pattern.**
- Adjustments were made to the main burner to further optimize flame characteristics, i.e. fuel efficiency and flame shape.

Field Trial Results:

-- Pull Rate and Glass Quality Maintained



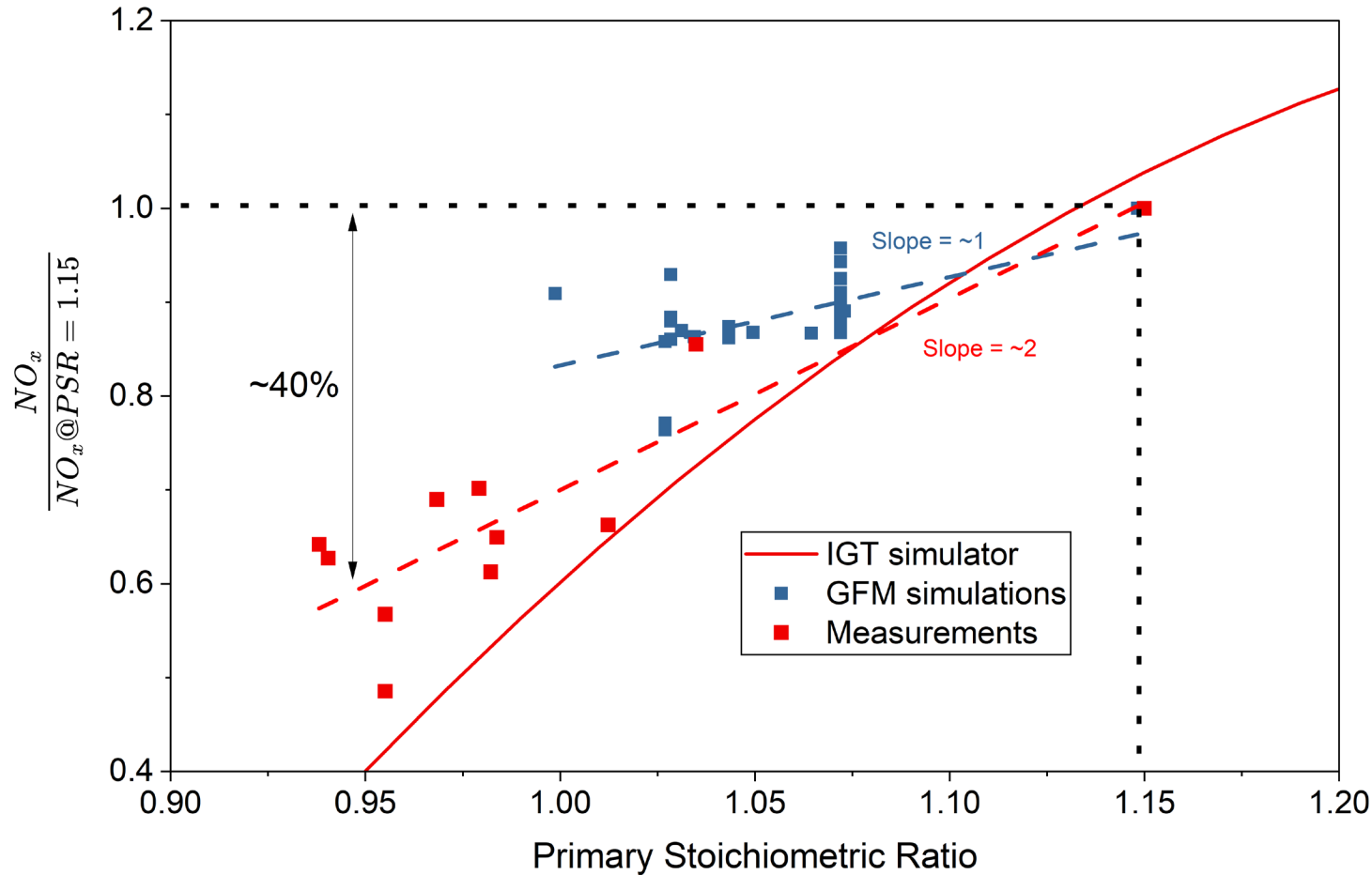
➤ Pull rates and seed counts are not affected by OENR

Pull rates: 291 – 307 tpd

Seed counts/oz.: ~8-~19

Field Trials Results:

-- Comparison of Measured and Predicted NO_x Reduction



- Actual reduction is greater than model prediction
 - GFM simulation: Slope = ~1
 - Measurements: Slope = ~2
- Both actual and predicted NO_x reductions are less than IGT simulator value, possibly due to
 - Uncertainty in air infiltration
 - More air leads to higher more NO_x
 - Uncertainty in heat loss from the furnace
 - Measurements methods
 - Less controlled environment

Conclusions



- Implementation of OENR technology on the end-port container glass furnace achieved > 40% NO_x reduction
- No impact on glass quality and the pull rate
- Fast project execution, completed in ~6 months
- Higher oxygen injection velocity (smaller nozzle) helps reducing NO_x, but could produce higher CO
 - Injection velocity was optimized to balance NO_x reduction while maintaining CO below acceptable level
 - Adjustments to the main burner were made accordingly to optimize flame characteristics.
- Varying the oxygen injection angles does not have significant impact on NO_x.



Thank you !

Carson Chu
carson.chu@linde.com

Appendix: Thermal NO_x formation mechanism



Thermal **NO_x** (Zeldovich) mechanism is employed. This mechanism is described, for example, in [4] and in [5].

It assumes the following reactions:



The mass fraction Y_{NO} is calculated by a standard transport equation with source term S_{NO}

$$\rho S_{NO} = M_{NO} \frac{d[NO]}{dt},$$
$$\frac{d[NO]}{dt} = 2k_{1f}[O][N_2] \frac{\left(1 - \frac{k_{1b}k_{2b}[NO]^2}{k_{1f}[N_2]k_{2f}[O_2]}\right)}{\left(1 + \frac{k_{1b}[NO]}{k_{2f}[O_2] + k_{3f}[OH]}\right)},$$

Where k_{1f} , k_{1b} , k_{2f} , k_{2b} and k_{3f} are forward and backward Arrhenius rates of reactions (7), (8) and (9), respectively.

The concentrations of radicals $[O]$ and $[OH]$ are approximated as

$$[OH] = 2.129 \times 10^2 T^{-0.57} \exp\left(\frac{-4595}{T}\right) [O]^{0.5} [H_2O]^{0.5}$$

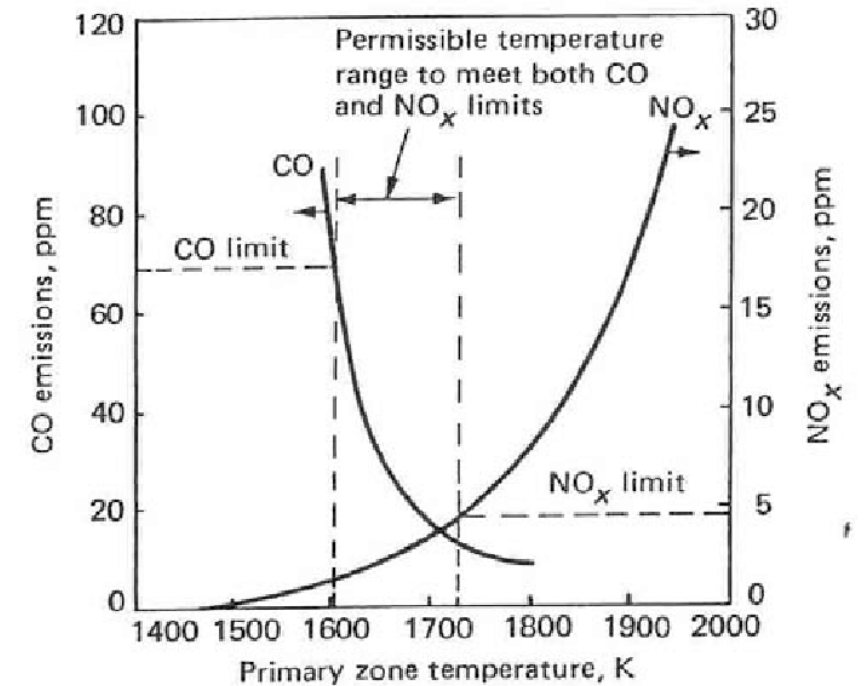
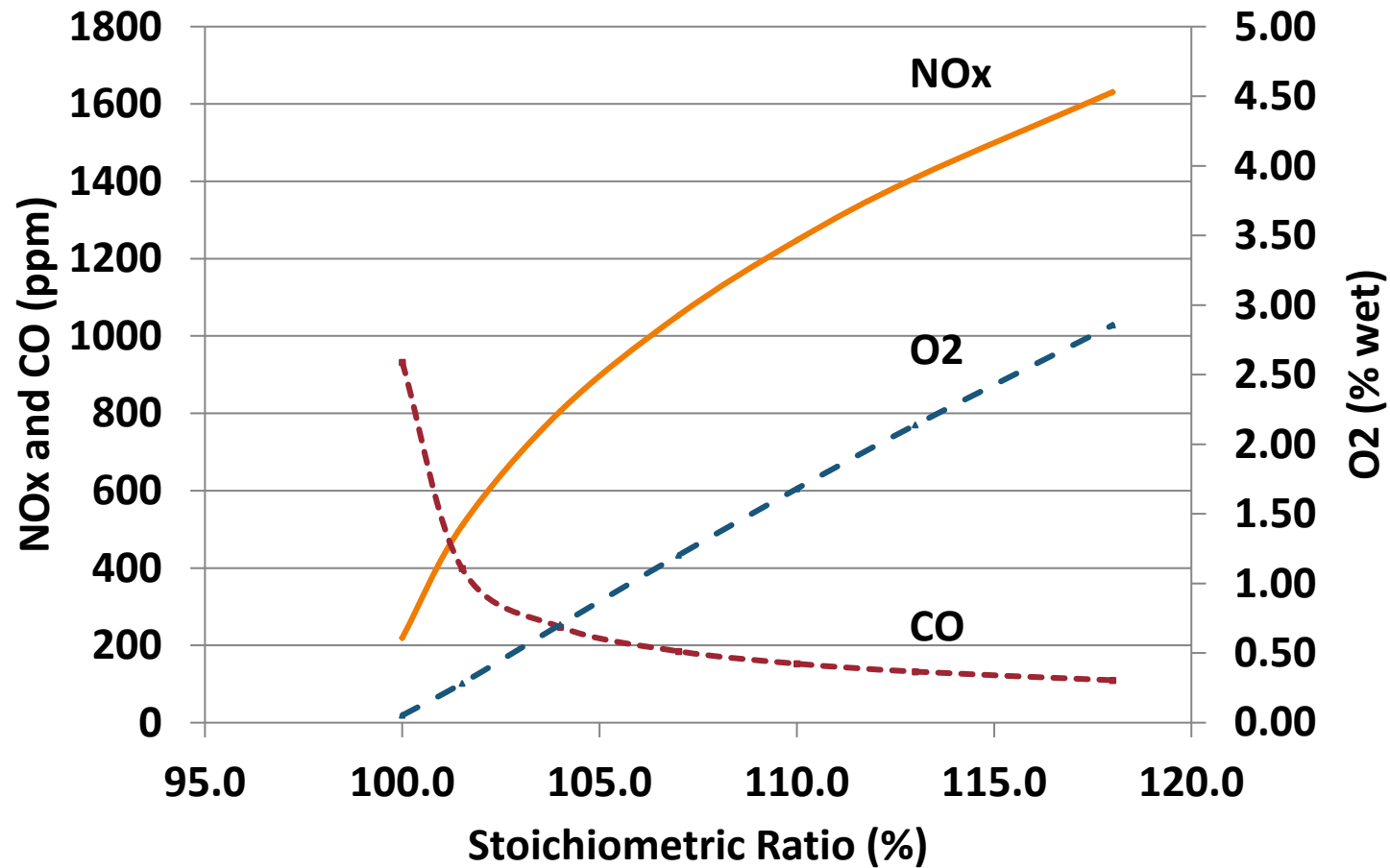
and

$$[O] = 36.64 T^{\frac{1}{2}} [O_2]^{\frac{1}{2}} \exp(-27123/T).$$

Appendix: NO_x vs CO over SR/Temperature



CH₄-Air Combustion at 2800 F (1538 C)



Appendix: NO_x in staged combustion

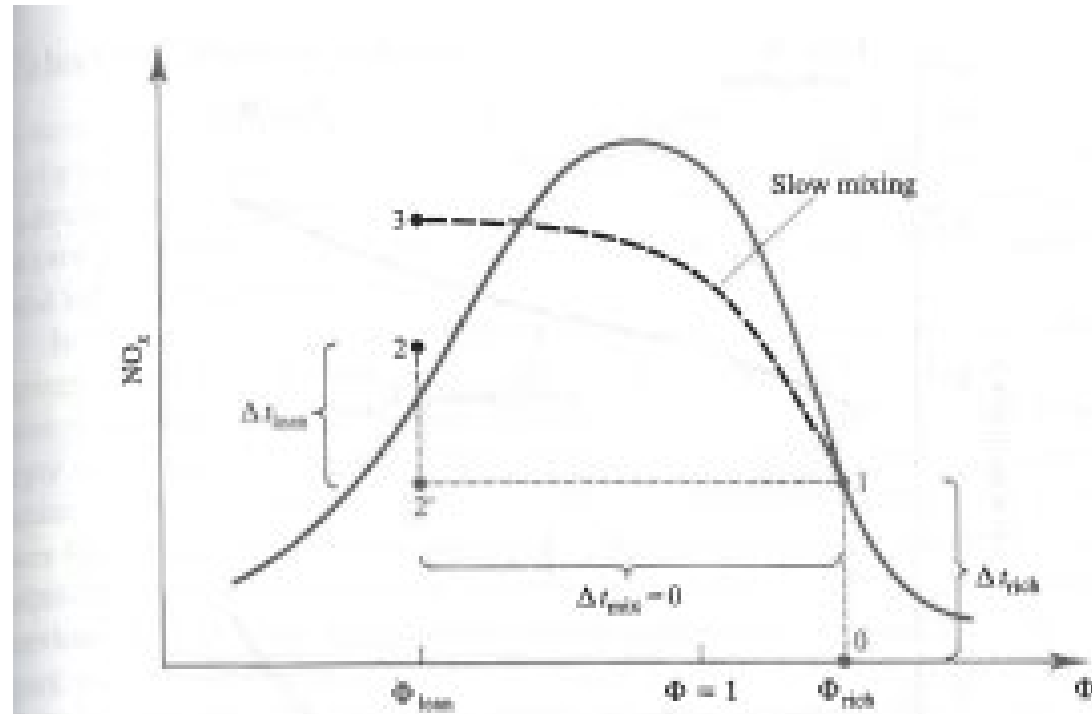


Figure 15.6 Schematic representation of staged combustion on NO_x-equivalence ratio coordinates. The path 0-1-2'-2 represents the ideal case of instantaneous secondary air mixing, while 0-1-3 indicates the path for slow secondary mixing.