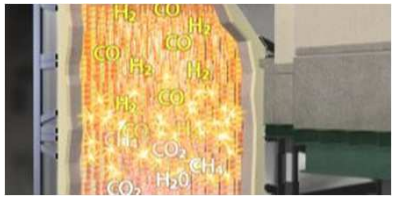
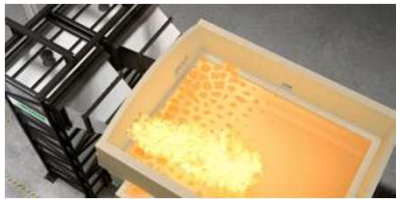
PRAXAIR

Making our planet more productive™





Advanced Heat Recovery for Oxy-Fuel Fired Glass Furnaces with OPTIMELT™ PLUS Technology

S. Laux, U. Iyoha, R. Bell, J. Pedel, A. Francis, K.T. Wu, and H. Kobayashi
Praxair, Inc., Danbury, CT, USA

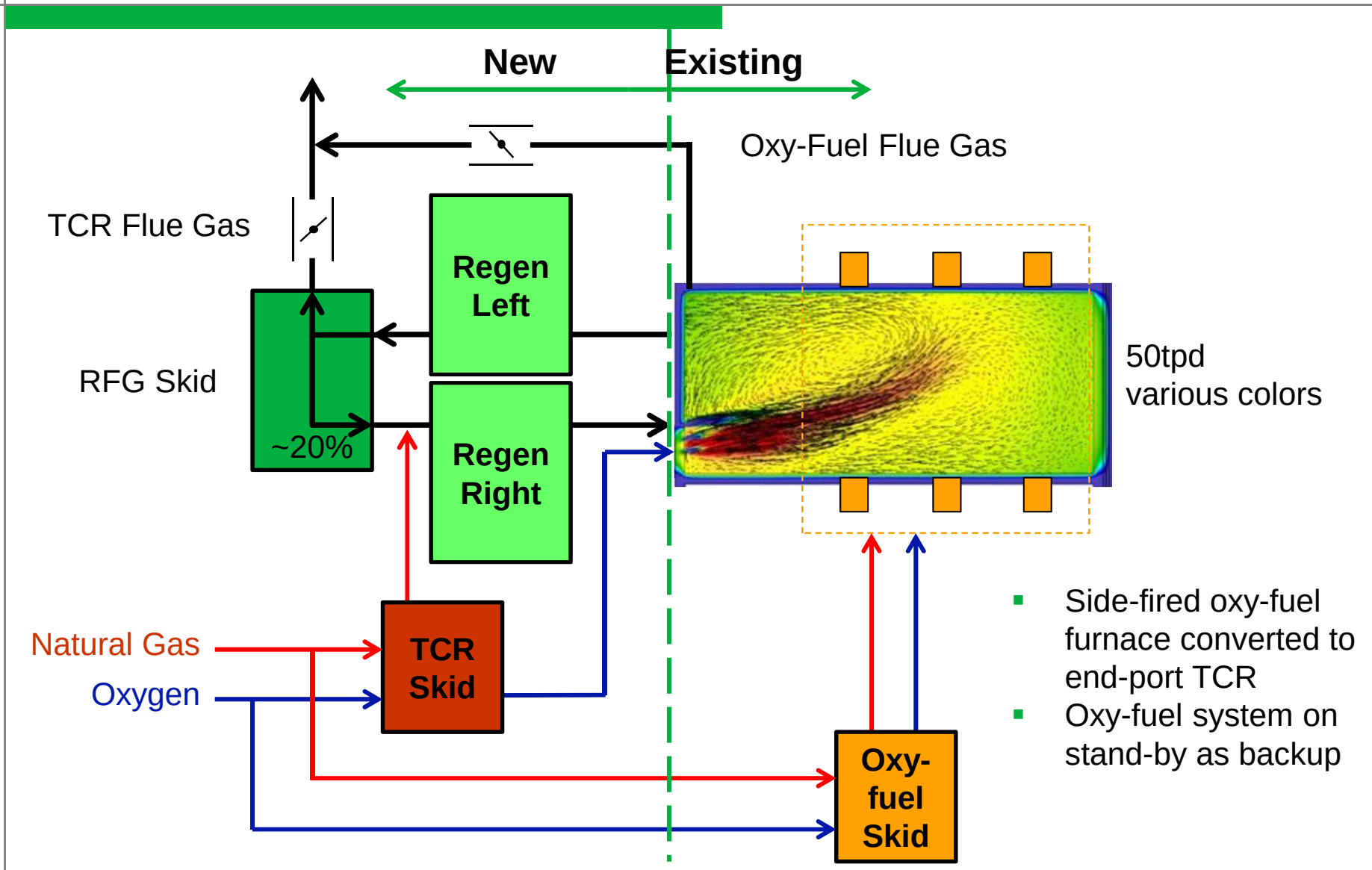
77th Conference on Glass Problems
Greater Columbus Convention Center | Hilton Columbus Downtown
November 7-10, 2016
glassproblemsconference.org

OPTIMELT™ Thermo-Chemical Regenerator

PRAXAIR
Making our planet more productive™

- Reforming of Natural Gas in regenerators recovers significant heat in the flue gas of oxy-fuel furnaces
  - Regenerative system takes advantage of high operating temperatures
  - High efficiency non-catalytic reforming process
  - Recycled flue gas with CO_2 and water vapor is used for endothermic CH_4 reforming to CO and Hydrogen (syngas)
- Hot syngas is burned with oxygen in the furnace
- Regenerators roughly 1/3 the size of air-fired regenerators
- OPTIMELT advantages
  - Reduced energy consumption (~20% vs oxy-fuel)
  - Reduced CO_2 emissions
  - Reduced air pollutants to the level of oxy-fuel performance (NOx, SOx, CO, etc.)
- Extensive Development program started 2011
  - Demonstration at Pavisa and commercialization of OPTIMELT TCR
  - Introduction of combination with oxygen preheating: OPTIMELT Plus

OPTIMELT System at Pavisa



- Side-fired oxy-fuel furnace converted to end-port TCR
- Oxy-fuel system on stand-by as backup

Status Pavisa Furnace 13

- Operation
  - System in automatic and continuous operation since September 2014
    - System turned over to Pavisa, formal acceptance by Pavisa
    - Reliable operation (99.7% availability May/June excluding power failures)
  - Glass pull rate and quality continue to be within Pavisa requirements
  - Emissions in the range of emissions for Low NOx glass oxy-fuel burners
  - Energy reduction 15 to 18% - in line with expectations for 50tpd furnace
  - No fundamental TCR technology issues identified
- Wide Flame Burner Gen III for OPTIMELT tested in Furnace 13
  - New cooling concept to allow idle burners for future commercial projects
  - Tested successfully two months, temperatures are within material limits
- End-firing of Oxy-fuel Combustion System as an alternative to the side-fired oxy-fuel burners installed in May
- Refractory testing in regenerators continues

Pavisa continues to support ongoing OPTIMELT development

Regenerator and Checker Performance

- Summer Inspection: Checker in very good condition after 22 months
  - Passages free of deposits
  - No signs of corrosion
  - Light deposits at bottom, easy to clean
- Port neck and regenerator top refractory was not the right choice for application
  - Nepheline spalling of material in hottest zone
  - Better material identified, replacement 2016
- Lower regenerator walls and rider arches in very good condition
- Dampers, ducts and fan deposits
  - Cleaning no problem, no operational impact

Very encouraging results, valuable information for scale-up

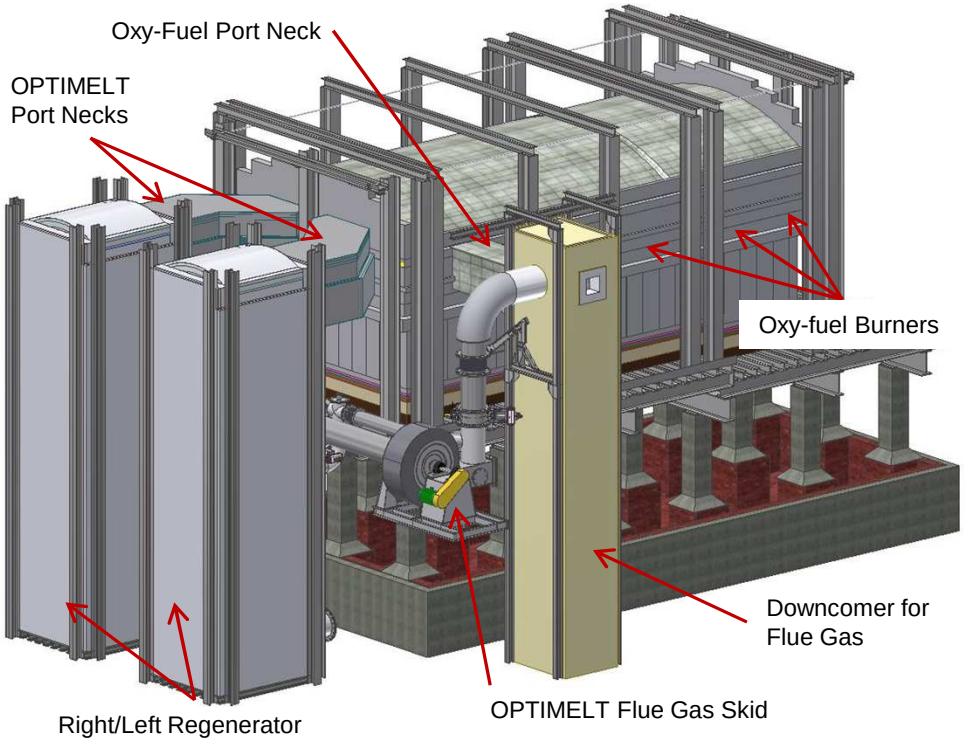
Refractory Test Program Continues

- Refractory selection program tests are ongoing
- Test Rounds:
  - 1 completed: 8 months
  - 2 completed: 1 month (quick screening test for exclusion of refractories)
  - 3 currently ongoing for ~9 months
  - 4 in preparation
- Round 1 and 2 results were used in the selection of the refractory for next commercial project
  - Observed corrosion patterns typical for glass furnace conditions
  - SiO2 reduction by H2 /CO/C in syngas was not observed
  - Selection not a straightforward scientific process, actual testing is important
    - Very high alumina and Magnesia samples promising
    - Fused-cast AZS refractories superior to bonded material
  - Surprising differences in same classes or material due to details in composition and manufacturing matter

Technology Development guided by Pavisa Refractory Exposure Tests

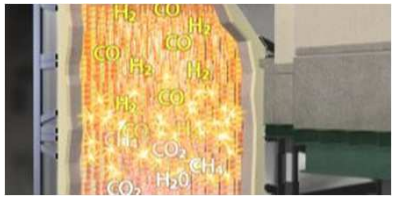
OPTIMELT Status Leerdam 1

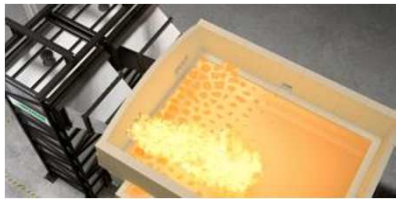
- Installation on tableware furnace
  - Praxair VPSA oxygen supply with liquid oxygen backup
  - Libbey Motivation: fuel and oxygen savings, emissions, sustainability
- Partial Project funding by EU (LIFE Grant LIFE15 CCM-NL-000121)
- Engineering and Design phase nearly complete
  - Sorg: Furnace, Regenerators and Oxy-fuel system
  - Praxair: OPTIMELT system and JL Oxy-fuel Burners
- Procurement underway
  - EU fabrication requirement
- Construction and startup 2017



PRAXAIR

Making our planet more productive™

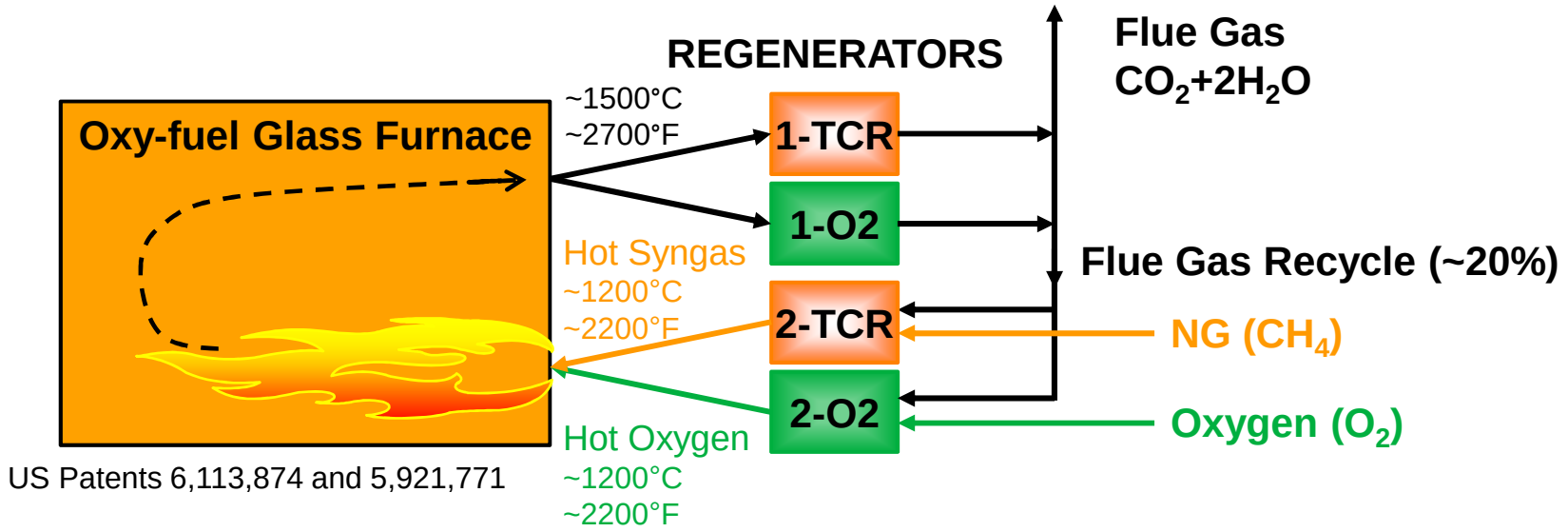




OPTIMELT™ PLUS Technology

OPTIMELT™ Plus Technology

- High efficiency non-catalytic reforming process (OPTIMELT) coupled with regenerative oxygen preheating (Plus)
- Recycled flue gas with CO_2 and water vapor is used for CH_4 reforming
- Regenerative system allows high operating temperatures/reforming rate



US Patents 6,113,874 and 5,921,771

TCR Endothermic reforming reactions

$CH_4 + H_2O \rightarrow CO + 3H_2$ 2060 kcal/Nm³ CH_4 (215 Btu/scf-CH_4)

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$ 2630 kcal/Nm³ CH_4 (275 Btu/scf-CH_4)

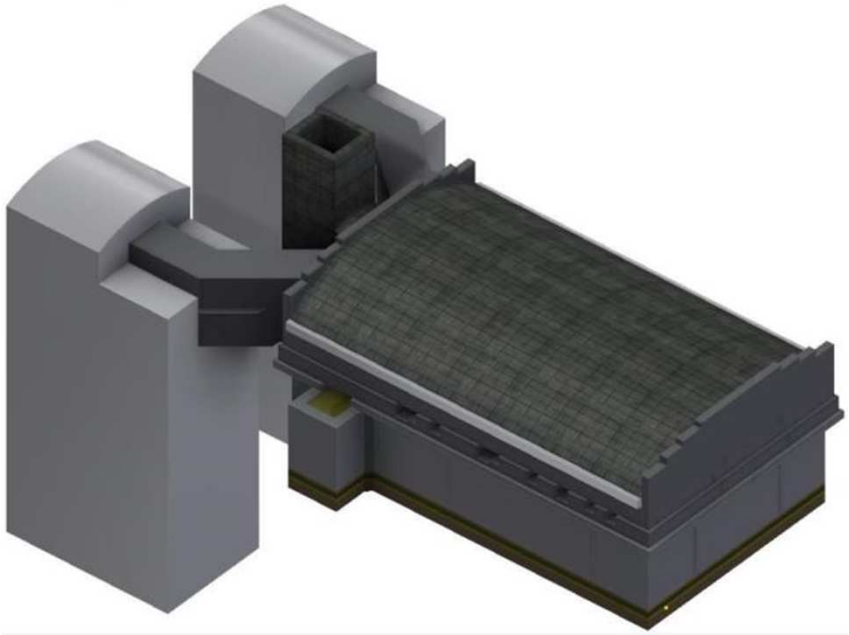
OPTIMELT Plus Benefit

- OPTIMELT Plus improves the heat recovery by another 5% in comparison to OPTIMELT
  - Example heat and mass balance comparison of the two heat recovery technologies below
  - 240 t/d container furnace with 1 MW electric boost and 30% cullet ratio

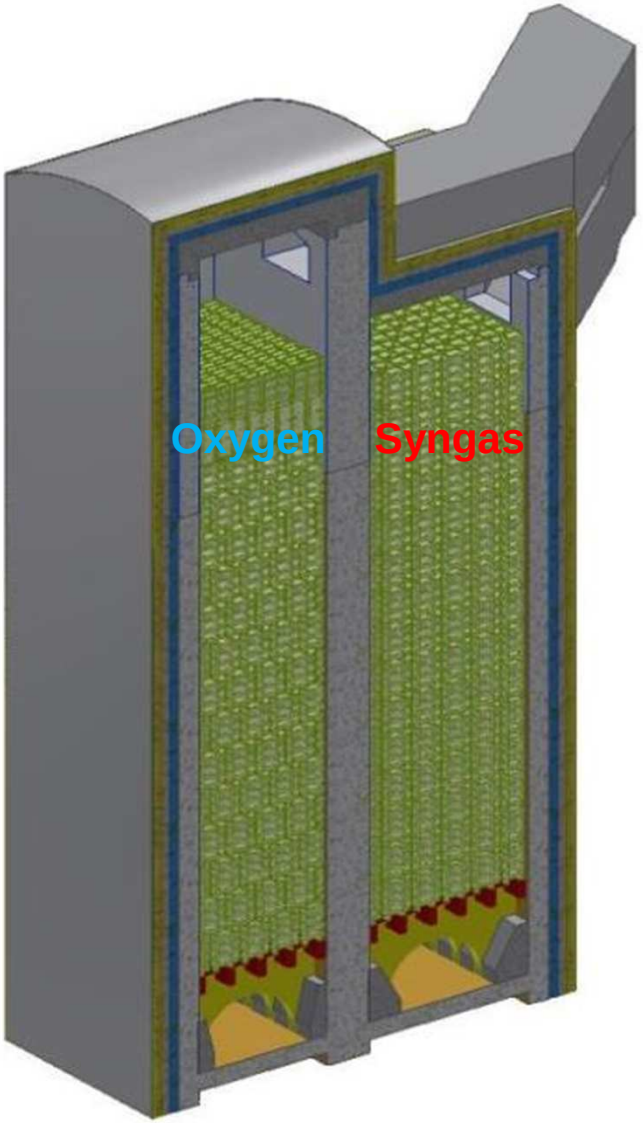
		Oxy-fuel baseline	**OPTIMELT TCR**	**OPTIMELT Plus**
Fuel Input	GJ/t	4.0	3.2	2.95
	MMBtu/ton	3.8	3.0	2.8
Fuel Savings	**%**	**base**	**21.3**	**26.6**
Flue Gas Temperature	°C	1500	650	400
	°F	2700	1200	750

System Layout

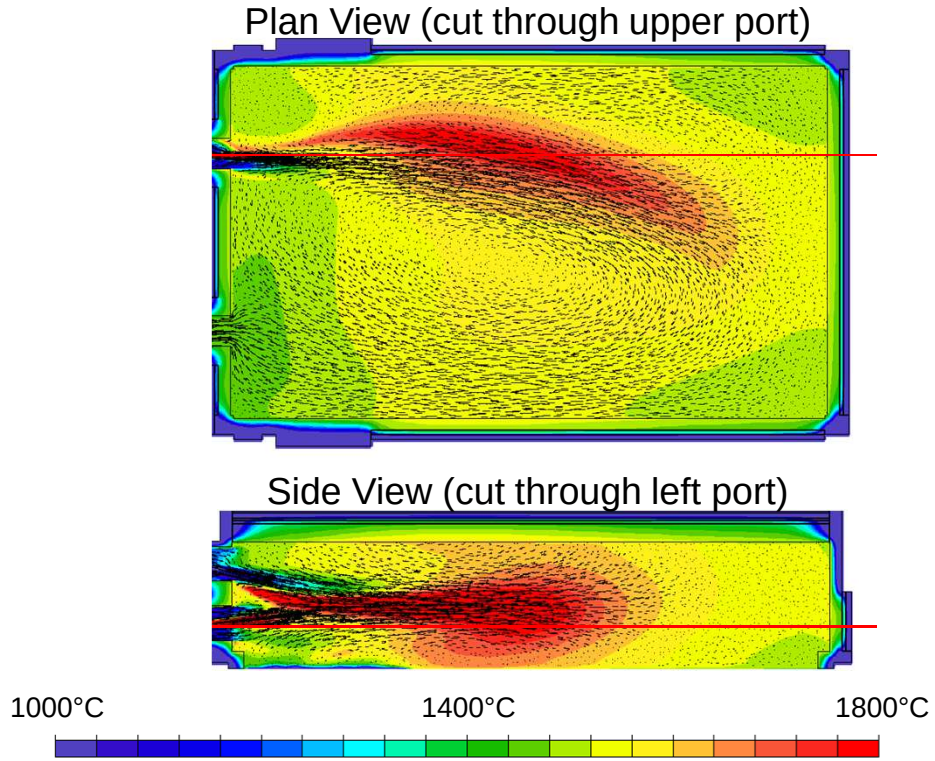
- Oxygen preheating to ~1200°C with second set of regenerators
- Total checker volume less than OPTIMELT
- Concept engineering and costing complete for 240tpd furnace



Front: TCR Syngas Regenerators
Back: Oxygen Regenerators



CFD Model OPTIMELT Plus 240tpd



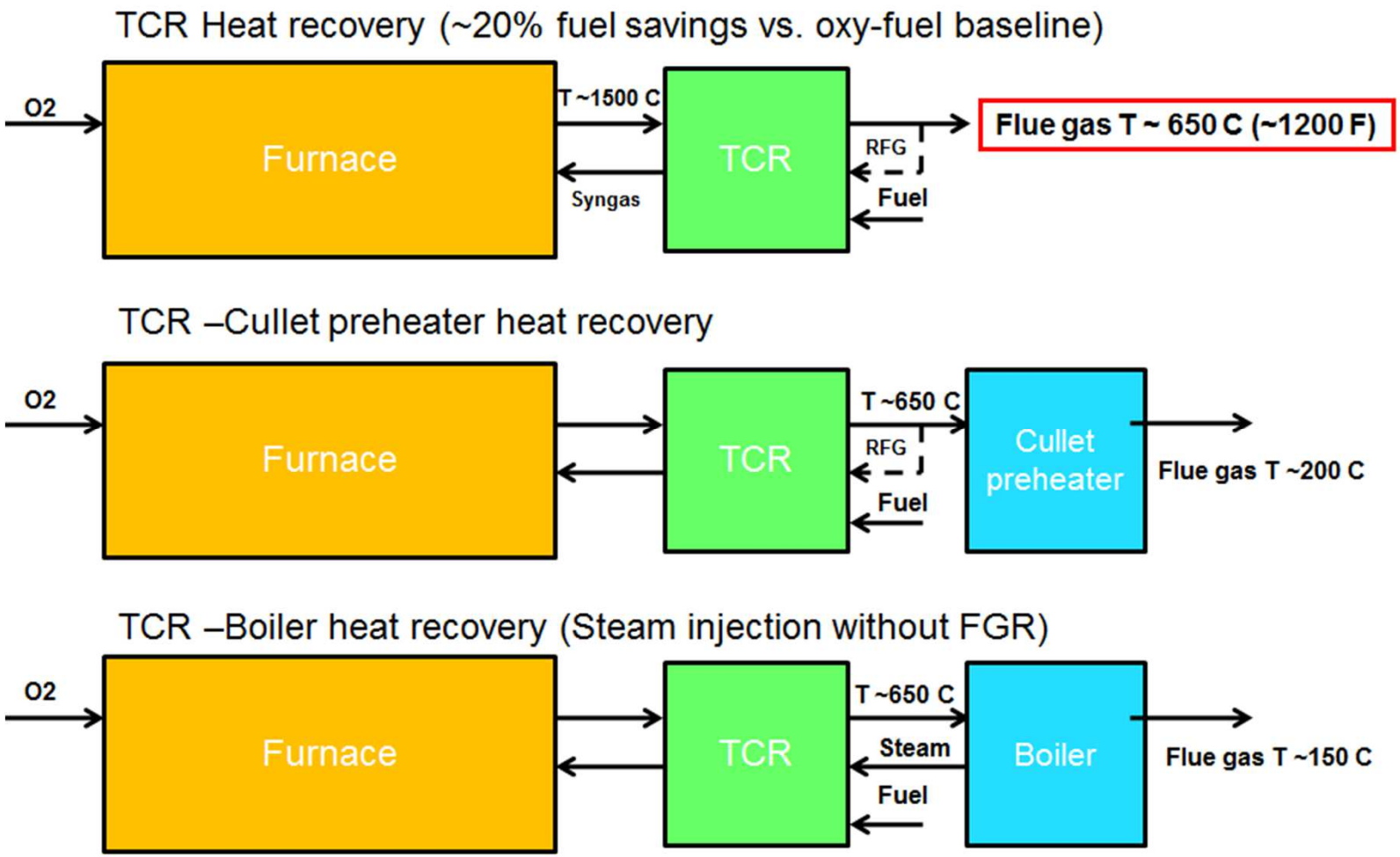
- Flame is formed at the interface of hot syngas with hot oxygen
  - Technology to shape flame similar to OPTIMELT TCR
  - No overheating of ports, walls or crown
  - Flame can be positioned in furnace to achieve desired heat transfer
  - Combustion technology prevents large area of unburned fuel in the furnace

Options for Heat Recovery

- OPTIMELT TCR flue gas leaves regenerators at ~650°C (1200°F)
- Technology can be combined with many heat recovery options
  - Regenerative oxygen preheat: OPTIMELT Plus
  - Integrated batch/cullet or cullet preheating
    - No air dilution required due to lower temperature of flue gas
    - Requirement to remove the organic fume/odor from the flue gas after a cullet preheater
  - Additional heat recovery options from flue gas
    - Boiler and turbine (ORC)
    - Steam boiler to generate reforming steam for TCR
    - Recuperative oxygen preheat to ~500°C
- Regenerative oxygen preheating
  - Stand-alone preheater to ~1200°C
  - Combination with batch/cullet preheating

Examples of Heat Recovery Options

PRAXAIR
Making our planet more productive



Fuel Savings of Heat Recovery Options

PRAXAIR
Making our planet more productive™

Results of heat and mass balances (300tpd container furnace at 50% cullet)

Case	Heat Recovery System	Fuel Savings (%)
1	Oxy-fuel	baseline
2	OPTIMELT Thermochemical Regenerator (TCR)	20
3	OPTIMELT Plus (TCR with O2 Regenerator)	25
4	OPTIMELT TCR with Cullet PH	29
5	Oxygen Regenerator (100% O_2 purity, PH to 1200°C)	11
6	Oxygen Regenerator with Cullet PH	22
7	Oxygen Regenerator with Batch/Cullet PH	28

- Efficient heat recovery with OPTIMELT lowers level of available heat
- Further heat recovery feasible (some options with diminishing returns)
- Integration issues and environmental impact must be considered

Additional CAPEX must be balanced against incremental heat recovery

Summary

- Praxair's OPTIMELT™ Thermochemical Regenerator (TCR)
  - High reduction of fuel consumption (container furnace: ~20% vs oxy-fuel, ~30% vs. air-regenerative)
  - Reduces CO_2 emissions
  - Reduces air pollutants to the level of oxy-fuel performance (NOx, SOx, CO, etc.)
- Pavisa System in automatic and continuous operation
- Two commercial size projects in engineering phase
  - Libbey L1: end-fired tableware furnace with side-fired oxy-burners
  - Customer 2: 240 tpd end-fired container furnace (flint glass) with end-fired oxy-burners
- OPTIMELT™ Plus – a novel technology that maximizes heat recovery without large equipment addition

PRAXAIR
Making our planet more productive™

Thank You for your Attention!

Please stop by at our booth at the Hilton!

Stefan_Laux@Praxair.com