Velocys Fischer-Tropsch Synthesis Technology – Comparison to Conventional FT Technologies

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Presentation Outline

- Who is Velocys
- Conventional FT Technologies
  - Multi-tubular Fixed Bed Reactors
  - Slurry Bubble Column Reactors
- Velocys Microchannel FT Technology

About Oxford Catalysts Group

- Unique innovative technology solution for distributed scale GTL
- **World-class pedigree** − 15+ yrs of development
  - University of Oxford: top global research centre; largest chemistry department in Western World
  - Battelle: world's largest independent science and technology organisation
- **Global leader**
  - World's strongest microchannel IP portfolio (>800 patents)
    - >7,500 granted GTL claims and 6,000 pending
- **Critical mass**: ~90 employees
  - Catalyst development near Oxford, UK
  - Process technology development near Columbus, Ohio, USA
- Oxford Catalysts Group listed on AIM (LSE:OCG) – sells under **Velocys** brand

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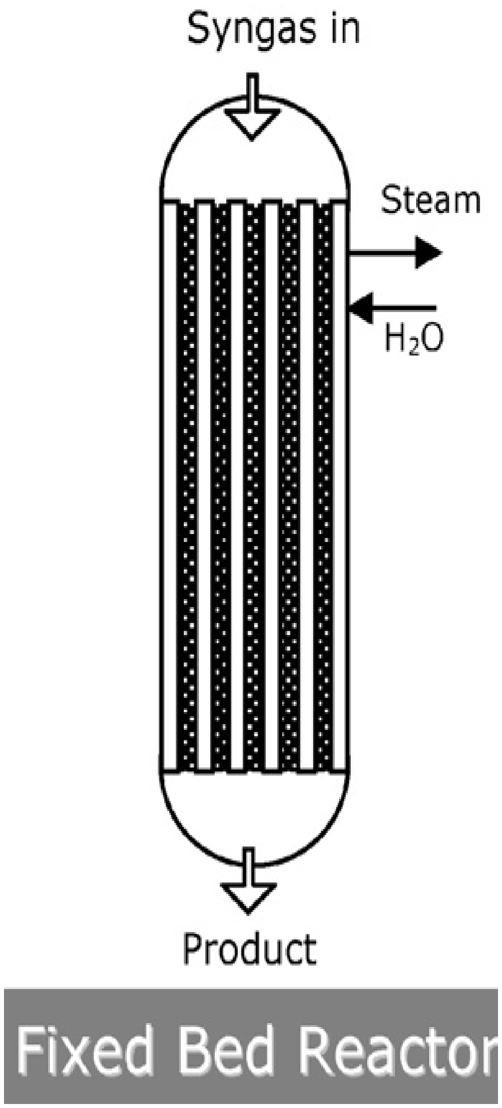
Conventional Fixed Bed Reactors



- Principles of design and operation
  - Catalyst-particles in long, small diameter tubes
  - Syngas inlet at top
  - 2-phase mixture (wax + gas) exits bottom
  - Boiler feed water in reactor shell
  - Heat removal by steam generation
- Strong points
  - Long established scale-up methodology
  - Strong economy of scale to maximum size
  - Plug flow behavior
  - “Simple” operations
  - Very high strength catalyst not required
  - Generally excellent catalyst/wax separation
  - Bed inlet acts as poison removal zone
  - Simple, in-situ catalyst regeneration process

Conventional Fixed Bed Reactors - Negatives

- Sub-optimal catalyst particle size vs. differential pressure trade-offs
  - FT selectivity considerations strongly favor small particles (< 0.5 mm)
  - Tube length and DP considerations strongly favor large particle (> 2-3 mm)
  - Typical 1-2 mm particles operate near/in mass transfer limited conditions
- Sub-optimal reactor tube diameter
  - Heat removal at high reaction rates requires small diameters (< 0.5”)
  - Reactor cost and weight requires large diameters (>2”)
  - Typical ~1” diameter tubes operate under heat transfer limited conditions
- Reactor must be taken off-line for catalyst regeneration
  - On stream service factor debit for all but the largest plants
- Reactor must be shut-down for catalyst replacement
  - On stream service factor debit for all but the largest plants
- Reactors are very large and heavy per unit of production

Conventional Fixed Bed Reactors – Implications

- Reaction rate is limited by heat transfer considerations
  - Control of hot spots requires relatively low average temperatures
  - Reactors are susceptible to thermal runaway under upset conditions
  - Exothermic regeneration procedures are also tricky
- High recycle to fresh feed ratios required – typically 3-5
  - Maintain high gas velocities in tubes
  - Minimize reactant concentration gradients through catalyst bed
  - Large recycle compressors and power loads
- Maximum productivity per reactor limited to about 6,000 BPD (Shell)
  - Reactors are still 20-25 ft in diameter, ~40 ft tube lengths, 30,000 tubes, 1200 tonnes
- Small plant service factor considerations lead to dis-economies of scale
  - Multiple reactors required to avoid severe downtime issues
- Even relatively small capacity reactors difficult to modularize
  - BP's 300 BPD demo plant (AK) had 2 reactors, ~5-6 ft OD by ~50 ft tall

Tubular Reactor Score Card

Property	Tubular Fixed Bed	Slurry Bubble Column	Velocys Microchannel
Flow Patterns	Plug flow		
Reactor Scale-up Methodology	Easy/known		
Heat Transfer Limitations	Very high		
Mass Transfer Limitations	High		
Thermal Stability	Poor		
Catalyst Reaction Rate	Low		
Reactor Volumetric Production	Low		
Differential Pressure	Moderate		
Gas Recycle Requirements	High		
Catalyst Wax Separation	Excellent		
Catalyst Strength Requirement	Low		
Regeneration Equipment	Minimal		
Regeneration Ease	Difficult		
Catalyst Replacement	Offline-slow		
On-stream Factor	Low		
Feed Poisoning	Local		
Upset Robustness	Low		
Shutdown Robustness	Good		
Modularization	Low		
Mass Manufacturing Economies	Low-Medium		
Boiler Feed Water Quality	Low		
Capital Cost per BPD	High		

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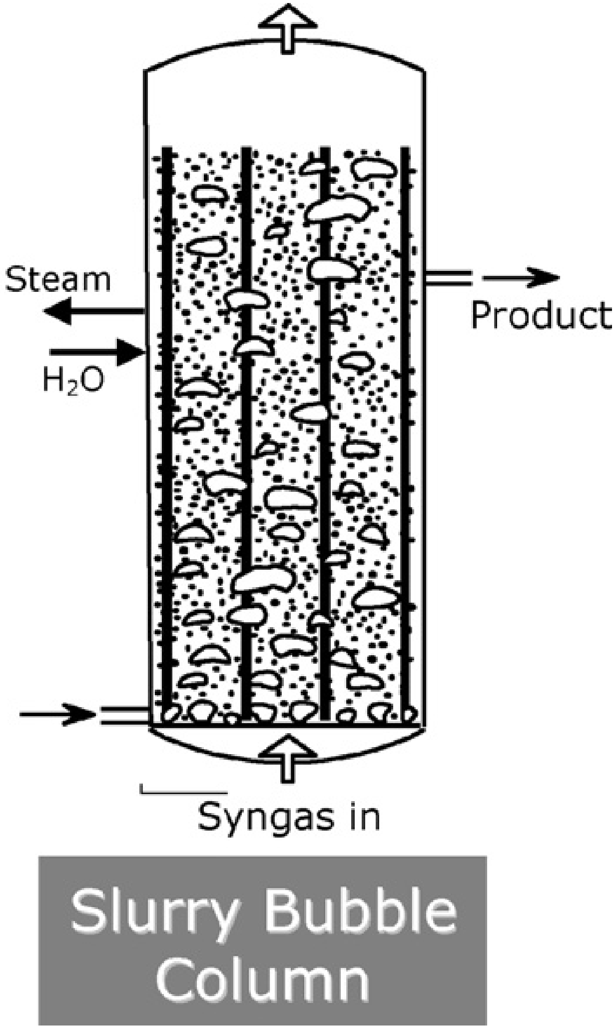
Slurry Bubble Column Reactors



- Principles of design and operation
  - Catalyst-wax slurry in reactor shell
  - Low catalyst volume fraction (< 20%)
  - Syngas bubbled through slurry
  - Wax removal by internal filtration
  - Boiler feed water in reactor tubes
  - Heat removal by steam generation
- Strong points
  - Isothermal behavior – thermally stable
  - Generally robust to upsets
  - Very strong economy of scale
  - Accommodates high activity catalysts
  - Low DP (liquid head and gas distributor)
  - Small particles not mass transfer limited
  - Catalyst replacement on line
  - High on-stream factor
  - Tail gas recycle only to achieve high conversion

Slurry Bubble Column Reactors - Negatives

- Reactor hydrodynamics are strong function of reactor diameter
  - Scale-up methodology not generally understood
  - Large reactors relatively well mixed
  - No inlet guard bed effect – all catalyst poisoned equally
- Significant solids handling issues
  - Addition and removal of small (50-100 micron) catalyst powder
  - Potential catalyst settling on shutdown (and in operation)
  - Near uniform gas distribution across 5-10 m diameter surface required
  - Catalyst-wax separation (filtration) potentially problematic
  - Very robust catalyst particles required – mechanically and chemically
  - Potential catalyst entrainment – overhead losses in gas outlet
  - Possibility of slurry "burp" overhead during severe pressure and/or flow upset
- Complicated catalyst regeneration equipment and procedures
  - Multi-step, batch processing
  - Catalyst settling, wax removal, fluidized bed oxidation and reduction, catalyst wax mixing

Slurry Bubble Column Reactors – Implications

- Very large high capacity reactors possible
  - 10 m diameter by 60 m tall, 2200 MT, 17,000 BPD (Sasol - Oryx)
  - Future plants based on ~24,000 BPD from same scale reactors
- Significant scale-up risk
  - Only Sasol (10 m) and Synfuels China (5 m) have experience with large reactors
    - Sasol not licensing, Synfuels China employs iron catalyst
  - GTL.F1 only comfortable increasing diameter by ~2 times
    - Ran a 1,000 BPD demo, “only” planning 2,000-4,000 BPD commercial reactors
  - Several large and costly demonstration efforts more-or-less abandoned
    - Exxon (200 BPD), ConocoPhillips (400 BPD), Syntroleum (100 BPD)
- Catalyst separation especially risky
  - Sasol Oryx plant at 1/3 capacity for > 1 year
- Solids handling requirements limit small-scale applications
  - Catalyst regeneration especially problematic at small scale

Slurry Bubble Column Score Card

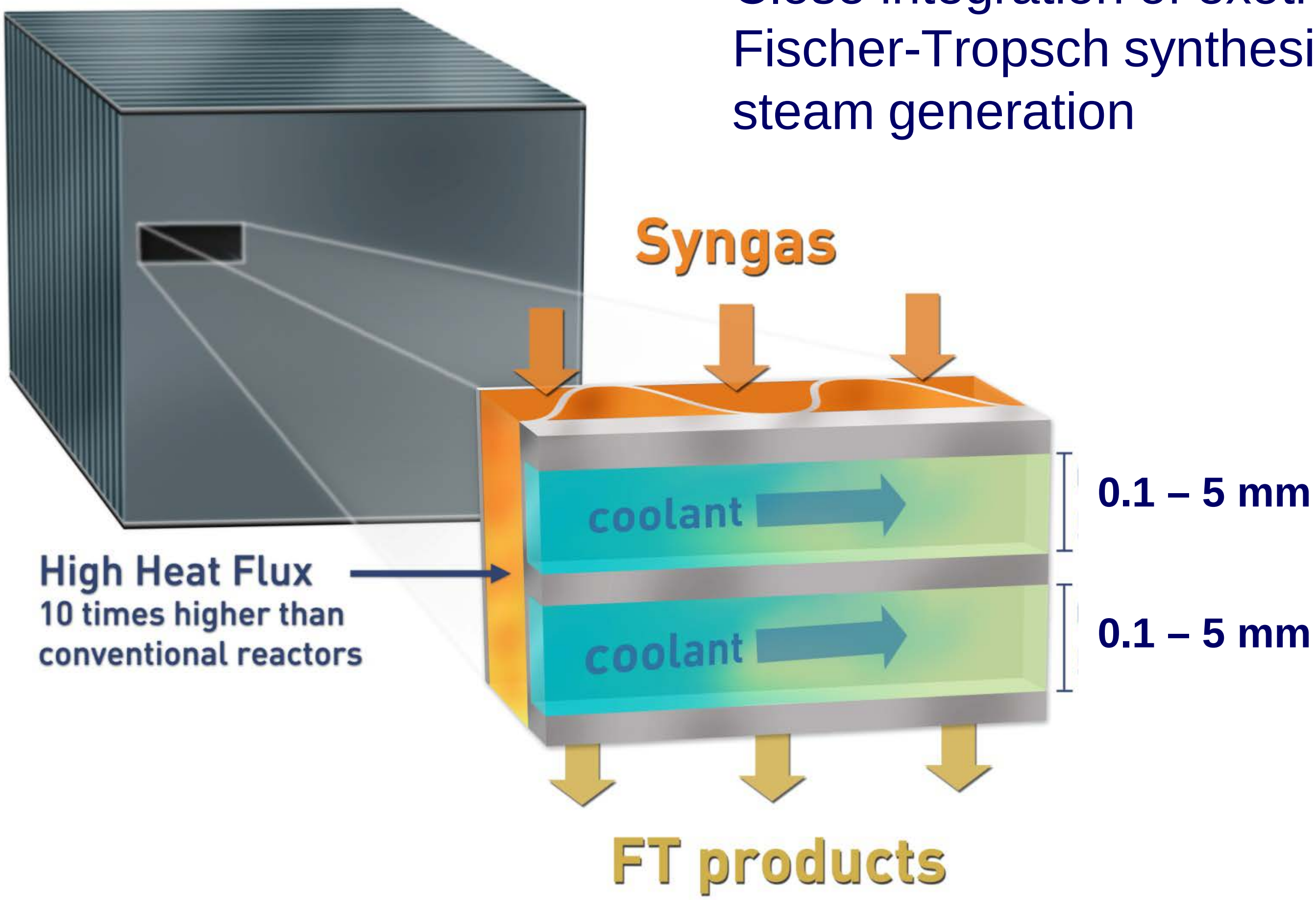
Property	Tubular Fixed Bed	Slurry Bubble Column	Velocys Microchannel
Flow Patterns	Plug flow	Well-mixed	
Reactor Scale-up Methodology	Easy/known	Not well-known	
Heat Transfer Limitations	Very high	Low	
Mass Transfer Limitations	High	Low	
Thermal Stability	Poor	Excellent	
Catalyst Reaction Rate	Low	Moderate	
Reactor Volumetric Production	Low	Low	
Differential Pressure	Moderate	Low	
Gas Recycle Requirements	High	Moderate	
Catalyst Wax Separation	Excellent	Problematic/Difficult	
Catalyst Strength Requirement	Low	High	
Regeneration Equipment	Minimal	Significant	
Regeneration Ease	Difficult	Complicated	
Catalyst Replacement	Offline-slow	On-stream	
On-stream Factor	Low	High	
Feed Poisoning	Local	Global	
Upset Robustness	Low	Generally Good	
Shutdown Robustness	Good	Poor	
Modularization	Low	Low	
Mass Manufacturing Economies	Low-Medium	Poor	
Boiler Feed Water Quality	Low	Low	
Capital Cost per BPD	High	Low (large plants)	

Velocys Microchannel Reactor Basics

- Reactors consist of alternating 2' x 2' process and coolant plates
  - Particulate catalyst poured in downflow process channels
  - Crossflow coolant channels with heat removed by steam generation
- Reactor capacity is a function of number of plates
  - All parts are identical
  - Process and coolant channel dimensions constant
- Catalyst is retained in the reactor exactly as it is in conventional multi-tubular fixed bed reactors
  - Screens on process channel top and bottom
  - Sized appropriately based on catalyst particle size

Velocys Fischer-Tropsch Reactor Core

Close integration of exothermic Fischer-Tropsch synthesis and steam generation



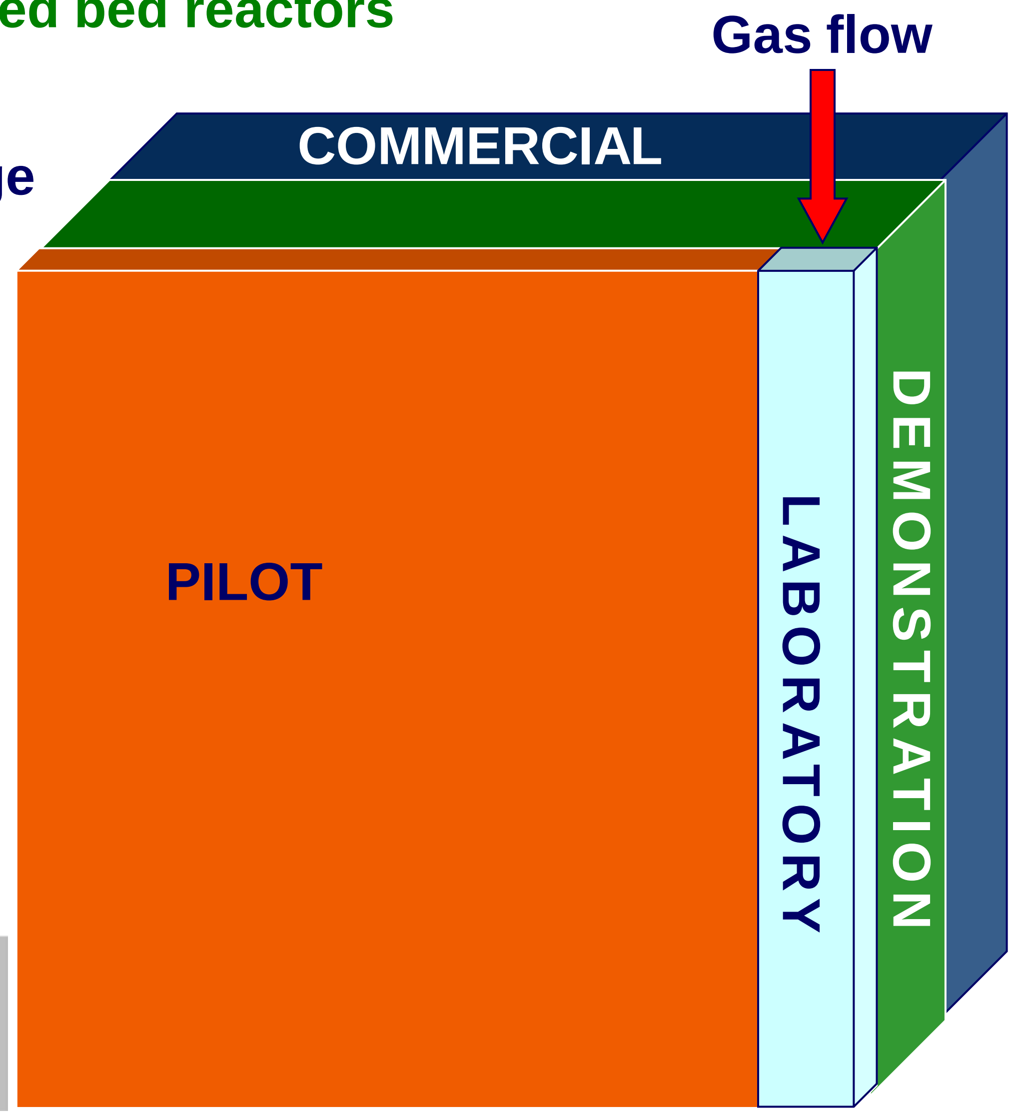
Microchannel Reactor Scale Up

Equivalent to conventional fixed bed reactors

Key dimensions do not change

- **Laboratory reactor**
  Channel dimensions same as commercial reactor
- **Pilot reactor**
  Full size repeating layer
- **Demonstration reactor**
  >1 full size repeating layer
- **Commercial reactor**
  Many full size repeating layers
- **Micro-macro interface** ensures consistent results in pilot and commercial installations

Number of channels increases, size does not



Demonstration & Commercial FT Reactors

2010

2011

2013

0.5 bpd → **50X** → **25 bpd** → **5-8X** → **125-200 bpd**

25 bpd: Full 2’^{3} single core

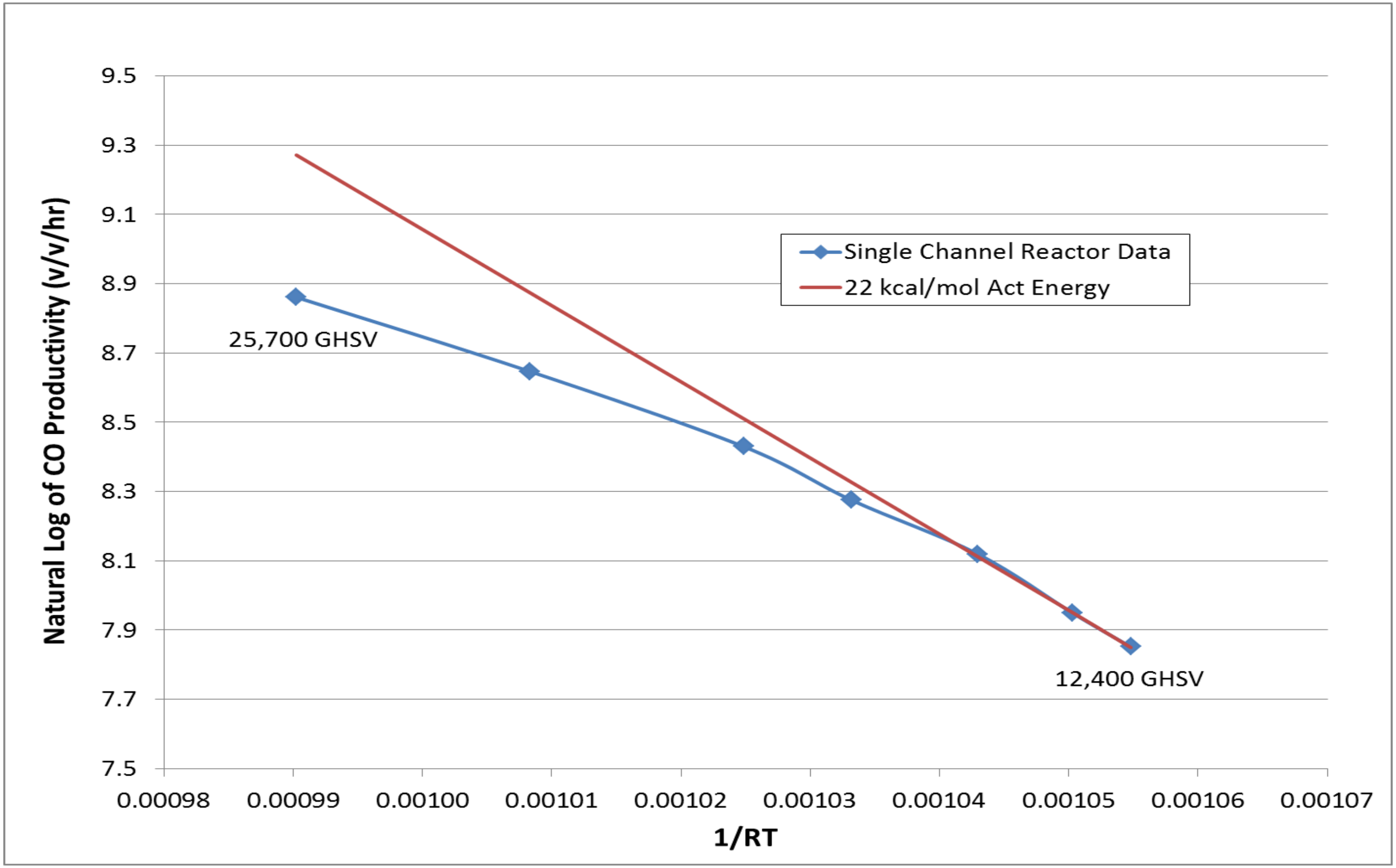
125-200 bpd: Multi-core 4.5 ft D x 13 ft long

Velocys Uses a Particulate Catalyst Loaded into Small Diameter "Tubes" (microchannels)

- Two world class heterogeneous catalyst manufacturers qualified for commercial production
- Approximately 1.5 mt produced 2011
- 1.1 mt single production batch in 3Q 2012
- QA/QC methodology developed
  - Physical/chemical properties well defined
  - Performance predictable based on properties
- Manufacturing capacity sufficient to meet all capacity needs
- **Following results are mostly* based on operations using these commercial catalyst batches**

***Exceptions will be noted**

Velocys Microchannel Reactor is Not Limited By Heat Transfer



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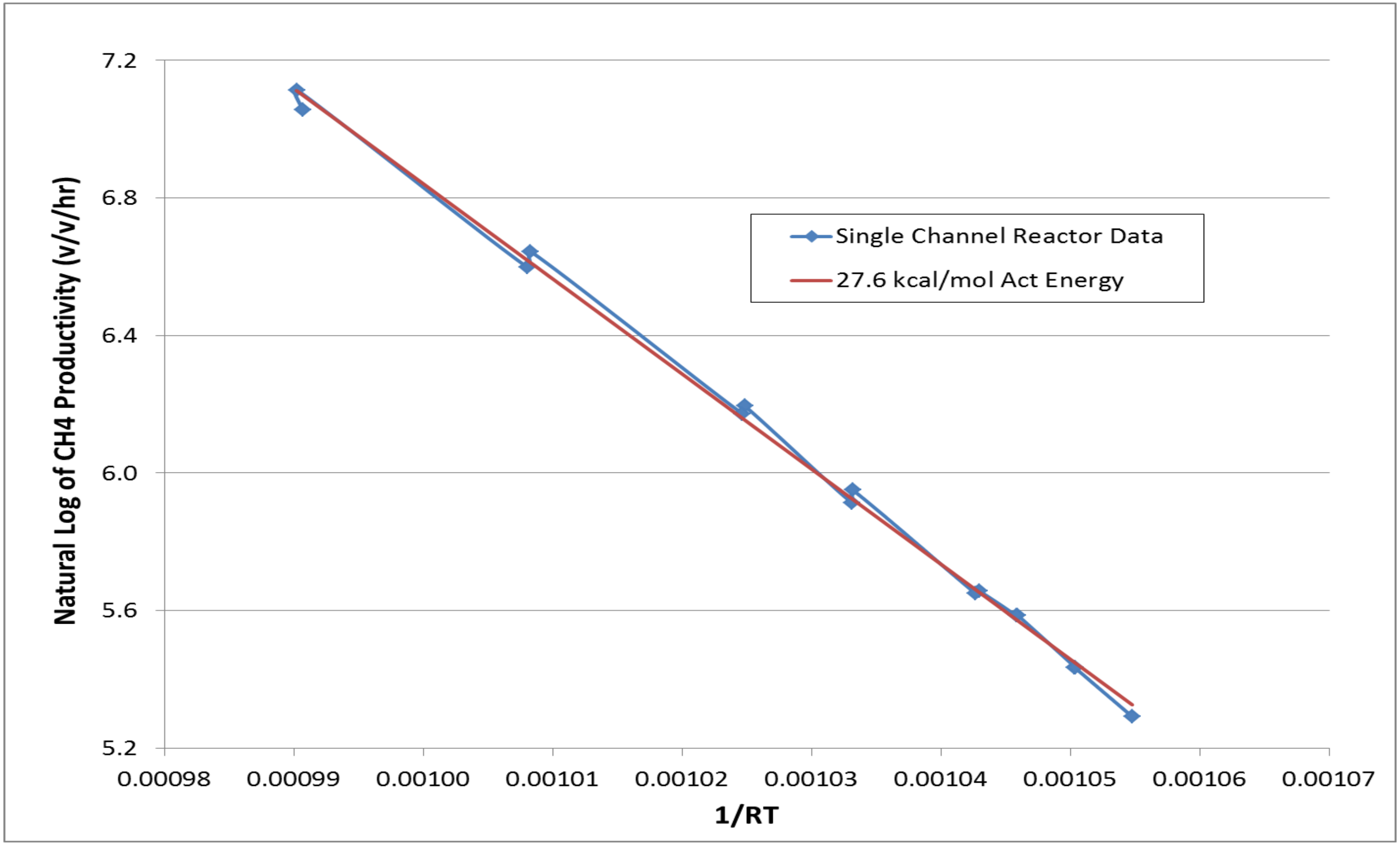
Methane Selectivity Shows No Indication of Significant Hot Spots



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Pilot FT Reactor Thermal Stability Demonstrated at Much Higher Throughputs

Feed Rate [GHSV]	Temperature [°C]	CO Conversion [%]	CH4 Selectivity [%]	Approx. Heat Duty per Channel [W]
12,414	207	74.1	8.7	1.2
17,142	215	72.2	9.5	1.7
24,000	222	71.0	14.3	2.3
36,000	241	70.2	26.5	3.6
42,353	253	71.0	34.8	4.4
51,428	263	69.6	39.9	5.3

- **All operations with 16.5% dilution, H_2:CO = 2, P = 350 psig**
- **Pilot reactor employed slightly less active pre-commercial catalyst**

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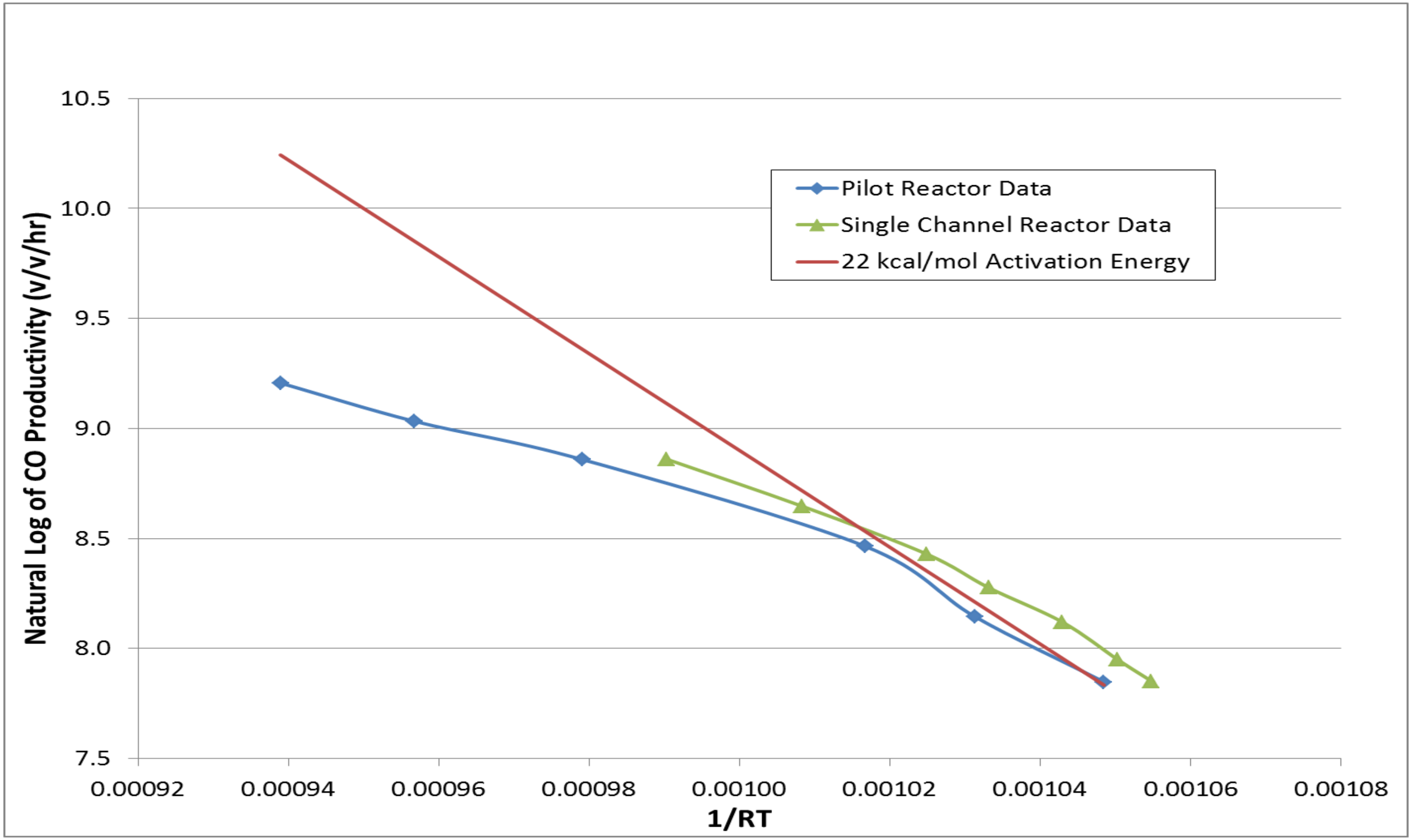
Pilot and Single Channel Reactors Show Nearly Identical Performance – CO Rate



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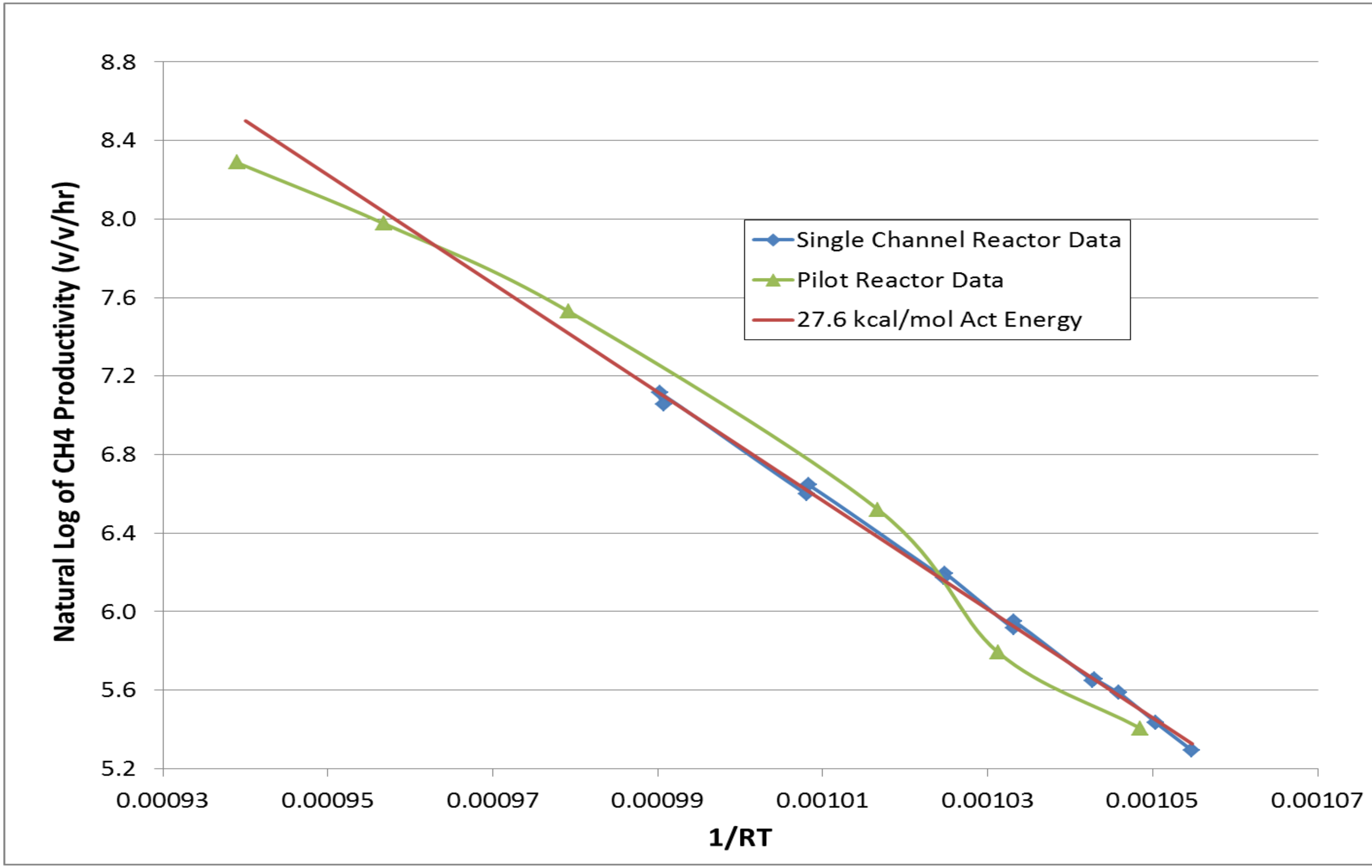
Pilot and Single Channel Reactors Show Nearly Identical Performance – CH_4 Rate



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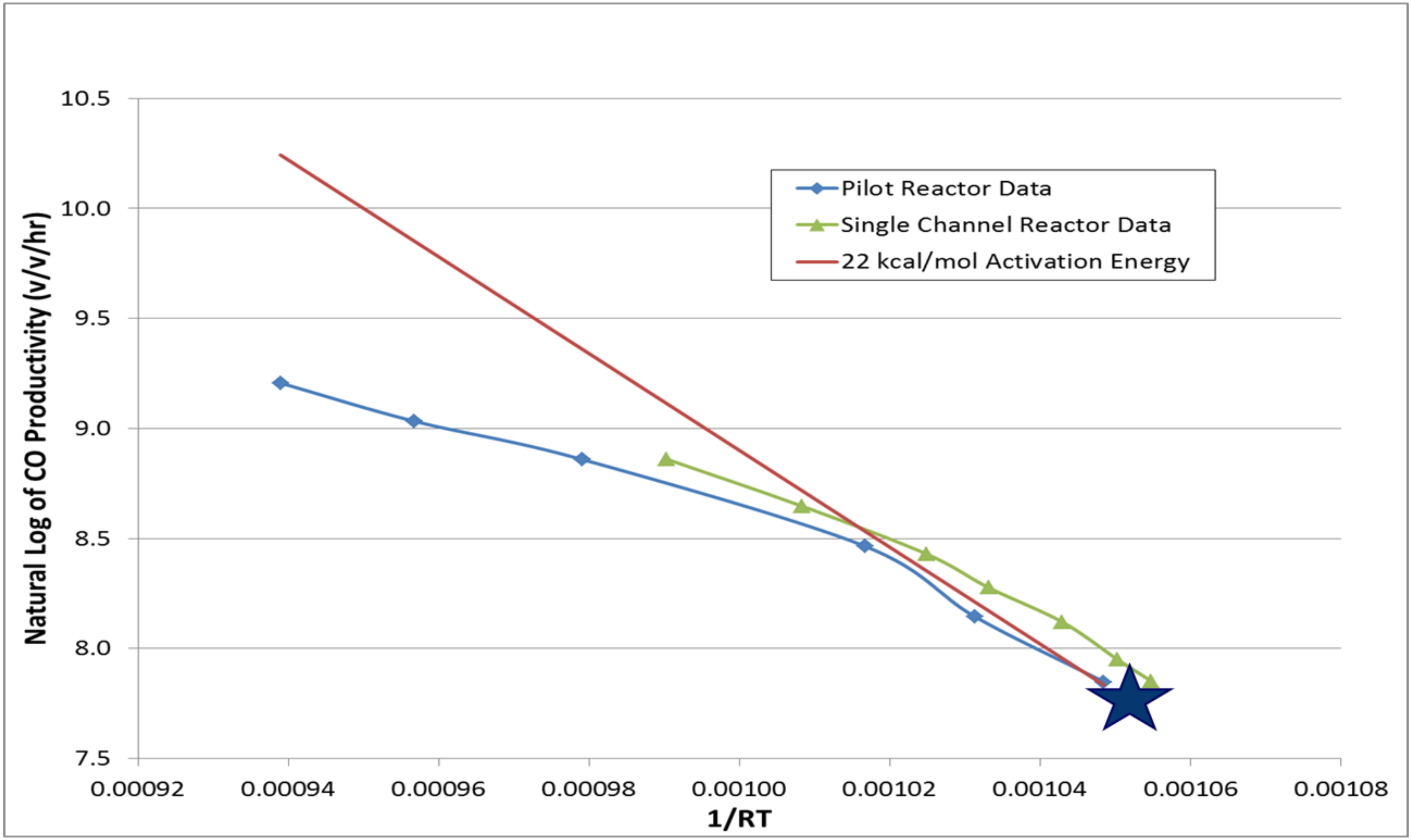
Velocys Standard Commercial Operating Condition is at < 25% of Max Heat Transfer Rate



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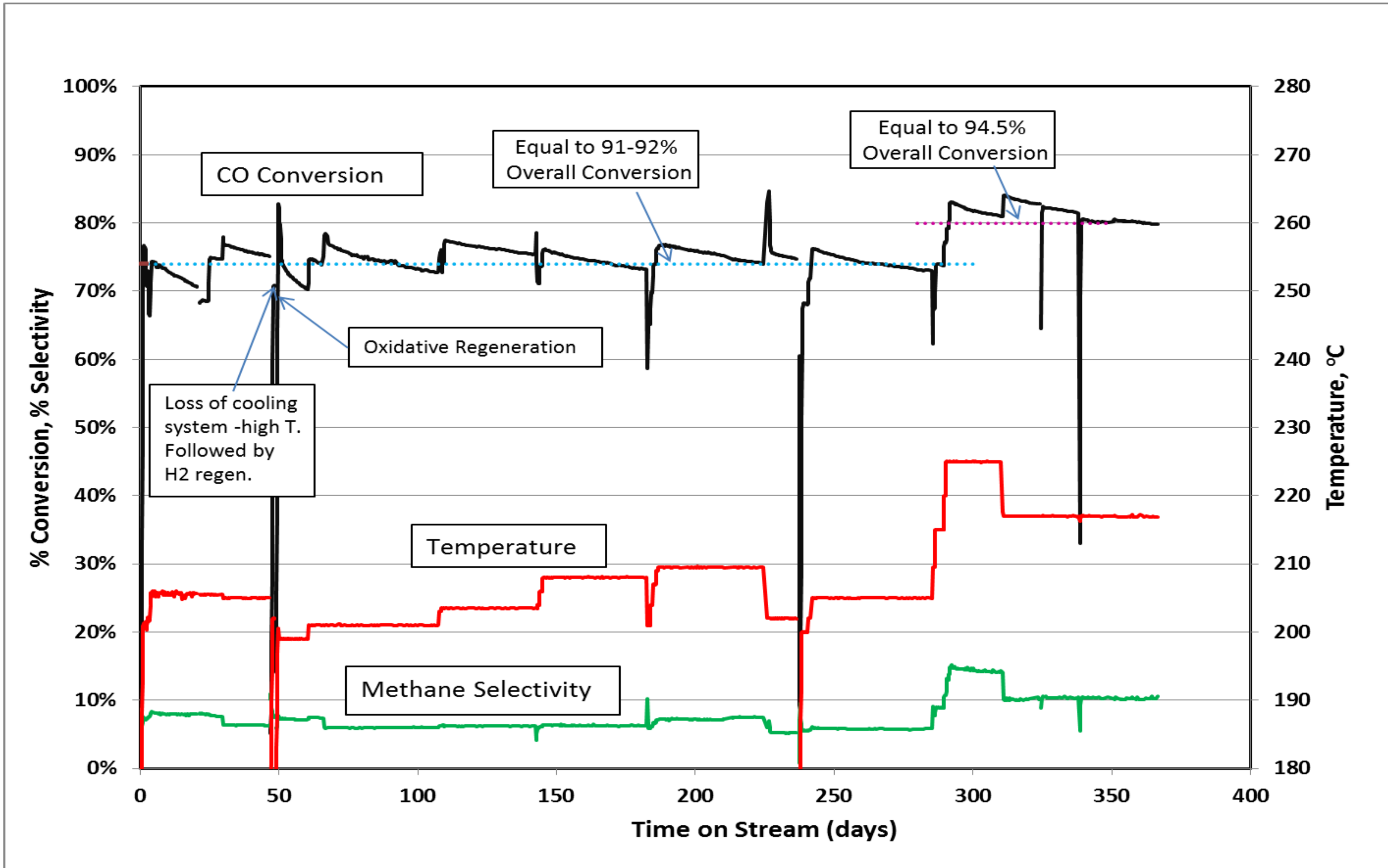
Single Stage With Recycle Results – High Overall Conversions at Commercial Conditions



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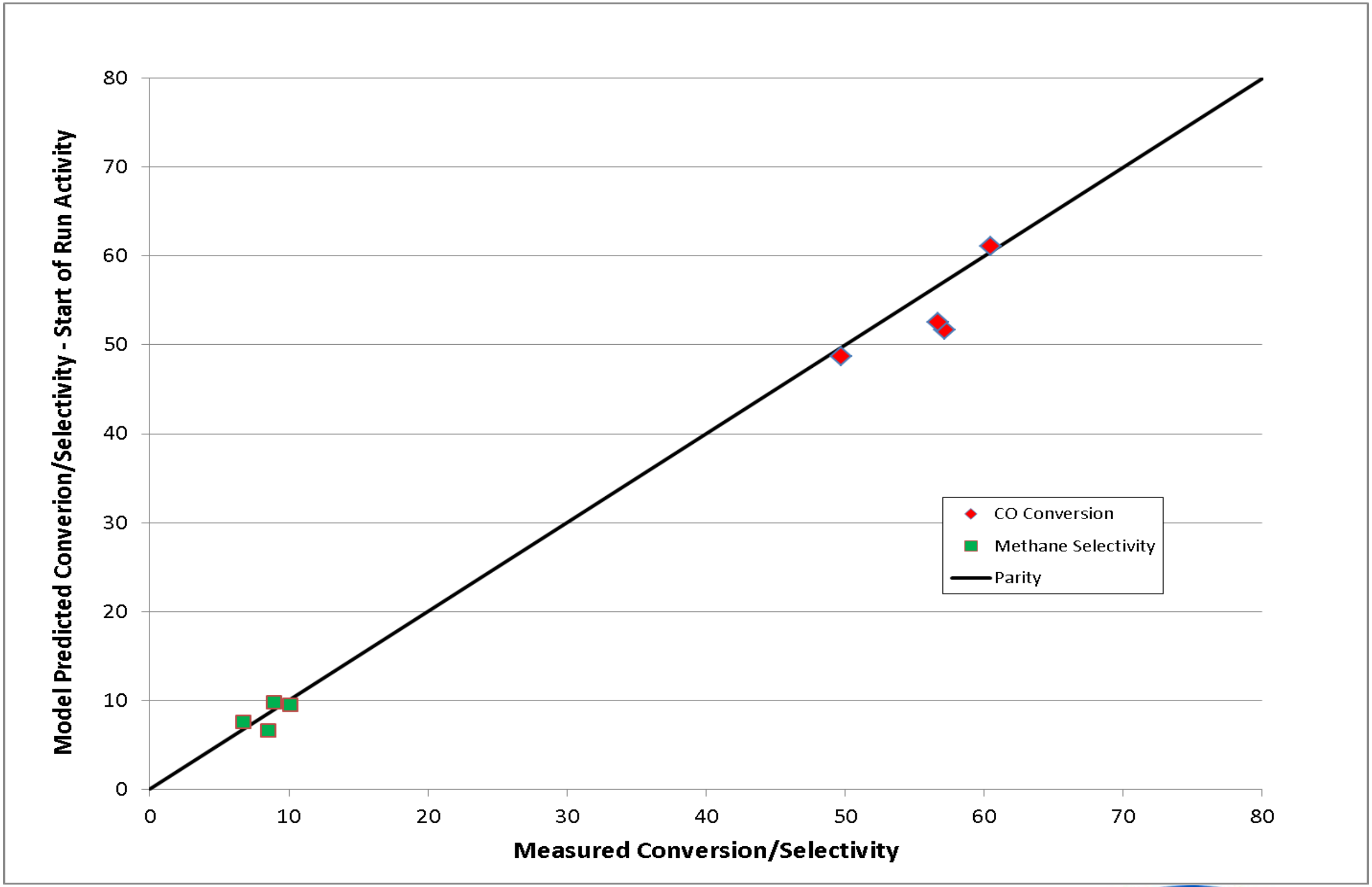
Initial Operating Results of FT Field Demonstration Unit Agree with Lab Experience



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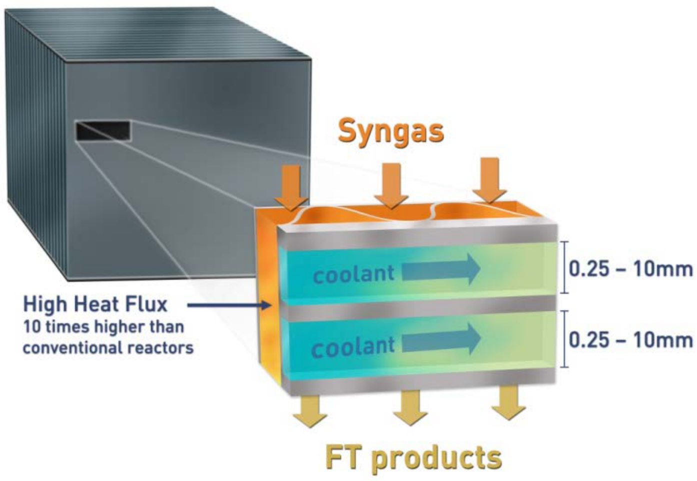
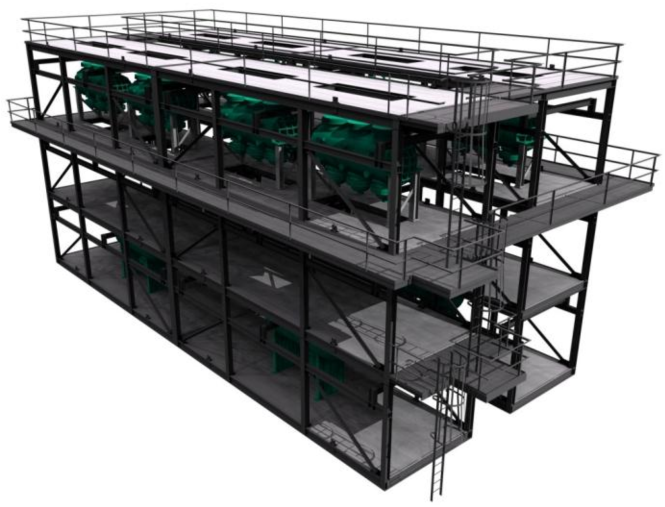
Velocys Microchannel Technology





- Principles of design and operation
  - Particulate catalyst in small channels
  - High catalyst volume fraction (~50%)
  - Syngas downflow, products exit bottom
  - Cross-flow coolant water/steam generation
  - Heat removal by steam generation
- Strong points
  - Isothermal behavior – thermally stable
  - Extremely robust to upsets
  - Strong economy of mass manufacturing
  - Accommodates high activity catalysts
  - Installed spares relatively cheap
  - High on-stream factor
  - Tail gas recycle only to achieve high conversion
  - Extremely high volumetric productivity
  - Ease of modularization

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Velocys Microchannel Technology - Negatives

- Small dimension coolant channels impose boiler feed water specifications equal to a typical syngas generation unit spec
  - BFW must also be filtered
- Small catalyst particles and high gas feed rates make the pressure drop the same as for conventional tubular reactors
- Short “tube” length results in only partial poison guard bed effect

Velocys Microchannel Technology–Implications

- Velocys microchannel technology combines the best of fixed and slurry bubble column reactor performance with very few of the negatives
  - Isothermal performance without catalyst/wax separation issues
  - High on-stream factor without complicated and expensive regeneration unit
  - High upset AND shutdown robustness
  - Very low recycle to fresh feed ratio requirements while achieving high conversion
- Velocys microchannel technology uniquely suitable for plants <15k bpd
  - Mass manufacturing economies
  - Shop fabricated and modularized
  - High productivities at small scales

Velocys Microchannel FT Reactor Score Card

Property	Tubular Fixed Bed	Slurry Bubble Column	Velocys Microchannel
Flow Patterns	Plug flow	Well-mixed	Plug flow
Reactor Scale-up Methodology	Easy/known	Not well-known	Easy/known
Heat Transfer Limitations	Very high	Low	Low
Mass Transfer Limitations	High	Low	Medium
Thermal Stability	Poor	Excellent	Excellent
Catalyst Reaction Rate	Low	Moderate	Very High
Reactor Volumetric Production	Low	Low	High
Differential Pressure	Moderate	Low	Moderate
Gas Recycle Requirements	High	Moderate	Low
Catalyst Wax Separation	Excellent	Problematic/Difficult	Excellent
Catalyst Strength Requirement	Low	High	Low
Regeneration Equipment	Minimal	Significant	Minimal
Regeneration Ease	Difficult	Complicated	Simple
Catalyst Replacement	Offline-slow	On-stream	Offline-rapid
On-stream Factor	Low	High	High
Feed Poisoning	Local	Global	Somewhat Local
Upset Robustness	Low	Generally Good	High
Shutdown Robustness	Good	Poor	Excellent
Modularization	Low	Low	High
Mass Manufacturing Economies	Low-Medium	Poor	Excellent
Boiler Feed Water Quality	Low	Low	Moderate
Capital Cost per BPD	High	Low (large plants)	Low (distributed plants)

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Summary

- Multi-tubular Fixed Bed Reactors
  - Excellent catalyst-wax separation, easily scaled up, simple hardware
  - Thermally unstable, extended down-time or dis-economies of scale
- Slurry Bubble Column Reactors
  - Excellent thermal stability, high on-stream factor, economies of scale
  - Catalyst-wax separation problematic, complicated solids handling
- Velocys Microchannel Reactors
  - Excellent catalyst wax separation and thermal stability
  - Easily scaled up and strong mass manufacturing economies
  - No complicated solids handling
  - High on-stream service factor

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