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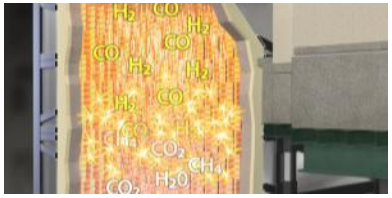
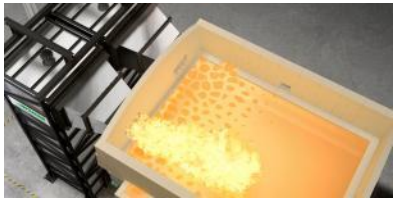




Improved Furnace Energy Efficiency with OPTIMELT™ Thermochemical Regenerator System

U. Iyoha, K. Wu, S. Laux, H. Kobayashi, J. de Diego

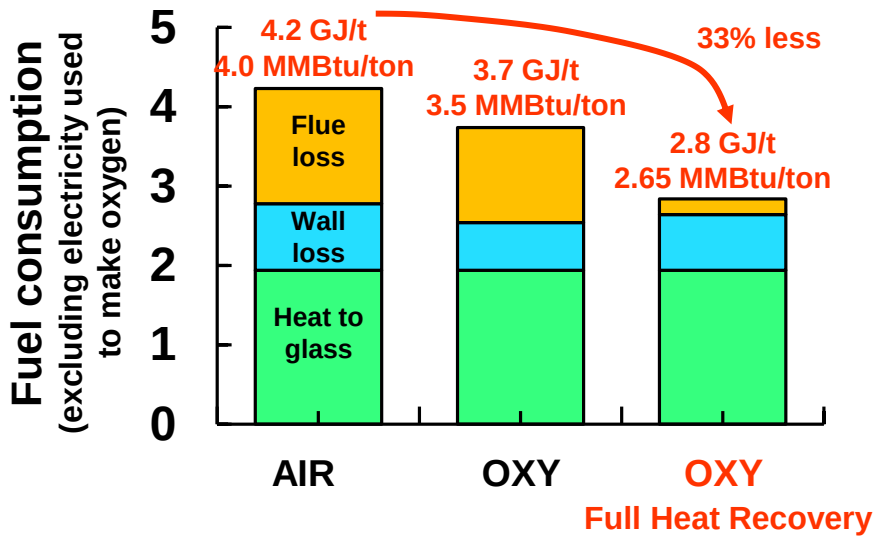
May 7th, 2015

Praxair Vision and Goals

"Make oxy-fuel fired glass melting the economic choice"

1. Reduce the cost to make oxygen
2. Reduce fuel and oxygen consumption by waste heat recovery

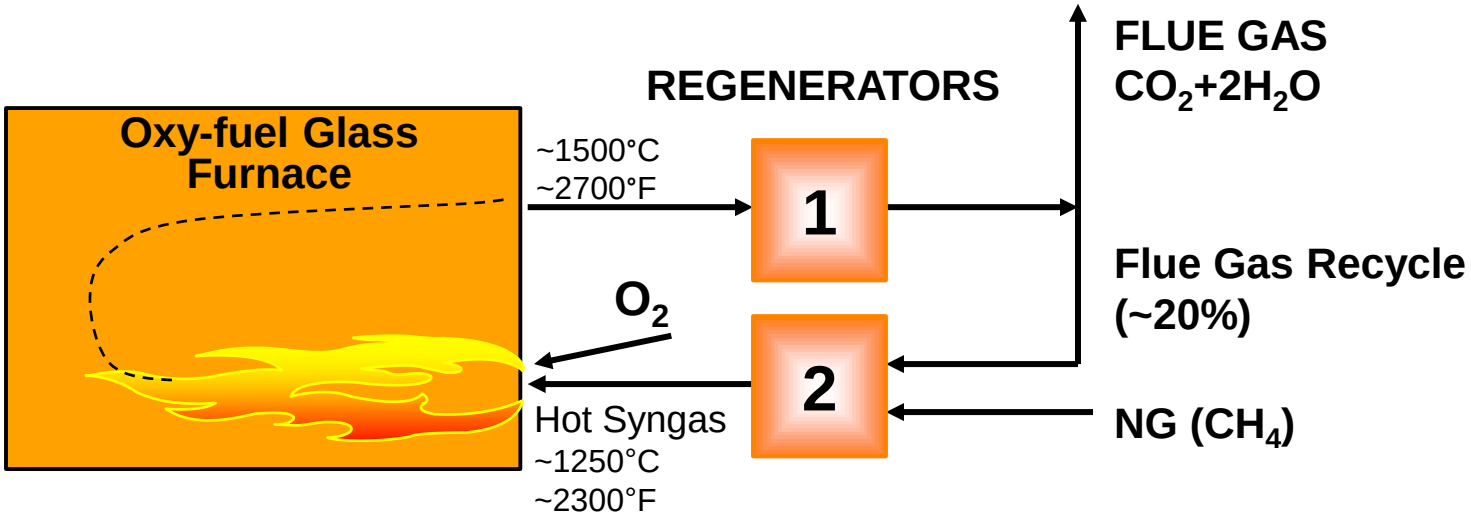
Example: Container Glass @ 50% Cullet and 300 t/d



Significant Heat Available for Recovery in Oxy-fuel Flue Gas

OPTIMELT™ Thermo-Chemical Regenerator

- High efficiency non-catalytic reforming process
- Recycled flue gas with CO_2 and water vapor is used for CH_4 reforming
- Regenerative system allows high operating temperatures/reforming rate
- Regenerators roughly 1/3 the size of air-fired regenerators



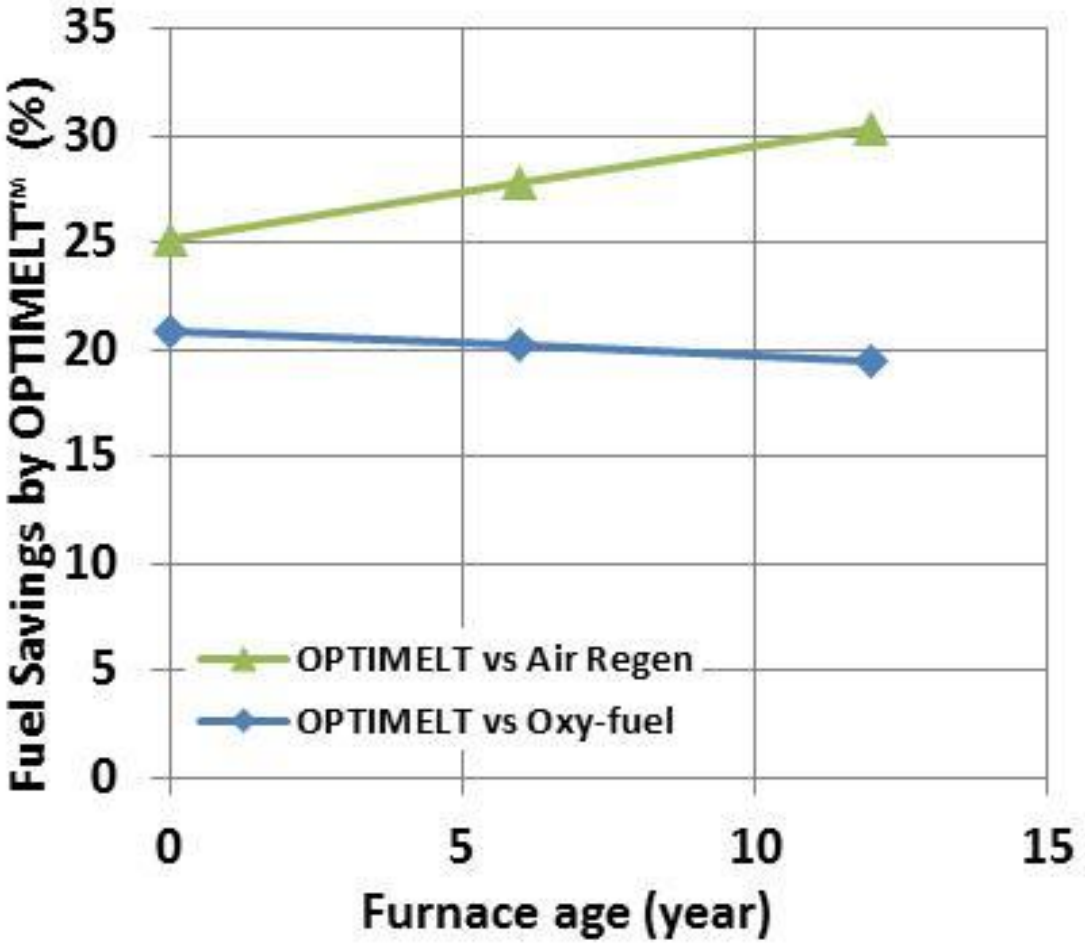
Endothermic reforming reactions

$CH_4 + H_2O \rightarrow CO + 3H_2$ 2060 kcal/Nm^3 CH_4 (215 Btu/scf-CH_4)

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$ 2630 kcal/Nm^3 CH_4 (275 Btu/scf-CH_4)

US Pat. 6,113,874

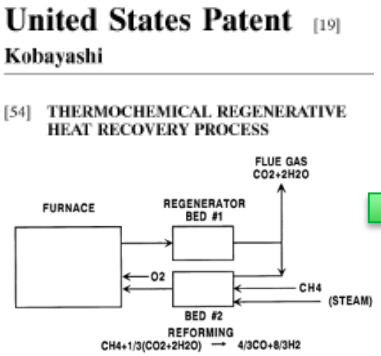
Comparison of Fuel Savings by OPTIMELT System



- Container furnace
- 300 tpd
- 50% cullet
- 500 kW E boosting

From Innovation to Commercial Offer

Development Path of Praxair's OPTIMELT™ TCR Technology


United States Patent [19]
Kobayashi

[54] THERMOCHEMICAL REGENERATIVE HEAT RECOVERY PROCESS

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Bench Scale Tests (2011)

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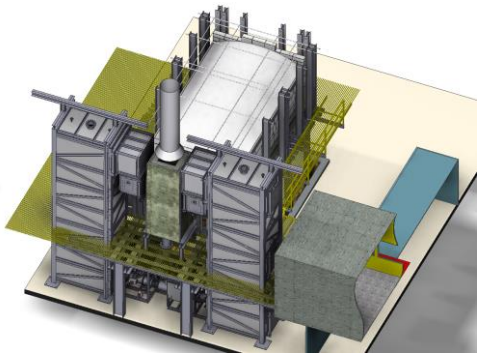
Pilot Scale Tests (2012)



PAVISA

Commercial Demonstration 50 t/d (2014)

Demonstration Project Background

- Pavisa
  - Specialty glass and crystal products for wine, liquor, food, cosmetic, and pharmaceutical industries
  - Several oxy-fuel furnaces supplied by 117tpd Praxair VPSA
  - 50tpd container glass furnace
  - Six Praxair oxy-fuel burners in the breast walls
  - Two regenerators added to the end wall
  - Very challenging site integration with little space

Outstanding collaboration on a complex construction project!

OPTIMELT™ Adaption to 50 tpd Furnace

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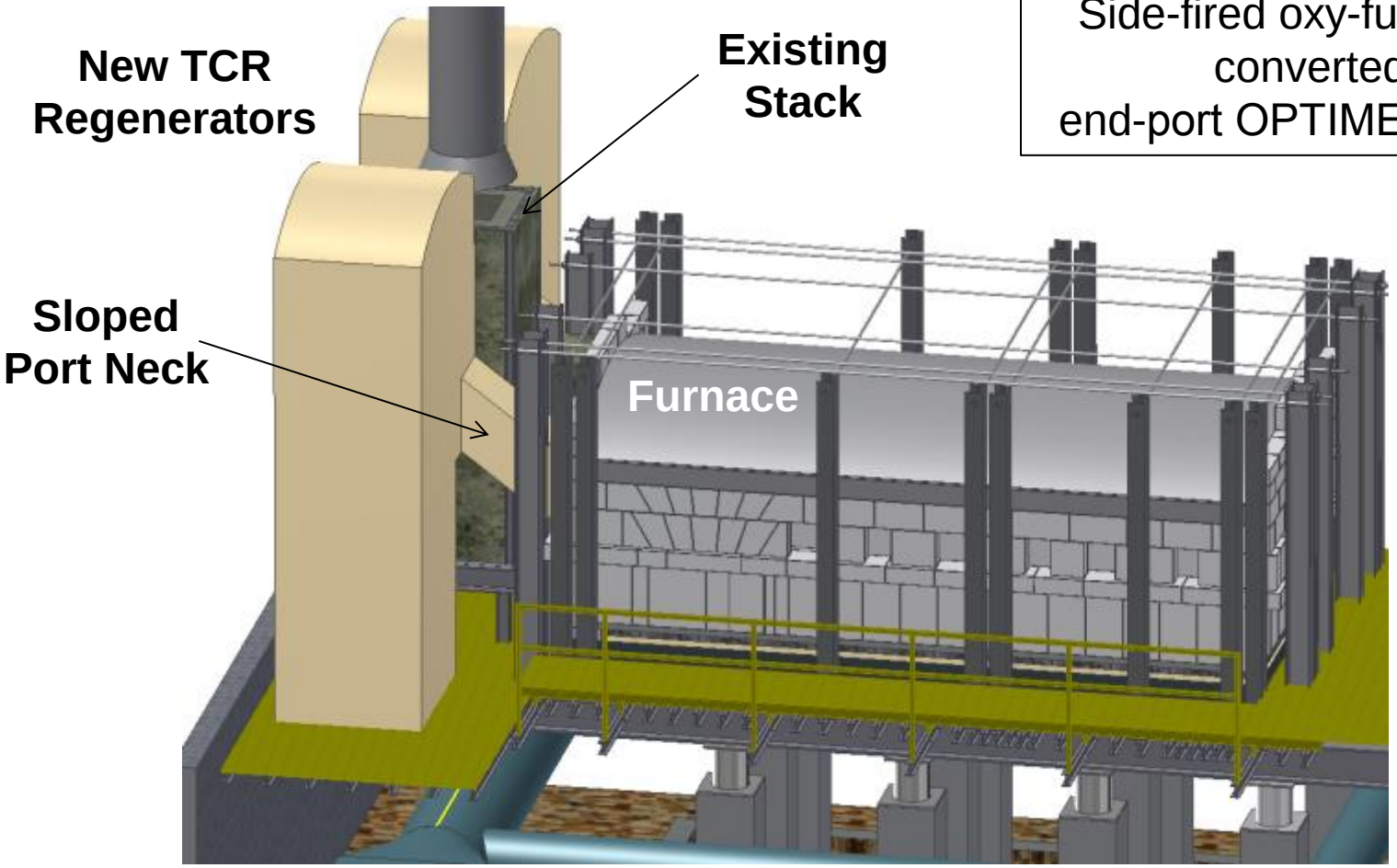
Side-fired oxy-fuel furnace converted to end-port OPTIMELT™ TCR.



Furnace can be operated with and without OPTIMELT™

Pictures from Demonstration System

Flue Gas Recirculation Skid

Bottom of Regenerator Tower

Top of Right Regenerator Tower

OPTIMELT™ TCR Flame

Right TCR Port Flue Gas Opening Left TCR Port

Results OPTIMELT™ at Pavisa

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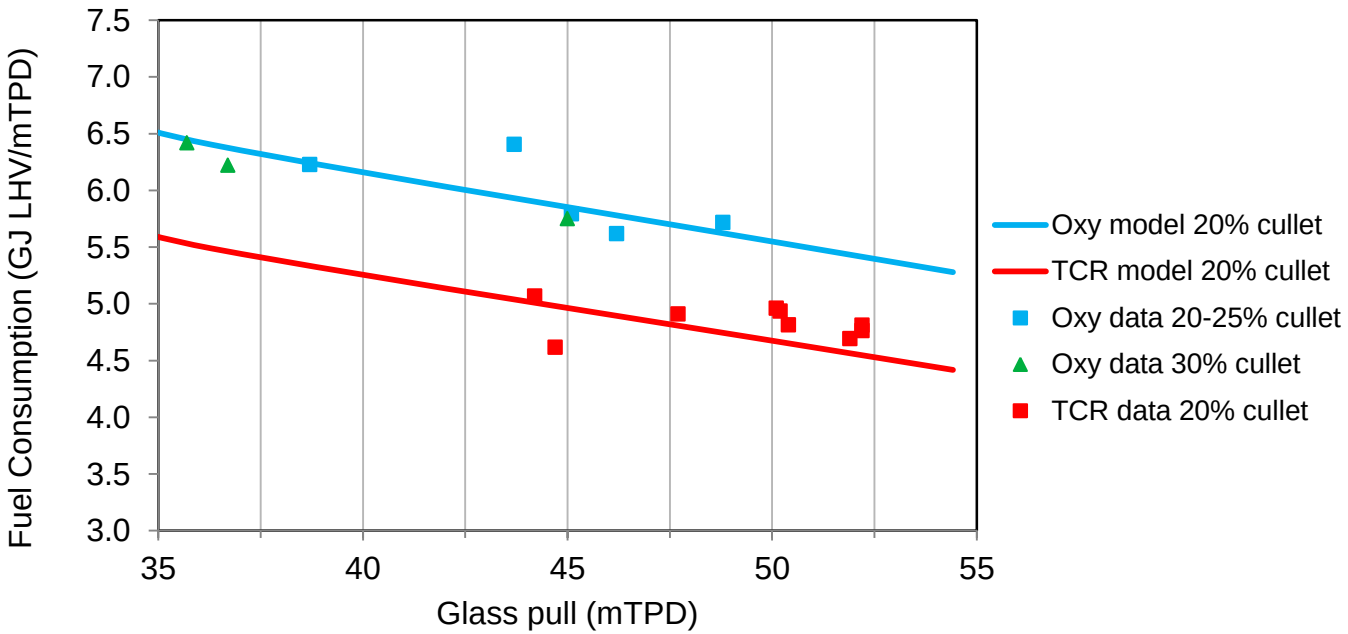
- Operation
  - Startup and process optimization complete
  - Automatic and continuous operation for cumulative 100+ days
  - ~91% availability achieved since end of October
    - Majority of unscheduled TCR shutdowns due to mechanical equipment (stack damper, air supply)
    - No fundamental TCR technology issues identified
  - Switching between TCR and Oxy-fuel has become routine
  - Pavisa operates TCR
- Results at Pavisa
  - Glass pull rate and quality required achieved - no production was lost
  - Integration of TCR into furnace has positive effect on quality
  - Energy consumption typically +16% lower than oxyfuel

Overall a very successful technology demonstration

Fuel Consumption Data and Model Prediction

Example: Pavisa “Rustic Flint Glass” (Dec 20 – Jan 9)



- Pavisa data and model show about 15 % fuel savings for “rustic flint” glass
- Results within expectations of 20% savings for commercial scale furnaces
- Commercial system savings depend on furnace size, cullet rate, insulation and flue gas temperature – range 18 to 22%, individual assessment required

Comparison with other furnace data from the CelSian Benchmark Study for container glass furnaces

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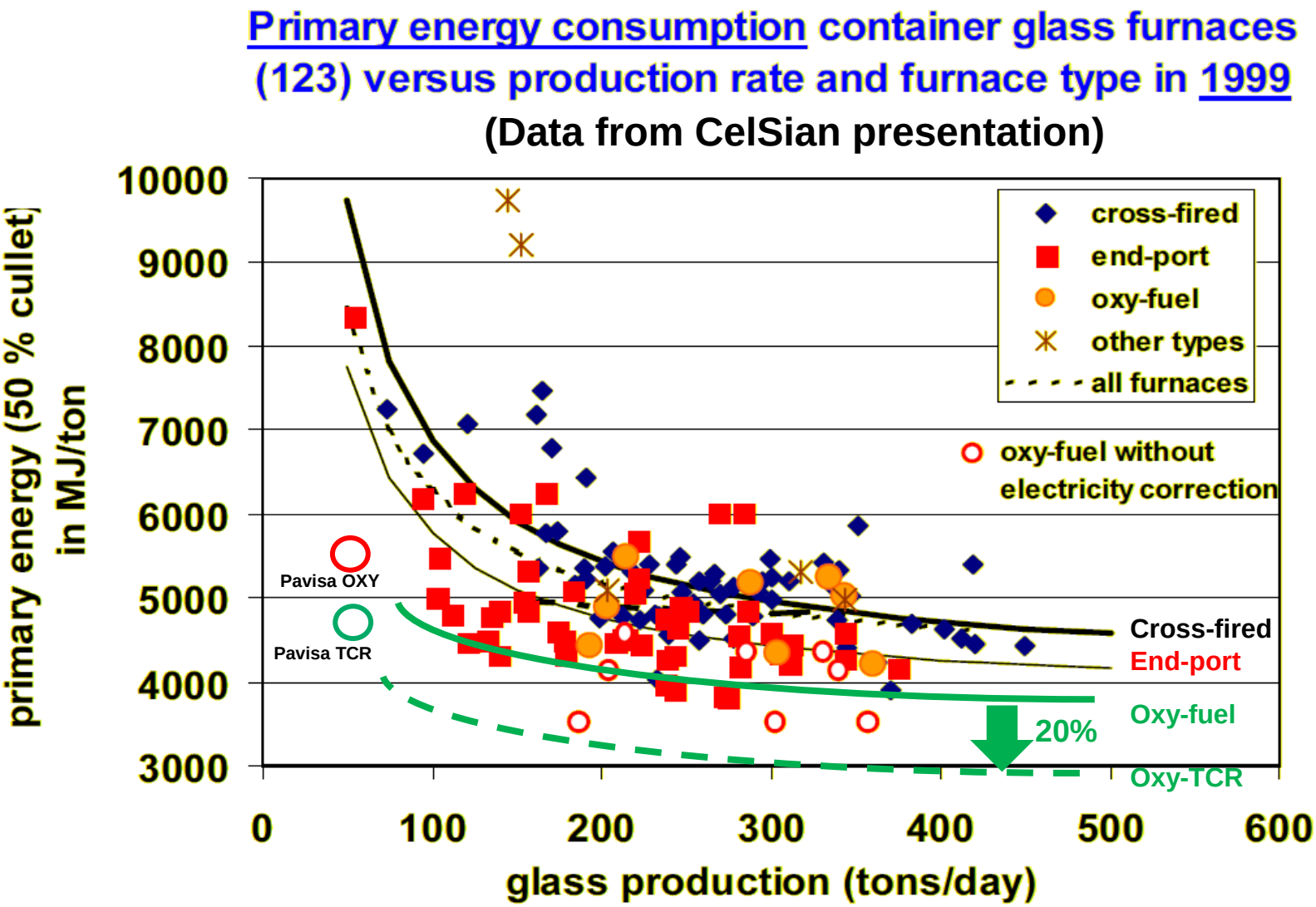

Key Technical Issues Addressed

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1. Process safety (syngas handling)
    1. Praxair's commercial experience (SMR & POX plants)
    2. Extensive process hazards analysis (PHA)
    3. Experience with the pilot unit
    4. Experience from commercial producer gas regenerators
    5. Review with insurance industry safety experts
2. Syngas flame and heat transfer in glass furnaces
    1. Praxair's broad industrial experience with oxy-fuel combustion
    2. Pilot scale test facility for shaping syngas flames
    3. CFD simulation
    4. Pavisa experience
3. Checker plugging and corrosion
    1. Collaboration with refractory companies
    2. Producer gas regenerator experience
    3. Pavisa experience

Summary

- Praxair's OPTIMELT™ Thermochemical Regenerator (TCR)
  - Reduces energy consumption (~20% vs oxy-fuel, ~30% vs. air-regenerative)
  - Reduces CO_2 emissions
  - Reduces air pollutants to the level of oxy-fuel performance (NO_x, CO, etc.)
  - Reduces flue gas volume and enables smaller air pollution control
- Successful commercial demonstration at Pavisa
  - System in automatic and continuous operation
  - Fuel savings well within expectations for size of installation and operating conditions
- 300 tpd size OPTIMELT™ TCR system is ready for commercial application

Praxair is committed to new technology development to support the cost reduction and sustainability goals of the glass industry