Energy Efficiency in the Carbon Fiber Conversion Process

Presented at JEC 2012 Paris, France

March 27, 2012 14:30

About Harper

- Headquartered outside of Buffalo, NY
- Established in 1924
- 45,000 ft^2 manufacturing facilities
- 5,500 ft^2 dedicated Technology Center
- Multi-disciplined engineering talent
  - Chemical
  - Ceramic
  - Mechanical
  - Electrical
  - Industrial
  - Systems integration

Harper Technical Profile

Core Skills:

- Scale up of New or Challenging Processes
  - 200 C – 3000 C
  - Atmospherically Controlled
  - Continuous Processing
- Construction Techniques in Metallic > Ceramic > Graphitic
- Integrated Systems Design – Plant Supply
- Complex Flows of Advanced Materials
- Precise Control of Gas - Solid Interactions

Carbon Fiber Market
Advanced Thermal Systems for Fiber Processing

- PAN based C-fiber
- Pitch based C-fiber
- Rayon based C-fiber
- Alternative Precursor Development
- Carbon Fiber Recycling

A Broad Experience Base

in a Range of Carbon Processes

Services to the Carbon Fiber Market

- Equipment Supply (~40 Years)
  - LT Furnaces, HT Furnaces and UHT Furnaces
  - Next-Generation Oxidation Ovens
  - Surface Treatment & Drying
  - Material Mass Transport & Waste Gas Treatment
- Complete System Supply (~15 Years; >10 contracts)
  - Systems Integration and Energy Recovery
- Feasibility Studies & Modeling
- Retrofits, Revamps & Upgrades
- Business Development & Consulting
- Training & Optimizations

Harper International

Presents

Beacon

Creating a Roadmap for Greater Efficiency in Process Integration and Systems Supply

Another innovation from Harper

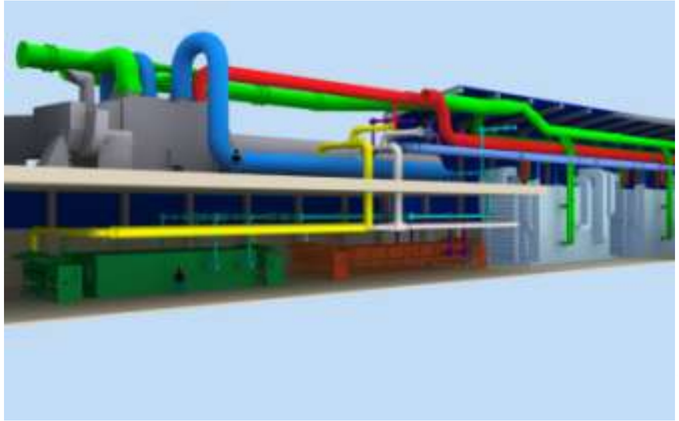
Harper Beacon – Development Rationale

Systems Integration – Historical Perspective:

- Late 1990s — Development of Systems Integration Offerings
- 1998 – 2006 — Execution of First Integrated Production Projects

Carbon Fiber Systems
Scale of Operations

Scale	Size Range (mm Width)	Capacity
Production	1000mm-4200mm	100tpy to more than 4000tpy
Industrial Scale Pilot	300mm-1000mm	20tpy-100tpy



Harper International
CF Line Full Line Scope of Supply

Leaders in the Supply of Complete Carbon Fiber Systems

Harper Beacon – Development Rationale

Systems Integration – Historical Perspective:

• Late 1990s	Development of Systems Integration Offerings
• 1998 – 2006	Execution of First Integrated Production Projects
• 2008 - 2009	Harper Unveils Ox Oven for Energy Recovery Harper Develops Process Based Cost Modeling; Predictive Roadmap for Scale Up; Harper Presents Predictions at InterTech Pira and Composites World (www.harperintl.com/resources)

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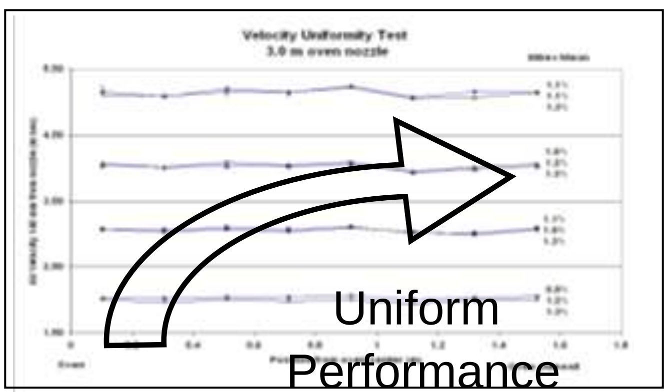
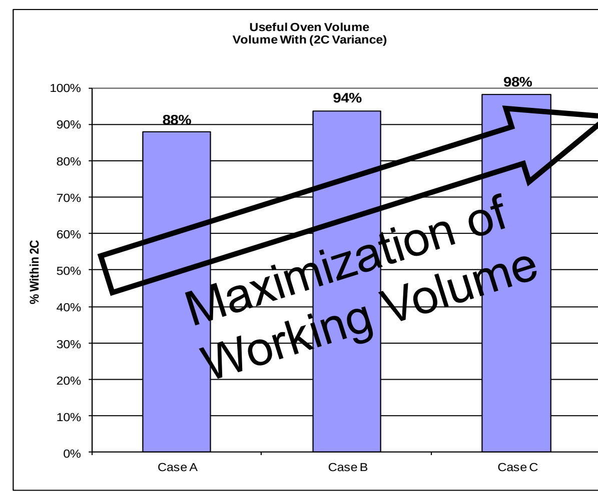
Leading Energy Efficiency in Oxidation

Performance Metrics

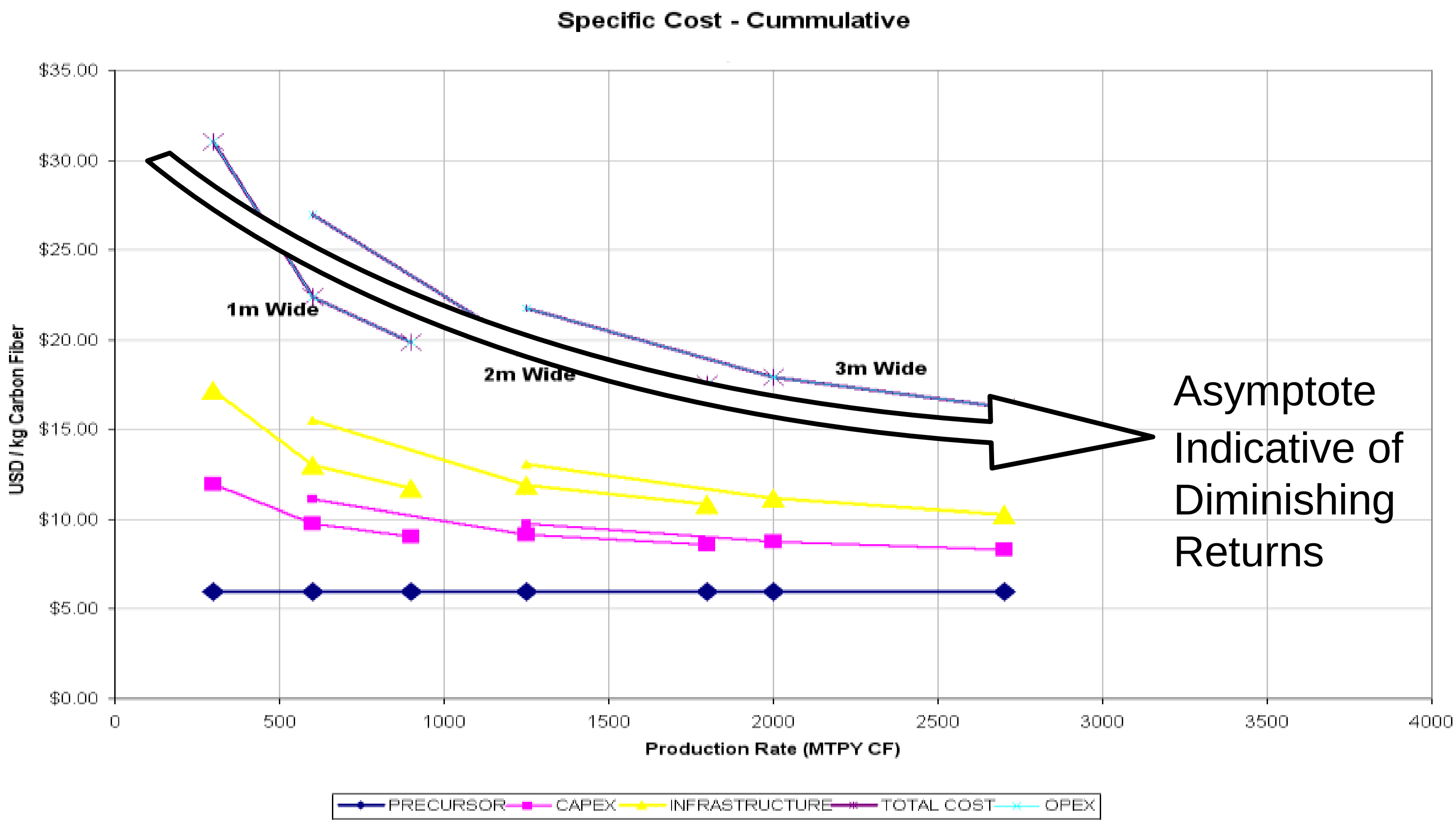
- Temperature (+ or – 2 C)
- **Velocity** **(2x – 3x More**)
- **Seal Performance** **(Absolute)**
- Construction Techniques (Modular)
- Inst. & Control Advances (Flow Control)
- **Heat Reutilization** **> 75%**

(Efficiency, Guaranteed)





Carbon Fiber Business Model & Cost Analysis



Cost Dynamics as a Function of Scale-Up

Harper Beacon – Development Rationale

Systems Integration – Historical Perspective:

- Late 1990s Development of Systems Integration Offerings
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- 2008 - 2009 Harper Unveils Ox Oven for Energy Recovery

  Harper Develops Process Based Cost Modeling;

  Predictive Roadmap for Scale Up; Presents Predictions at InterTech and Composites World
- 2010 Harper Develops MicroLine Product for R&D

  Unveils MicroLine at InterTech Pira
- 2011 Industry Expansions follow Predicted Path

  Single Line Capacities Approach Asymptote

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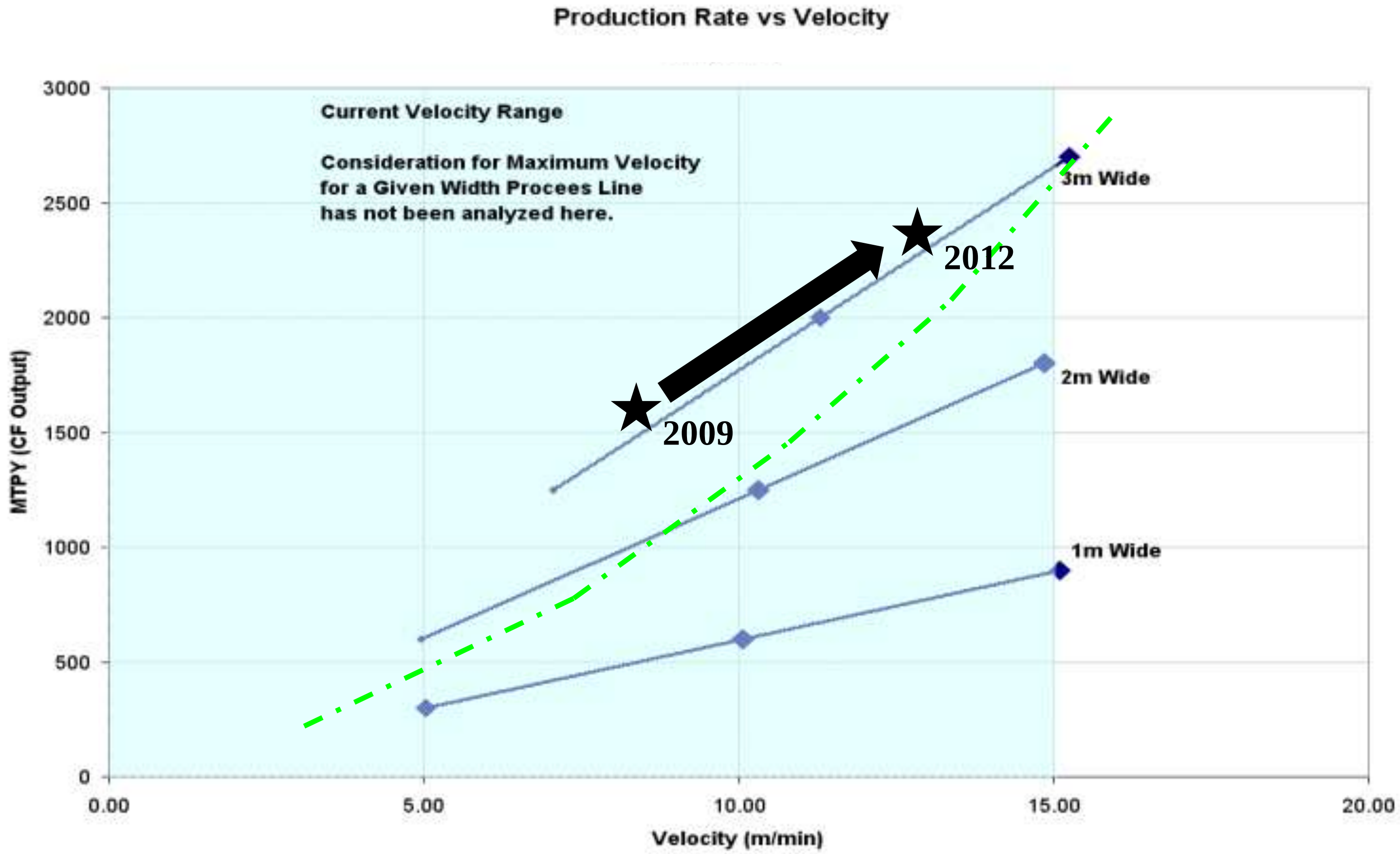
Carbon Fiber Systems
Scale of Operations

Scales	Size Range (mm Width)	Capacity
Production	1000mm-4200mm	100tpy to more than 4000tpy
Industrial Scale Pilot	300mm-1000mm	20tpy-100tpy
Micro Scale (University, Institute)	<100mm	Less than 1tpy

Helping Clients with Carbon Fiber Business Model & Cost Analysis



Capacity Expansion 2011 Based on Faster Line Velocities;
Higher Production Rates from 3m Single Muffle

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Harper Beacon – Development Rationale

Systems Integration – Historical Perspective:

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Predictive Roadmap for Scale Up; Presents Predictions at InterTech and Composites World

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Unveils MicroLine at InterTech Pira

- 2011 Industry Expansions follow Predicted Path

Single Line Capacities Approach Asymptote

- 2012 Develop Tools Needed for Higher Efficiency and Consumer Market Impact;

2012 Harper Beacon is Launched

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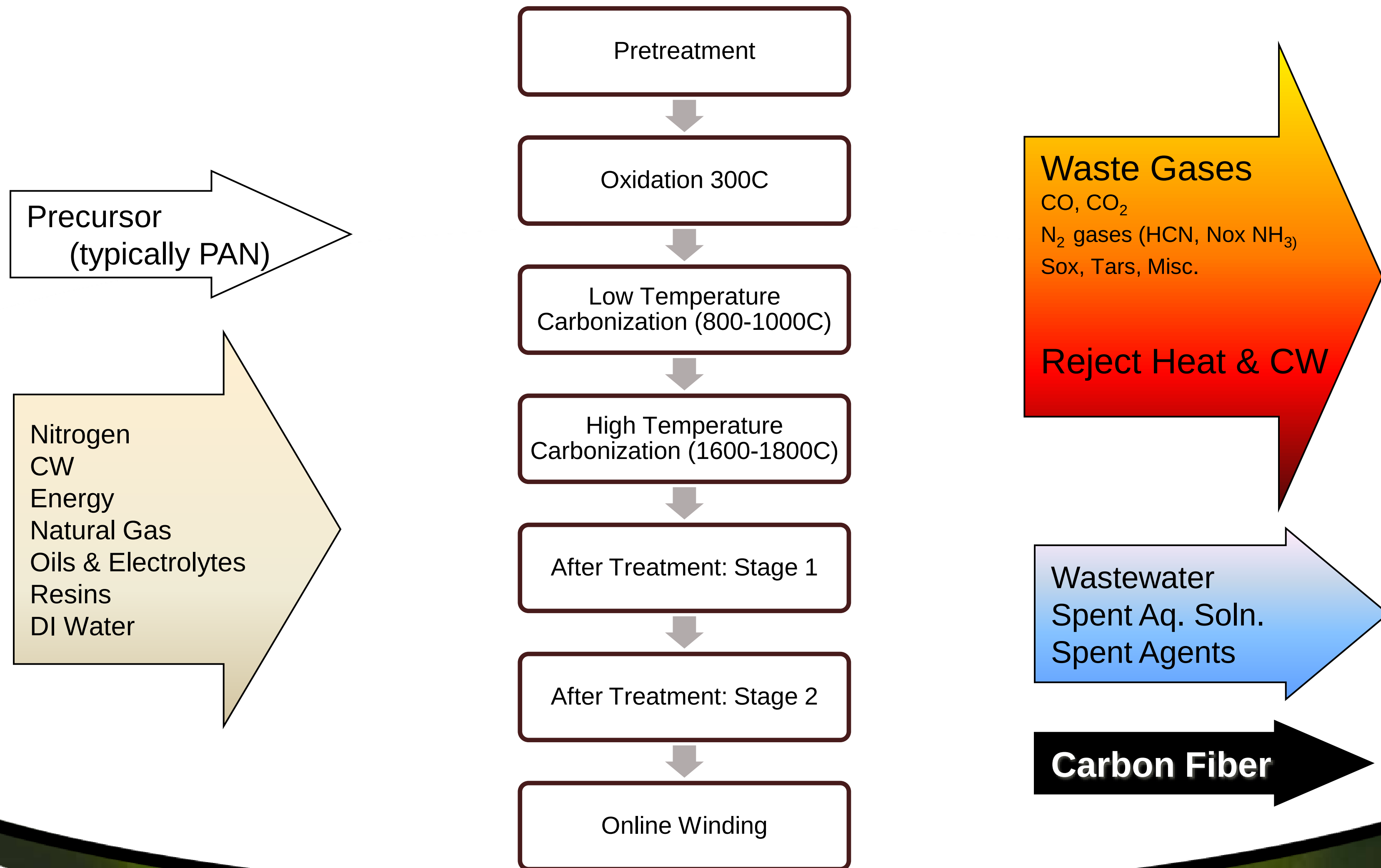
Challenges:

1) Diminishing Returns: The Opportunity for Increased Efficiency In Scale is Declining
2) Consumer Market Adoption: At Higher Volumes a Better Understanding of Environmental Impact is Required (Automotive)

Opportunities:

1) Create Tool to Rank Environmental Impact of Various Production Schemes
2) Understand Impact of Scale and Configuration on Environmental as well as Cost
3) Use the Tool to Identify Opportunities for Greater Total Efficiency

Carbon Fiber Conversion Process
Beacon Evaluates Impact of Total Operations



Harper Beacon: Inputs

Harper's

Process-Based Cost Model

82 Variable Cost Model

Cost Factors:

41 Variables

in Core Cost Model

Line Sizing Factors:

41 Variables

in Core Cost Model

Harper Beacon: Inputs

Harper's

Beacon
Model

70
Variable

Beacon
Model

Waste Gas Treatment Configuration:

15 Variables

Energy Source:

15 Variables

Theoretical Factors:

10 Variables

Environmental Losses:

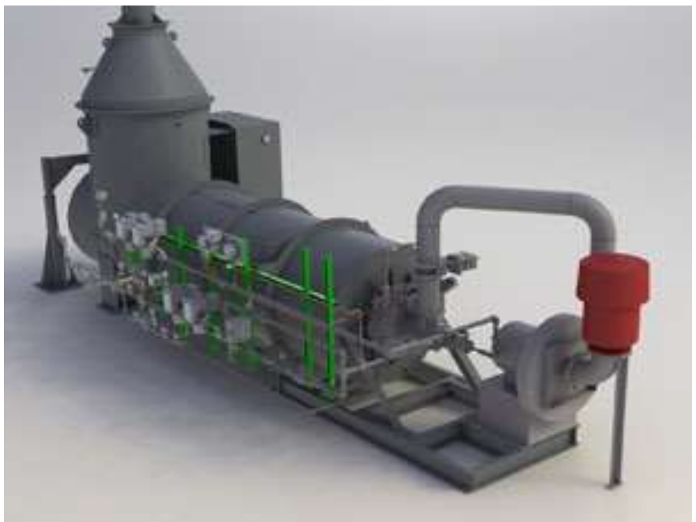
30 Variables

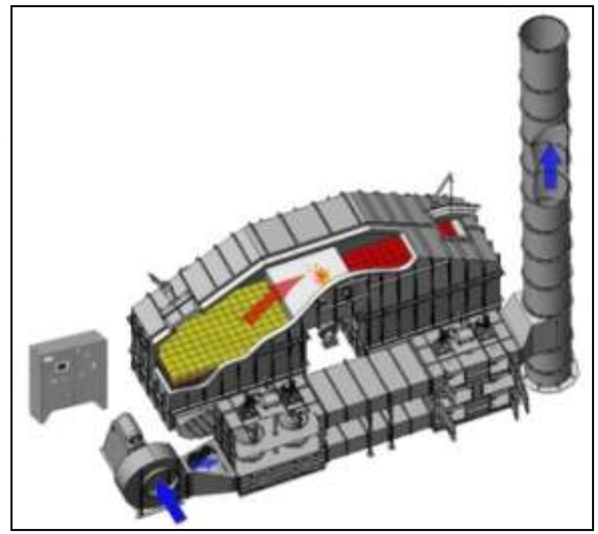
Beacon Comprehensively Evaluates 152 Variables

Waste Gas Treatment Systems

Beacon Evaluates Impacts of System Selection:

- Direct Fired TO
- Multi-Stage Direct Fired TO
- Regenerative TO





Images Courtesy of ANGUIL Environmental

Beacon Quantifies and Evaluates:

Heat Recovery
NOx Generation
Environmental Losses

Carbon Dioxide Emission
HCN Destruction Efficiency
all as a Functions of Scale

Waste Gas Treatment Systems: Influents

Sources of Off Gas - Categories:

1. Process Off Gases

   Oxidation Oven Thermal Chamber Exhaust

   LT Muffle Exhaust

   HT Muffle Exhaust

2. Vent Hood Off Gases

   Collection at Oxidation Oven Slots (Seal Design, Vestibules or Hoods)

   Hoods at LT Muffle and HT Muffle; Entrance and Exit

3. Auxiliary Off Gases

   Collection at Oxidation Oven Slots (Seal Design, Vestibules or Hoods)

   Dryer Exhaust; Hoods at Pretreatment, Surface Treatment

4. General Plant HVAC

5. MCC, Electrical & Control Room HVAC

Waste Gas Treatment Systems: Effluents

Typical Emission Limits:

Total organic C	< 20 - 50	mg/Nm^3
CO	< 100 - 200	mg/Nm^3
NOx	< 200	mg/Nm^3
SOx	<100 - 200	mg/Nm^3
HCN	< 2 - 5	mg/Nm^3
NH3	< 30	mg/Nm^3
Particulates, Dust	< 100	mg/Nm^3
TAR	< 50	mg/Nm^3

Regenerative Thermal Oxidizer

Direct Fired Thermal Oxidizer

Waste Gas Treatment Systems: Effluents

Hydrogen Cyanide (HCN)

- Immediately Dangerous to Life & Health

Silicone

- Will convert to Silica (SiO_2)

Nitrogen Oxides (NO_X)

- Green House Gas Emissions

Carbon Dioxide (CO_2)

- From Natural Gas Combustion and From Waste Gas Abatement

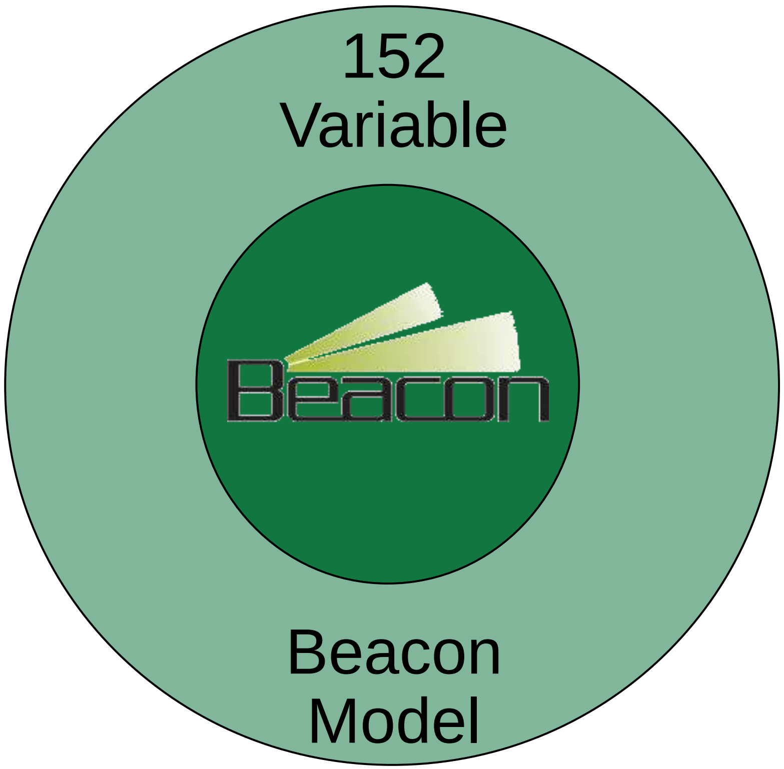
Tar, Hydrocarbons & Ammonia

Sulfur Oxides (SOX) & Other Species

- Concern for Alternative Precursors

CO2, NOx, HCN and NH3 Modeled With Beacon

Harper Beacon: Outputs
Quantifies Environmental and Energy Efficiency



Cost Model Outputs:

CAPEX and OPEX Per Unit Operation for Various Line Configurations.

Outputs Tailored to Specific Site Conditions and Client Circumstances

Carbon Footprint:

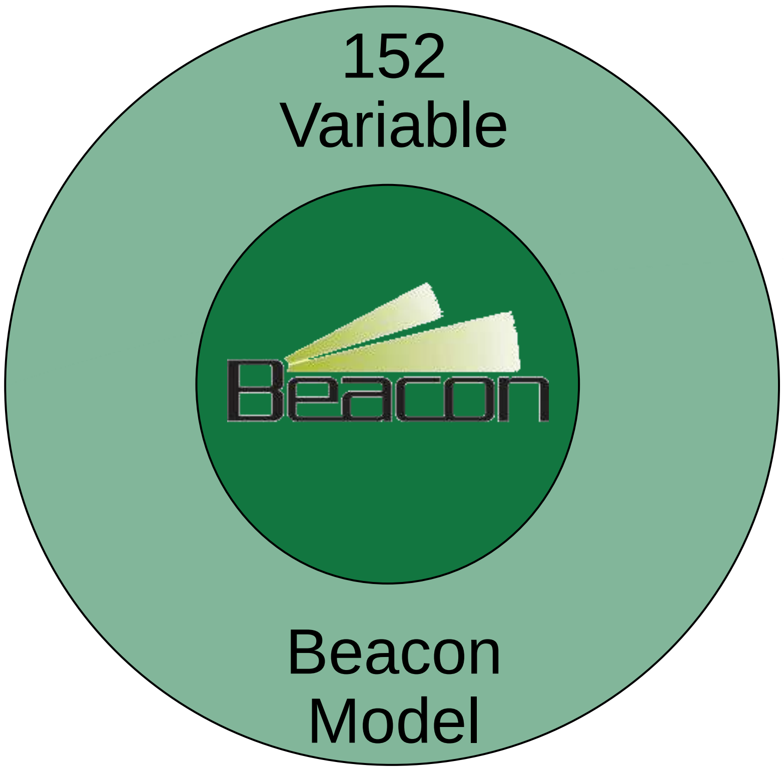
kg/hr of Carbon Dioxide Per kg of CF

Compares to Theoretical Minimum as Benchmark of Efficiency

Comprehensive Function

For a Full List of Capabilities Consult Harper

Harper Beacon: Outputs
Quantifies Environmental and Energy Efficiency



Nitrogen Oxides Emissions:

kg/hr of Nitrogen Oxides Per kg of CF

Varies with Selection of Waste Gas Abatement and Line Configuration

Impact of HCN Destruction:

CAPEX, OPEX and Environmental Impacts of Achieving Lower Levels of HCN.

Evaluate Trade of of Lower HCN and Higher CO2

Thermal Losses:

kWh of Losses as a function of Scale and Operating Paramenters.

Allows for Quantification of Anticipated Thermal Losses and Design Optimization

For a Full List of Capabilities Consult Harper

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Carbon Dioxide Emissions:

- Expressed in total kg/hr of CO_2 Emitted and kg/hr of CO_2 Per kg of CF
- Compare to Theoretical Minimum. Baseline Value based on:
    - Carbon Recovery of Feedstock
    - Specific Heat to Reach Process Temperatures
- Comparison of Carbon Emission to Theoretical Limit Provides a Metric for Optimization and Continued Process Refinement

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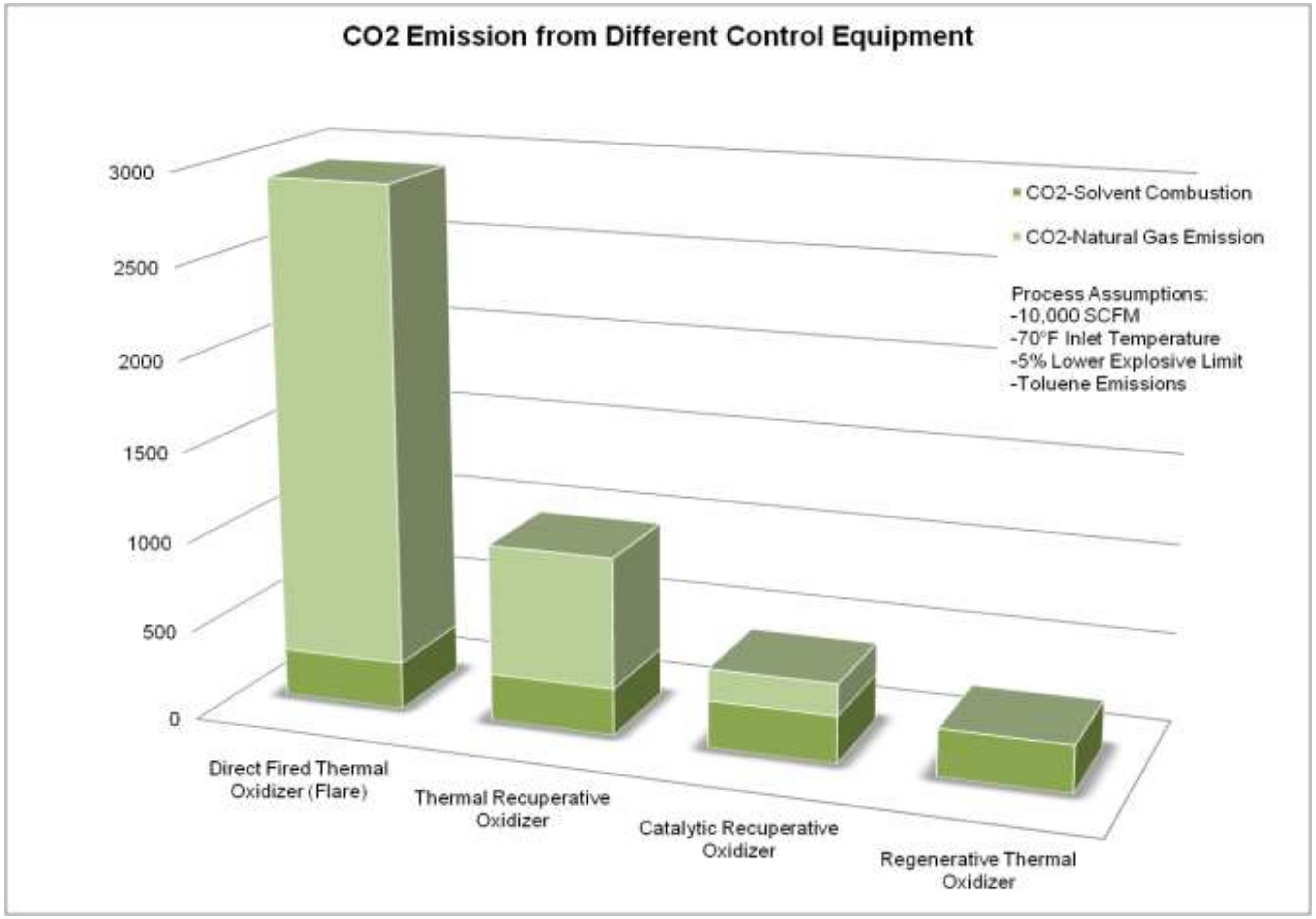
Carbon Dioxide Emissions:



Courtesy of ANGUIL Environmental

Harper Thanks Anguil for Support of Beacon

ANGUIL ENVIRONMENTAL SYSTEMS, INC.

Innovative Air Pollution Control Solutions

- Over 35 Years of Experience in the Oxidizer Industry and 1,700 Installations
- Numerous Installations on Carbon Fiber Emissions Using Various Oxidizer Technologies
- Fabrication, Installation and Service Capabilities in Asia, Europe and North America
- Financially Sound Supplier Focused on Engineered Solutions for Emission Abatement

www.anguil.com

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Harper International
Thanks You for Your Attention

Visit Harper at Booth T51

Learn More About Beacon at *www.harperbeacon.com*

Contact us at *info@harperintl.com* or *rblackmon@harperintl.com* to schedule an evaluation and learn how Beacon can help you along the path to efficiency.

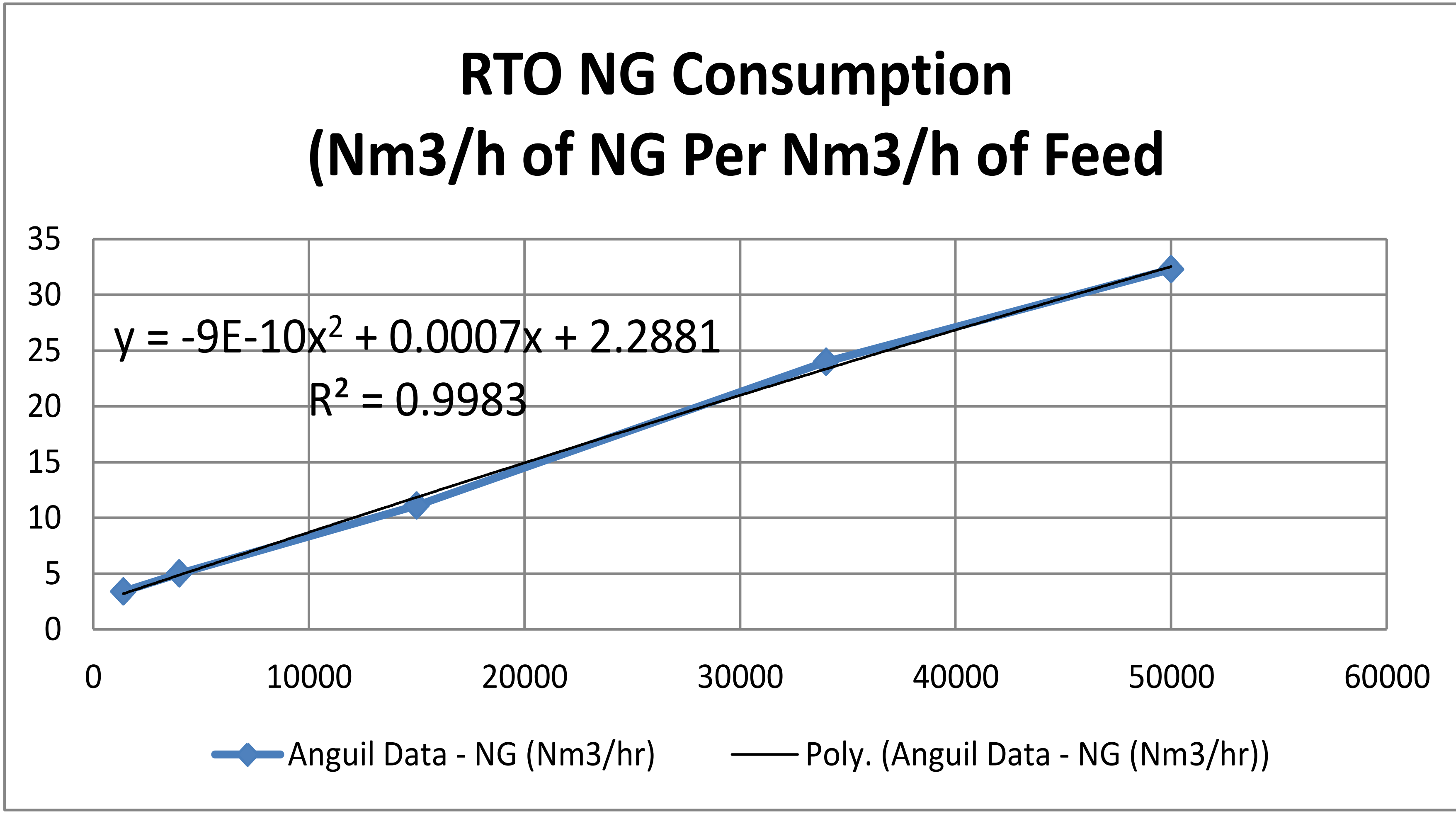
Harper International Presentation
JEC 2012, March 27, 2012 14:30

Technical Appendix

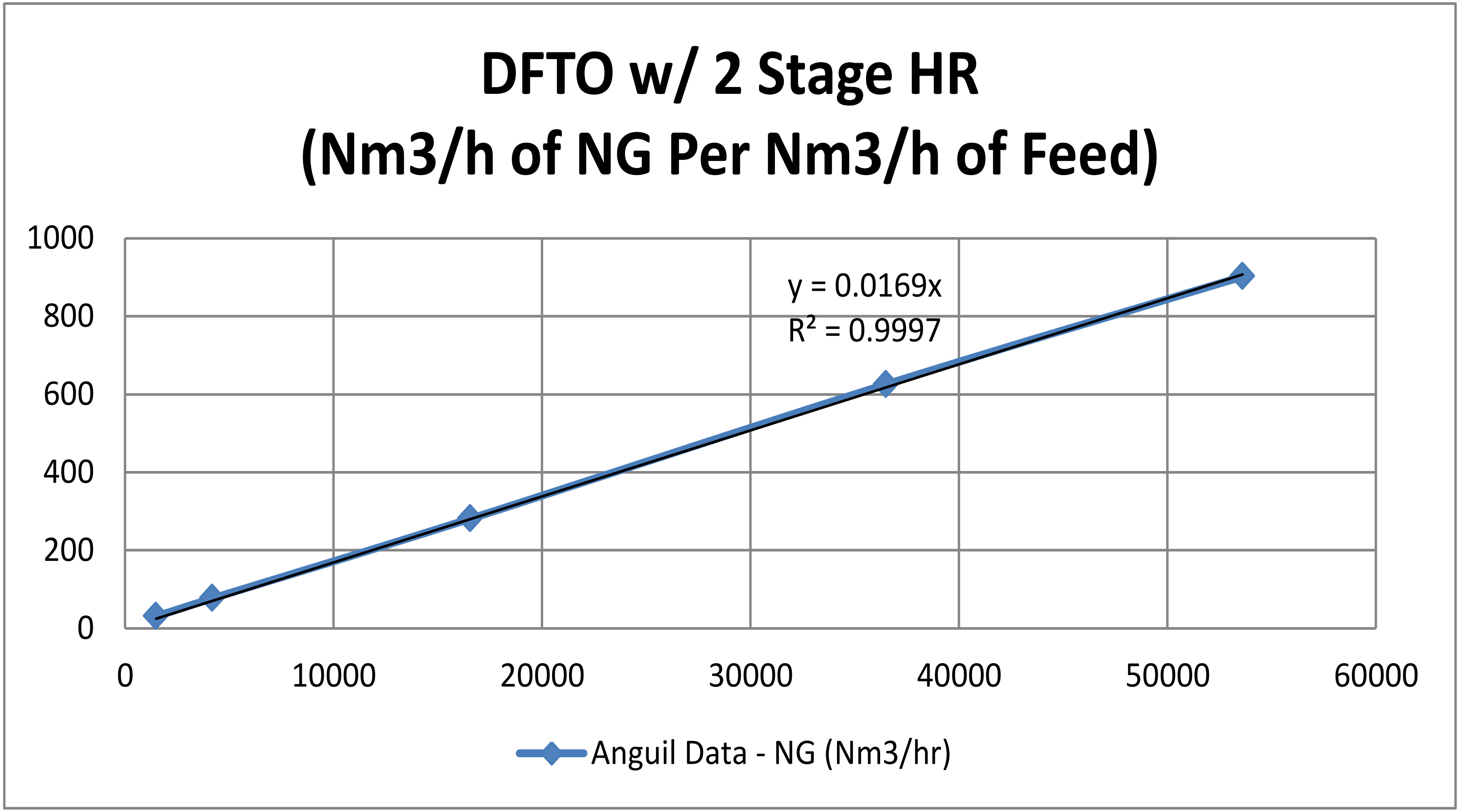
Emissions Model Outputs

Sample Modeling Inputs

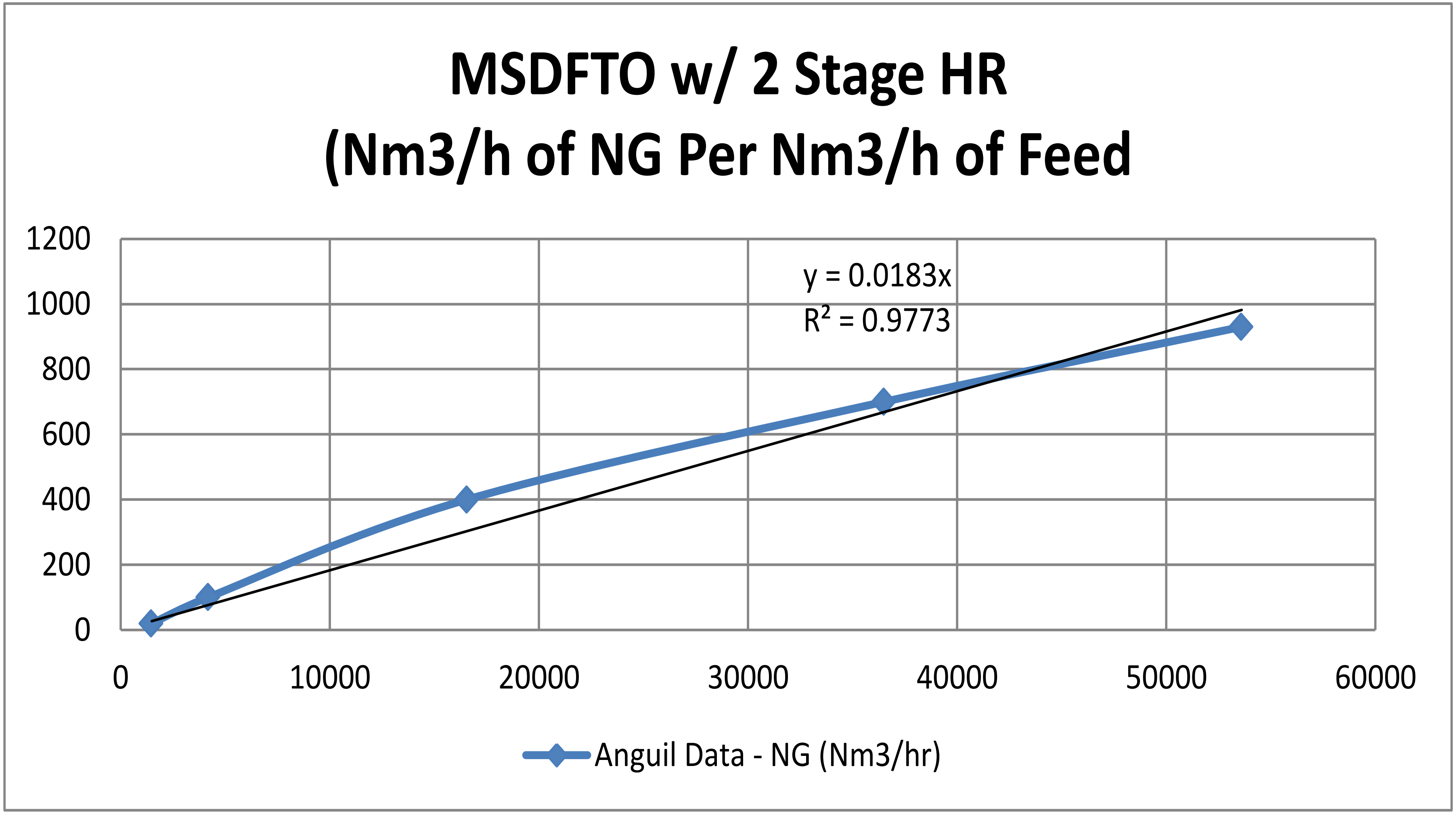
Beacon Model Emissions Modeling



Beacon Model Emissions Modeling



Beacon Model Emissions Modeling



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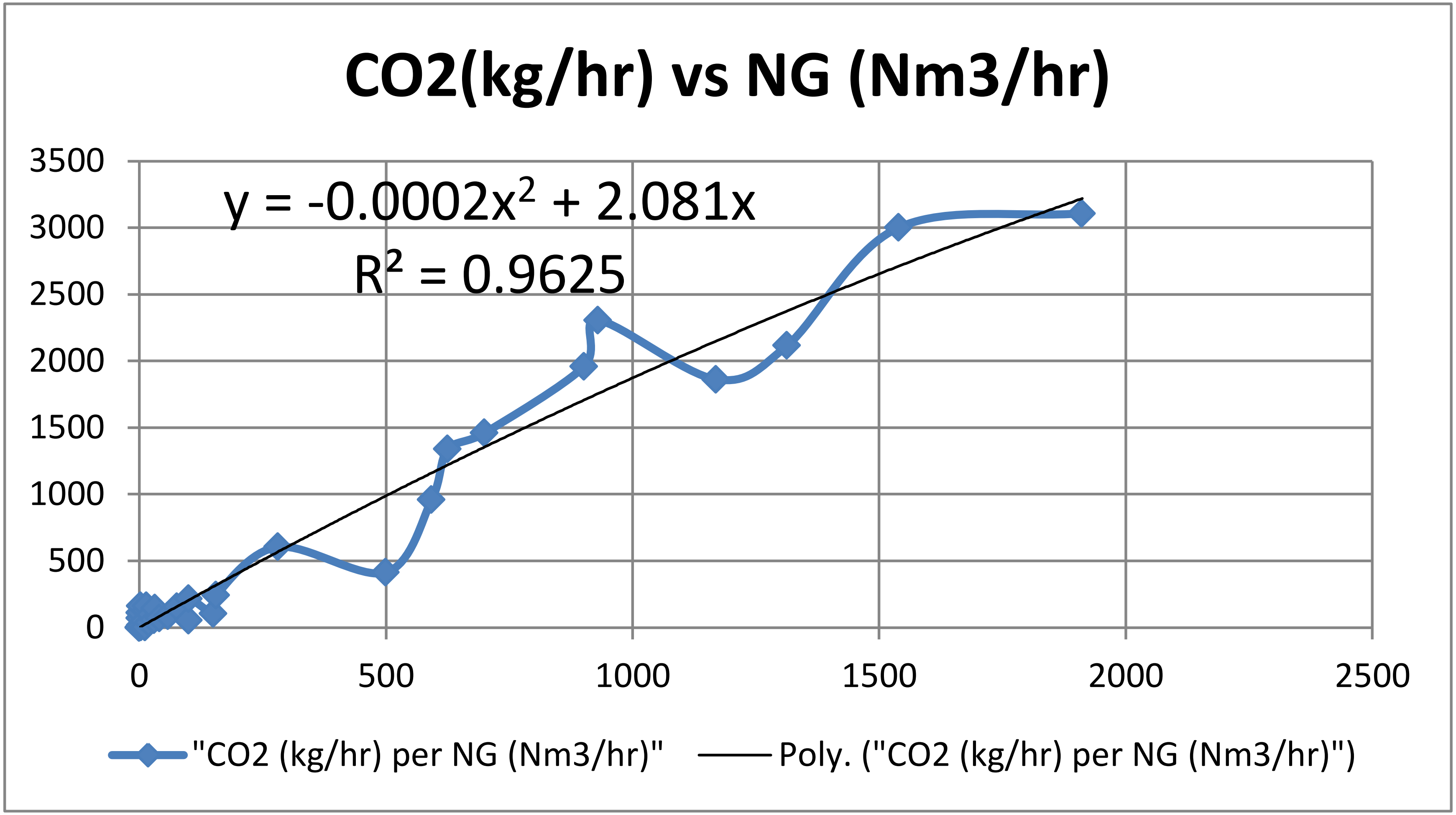
Beacon Model Emissions Modeling



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Emissions Model Outputs

Sample Results from Beacon Model
www.harperbeacon.com

Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		1	2	3	4	5	6
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	3,000mm Wide	3,000mm Wide	3,000mm Wide	1,750mm Wide	3,000mm Wide	3,000mm Wide
Annual Capacity	TPY	2,250 TPY Line	1,500 TPY Line	1,000 TPY Line	1,000 TPY Line	2,250 TPY Line	2,250 TPY Line
Waste Gas Configuration		TOX2 RTO	TOX2 RTO	TOX2 RTO	TOX2 RTO	TOX1	TOX2 RTO
Het Recovery Used	?	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY	
Theoretical Minimum Power Input	kWh Per kg CF	4.55	5.23	6.07	4.99	4.55	4.55
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.3	2.5	2.6	2.4	2.3	2.3
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	312.5	208.3	138.9	138.9	312.5	312.5
Operating Power Input	kWh Per kg CF	27.3	31.3	34.0	37.8	23.0	43.8
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	9.7	10.9	11.9	12.5	12.6	12.7
Operating Thermal Losses	kWh Per kg CF	10.1	10.9	11.7	12.1	10.2	11.0
Operating Total CO2 Emission	kg/hr CO2	3039.3	2274.6	1652.6	1749.3	3949.5	3972.0
CAPEX	USD $ / kg CF	$2.18	$2.89	$3.73	$2.47	$2.33	$2.17
OPEX	USD $ / kg CF	$6.27	$7.81	$9.85	$8.37	$6.64	$7.43

Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		7	8	9	10	11	12
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	1,750mm Wide	3,000mm Wide	3,000mm Wide	3,000mm Wide	3,000mm Wide	3,000mm Wide
Annual Capacity	TPY	750 TPY Line	2,250 TPY Line	1,500 TPY Line	1,500 TPY Line	1,500 TPY Line	1,000 TPY Line
Waste Gas Configuration		TOX2 RTO	TOX1 TOX2	TOX1	TOX1 TOX2	TOX2 RTO	TOX1
Het Recovery Used	?	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY		HEAT RECOVERY
Theoretical Minimum Power Input	kWh Per kg CF	5.53	4.55	5.23	5.23	5.23	6.07
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.5	2.3	2.5	2.5	2.5	2.6
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	104.2	312.5	208.3	208.3	208.3	138.9
Operating Power Input	kWh Per kg CF	37.3	25.6	26.3	29.3	47.8	28.4
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	12.7	12.8	13.8	14.0	14.1	14.7
Operating Thermal Losses	kWh Per kg CF	12.3	10.3	11.0	11.1	11.7	11.9
Operating Total CO2 Emission	kg/hr CO2	1324.5	4024.3	2878.3	2929.1	2940.8	2048.3
CAPEX	USD $ / kg CF	$2.95	$2.38	$3.05	$3.12	$2.88	$3.92
OPEX	USD $ / kg CF	$9.54	$6.77	$8.15	$8.29	$8.97	$10.15

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Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		13	14	15	16	17	18
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	3,000mm Wide	1,750mm Wide	1,750mm Wide	3,000mm Wide	1,750mm Wide	1,750mm Wide
Annual Capacity	TPY	1,000 TPY Line	1,000 TPY Line	750 TPY Line	1,000 TPY Line	1,000 TPY Line	750 TPY Line
Waste Gas Configuration		TOX1 TOX2	TOX1	TOX1	TOX2 RTO	TOX1 TOX2	TOX1 TOX2
Het Recovery Used	?	HEAT RECOVERY	HEAT RECOVERY	HEAT RECOVERY		HEAT RECOVERY	HEAT RECOVERY
Theoretical Minimum Power Input	kWh Per kg CF	6.07	4.99	5.53	6.07	4.99	5.53
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.6	2.4	2.5	2.6	2.4	2.5
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	138.9	138.9	104.2	138.9	138.9	104.2
Operating Power Input	kWh Per kg CF	31.8	32.9	32.0	50.5	35.7	35.1
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	15.0	15.1	15.2	15.2	15.4	15.4
Operating Thermal Losses	kWh Per kg CF	12.0	12.3	12.4	12.6	12.3	12.5
Operating Total CO2 Emission	kg/hr CO2	2084.1	2110.4	1589.6	2120.1	2140.9	1614.4
CAPEX	USD $ / kg CF	$4.00	$2.64	$3.14	$3.72	$2.71	$3.23
OPEX	USD $ / kg CF	$10.30	$8.65	$9.79	$11.01	$8.78	$9.93

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Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		19	20	21	22	23	24
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	1,750mm Wide	1,750mm Wide	3,000mm Wide	1,750mm Wide	3,000mm Wide	3,000mm Wide
Annual Capacity	TPY	1,000 TPY Line	750 TPY Line	2,250 TPY Line	500 TPY Line	2,250 TPY Line	1,500 TPY Line
Waste Gas Configuration		TOX2 RTO	TOX2 RTO	TOX1 TOX2	TOX2 RTO	TOX1	TOX1 TOX2
Het Recovery Used	?				HEAT RECOVERY		
Theoretical Minimum Power Input	kWh Per kg CF	4.99	5.53	4.55	6.44	4.55	5.23
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.4	2.5	2.3	2.7	2.3	2.5
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	138.9	104.2	312.5	69.4	312.5	208.3
Operating Power Input	kWh Per kg CF	52.7	52.2	42.1	49.9	44.0	45.8
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	15.6	15.8	15.8	16.1	16.3	17.2
Operating Thermal Losses	kWh Per kg CF	12.9	13.0	11.1	15.1	11.3	11.9
Operating Total CO2 Emission	kg/hr CO2	2169.1	1650.6	4956.4	1124.7	5122.1	3592.5
CAPEX	USD $ / kg CF	$2.46	$2.94	$2.27	$4.21	$2.21	$2.99
OPEX	USD $ / kg CF	$9.42	$10.59	$7.92	$12.82	$8.09	$9.44

Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		25	26	27	28	29	30
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	3,000mm Wide	3,000mm Wide	1,750mm Wide	1,750mm Wide	1,750mm Wide	1,750mm Wide
Annual Capacity	TPY	1,500 TPY Line	1,000 TPY Line	1,000 TPY Line	750 TPY Line	500 TPY Line	1,000 TPY Line
Waste Gas Configuration		TOX1	TOX1 TOX2	TOX1 TOX2	TOX1 TOX2	TOX1	TOX1
Het Recovery Used	?					HEAT RECOVERY	
Theoretical Minimum Power Input	kWh Per kg CF	5.23	6.07	4.99	5.53	6.44	4.99
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.5	2.6	2.4	2.5	2.7	2.4
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	208.3	138.9	138.9	104.2	69.4	138.9
Operating Power Input	kWh Per kg CF	47.6	48.2	50.6	50.0	43.6	52.3
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	17.8	18.3	18.3	18.5	18.9	19.0
Operating Thermal Losses	kWh Per kg CF	12.1	12.8	13.1	13.3	15.3	13.2
Operating Total CO2 Emission	kg/hr CO2	3722.3	2548.6	2557.6	1937.8	1316.0	2642.3
CAPEX	USD $ / kg CF	$2.92	$3.86	$2.58	$3.08	$4.43	$2.50
OPEX	USD $ / kg CF	$9.62	$11.45	$9.82	$10.97	$13.07	$9.98

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Beacon Model Sample Outputs
As Outlined on Test Quiz www.harperbeacon.com

		31	32	33	34	35	36
Retention Time Oxidation	Minutes	90	90	90	90	90	90
Retention Time LT Furnace	Seconds	90	90	90	90	90	90
Retention Time HT Furnace	Seconds	90	90	90	90	90	90
Tow Size and Tow Spacing	k on mm Spacing	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm	12k on 6mm
Line Width	mm	3,000mm Wide	1,750mm Wide	1,750mm Wide	1,750mm Wide	1,750mm Wide	1,750mm Wide
Annual Capacity	TPY	1,000 TPY Line	500 TPY Line	750 TPY Line	500 TPY Line	500 TPY Line	500 TPY Line
Waste Gas Configuration		TOX1	TOX1 TOX2	TOX1	TOX2 RTO	TOX1 TOX2	TOX1
Het Recovery Used	?		HEAT RECOVERY				
Theoretical Minimum Power Input	kWh Per kg CF	6.07	6.44	5.53	6.44	6.44	6.44
Theoretical Minimum Total CO2 Emission	kg/hr CO2 Per kg CF	2.6	2.7	2.5	2.7	2.7	2.7
Theoretical Thermal Losses	kWh Per kg CF	0.0	0.0	0.0	0.0	0.0	0.0
Carbon Fiber Output	kg / hr CF	138.9	69.4	104.2	69.4	69.4	69.4
Operating Power Input	kWh Per kg CF	50.0	47.2	51.6	66.4	63.8	65.5
Operating Total CO2 Emission	kg/hr CO2 Per kg CF	19.0	19.1	19.2	19.6	22.6	23.4
Operating Thermal Losses	kWh Per kg CF	13.0	15.4	13.4	15.9	16.2	16.3
Operating Total CO2 Emission	kg/hr CO2	2648.7	1334.3	2007.8	1369.2	1576.5	1630.4
CAPEX	USD $ / kg CF	$3.76	$4.55	$2.98	$4.19	$4.37	$4.24
OPEX	USD $ / kg CF	$11.64	$13.24	$11.15	$13.98	$14.39	$14.58

Beacon

Harper International

3000 TPY Capacity Options Overview and Cost Model Summary

Data From Intertech Pira 2009
www.harperintl.com/resources

Future Line Capacity Evaluation

Capacities (Cerca 2009): 1500 tpy to >2000+ tpy

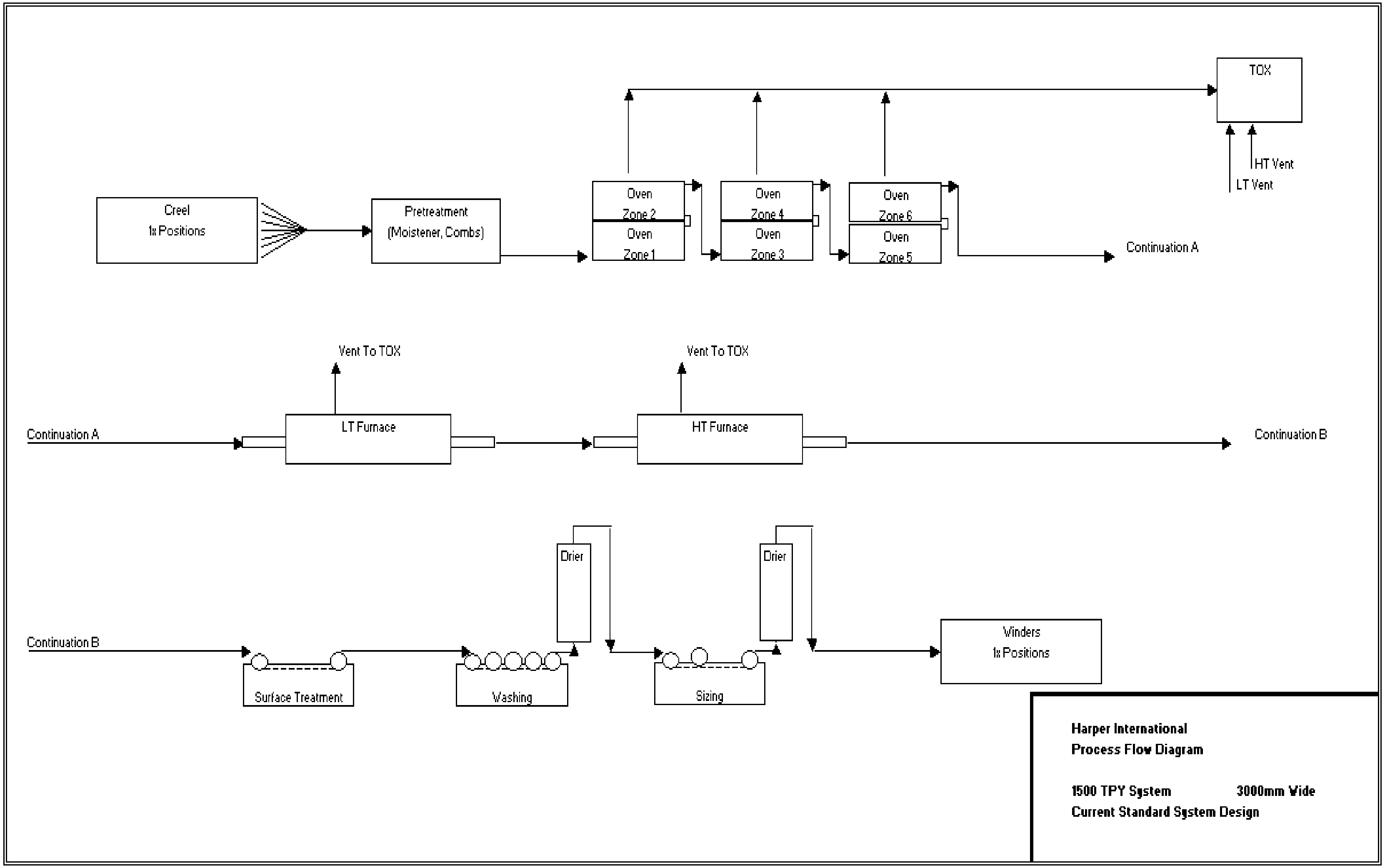
Next Generation Line Capacities >3000 tpy
(following the tendency for doubling of capacities)

Evaluated Scenarios for Next Generation Line Design

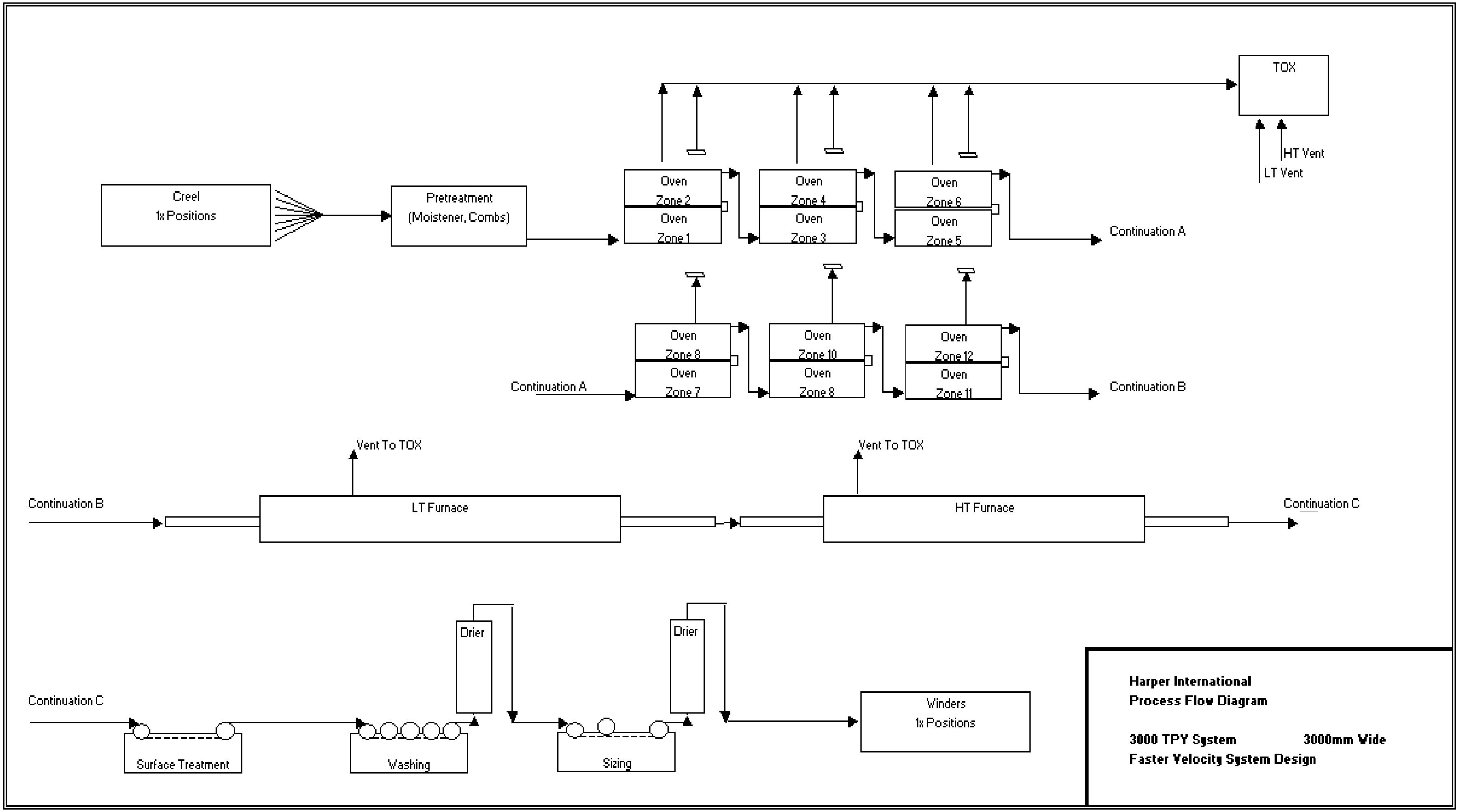
- Faster Lines, Existing Widths
- Novel Configurations (Multiple, Stacked Tow Bands)
- Wider Lines, Existing Speeds

Cost Differentials Must be Evaluated Against Developmental Risks

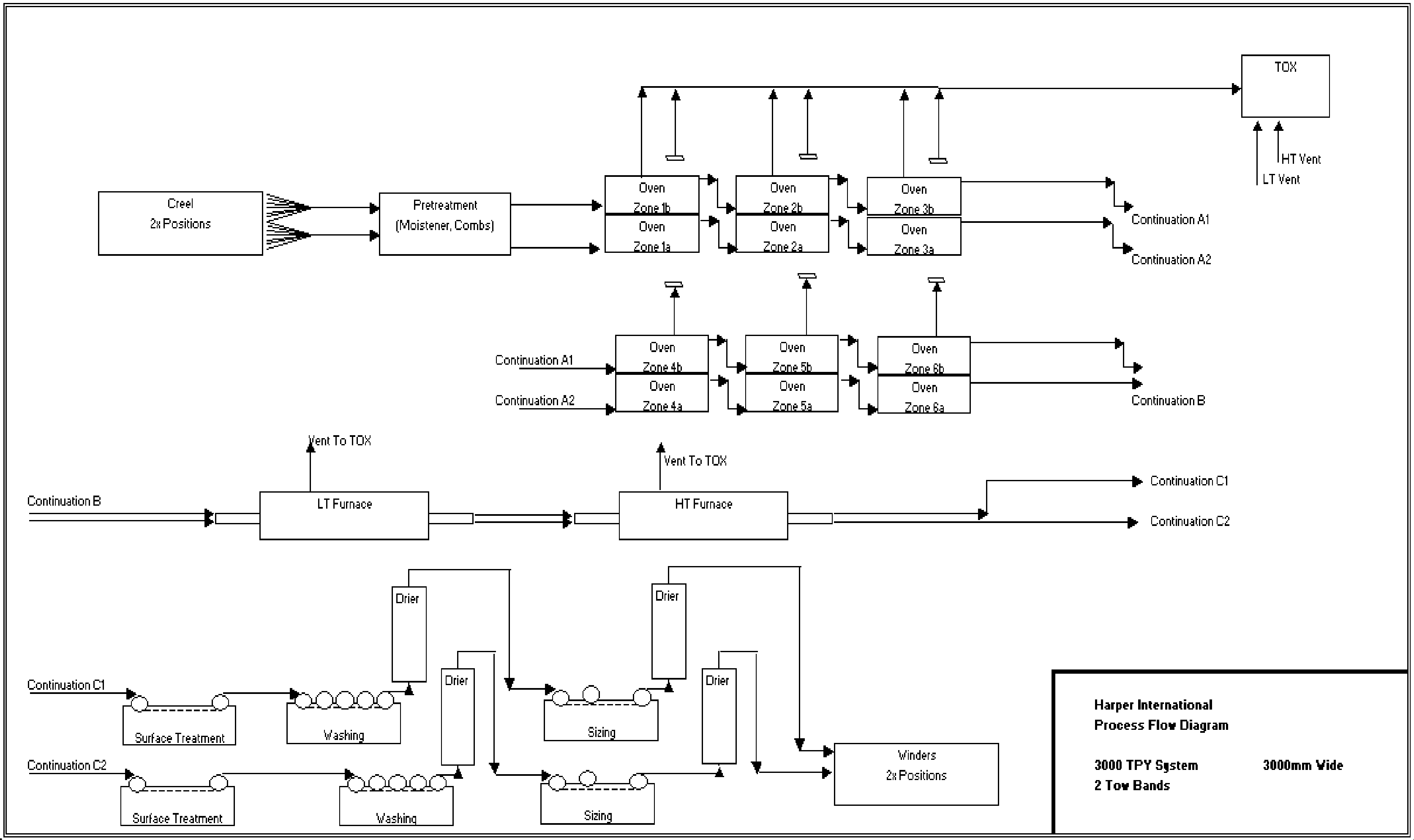
Block Diagram
1500 TPY – 3000mm Wide



Block Diagram
3000 TPY – 3000mm Wide



Block Diagram
3000 TPY – 3000mm Wide
2 Tow Bands (Stacked)



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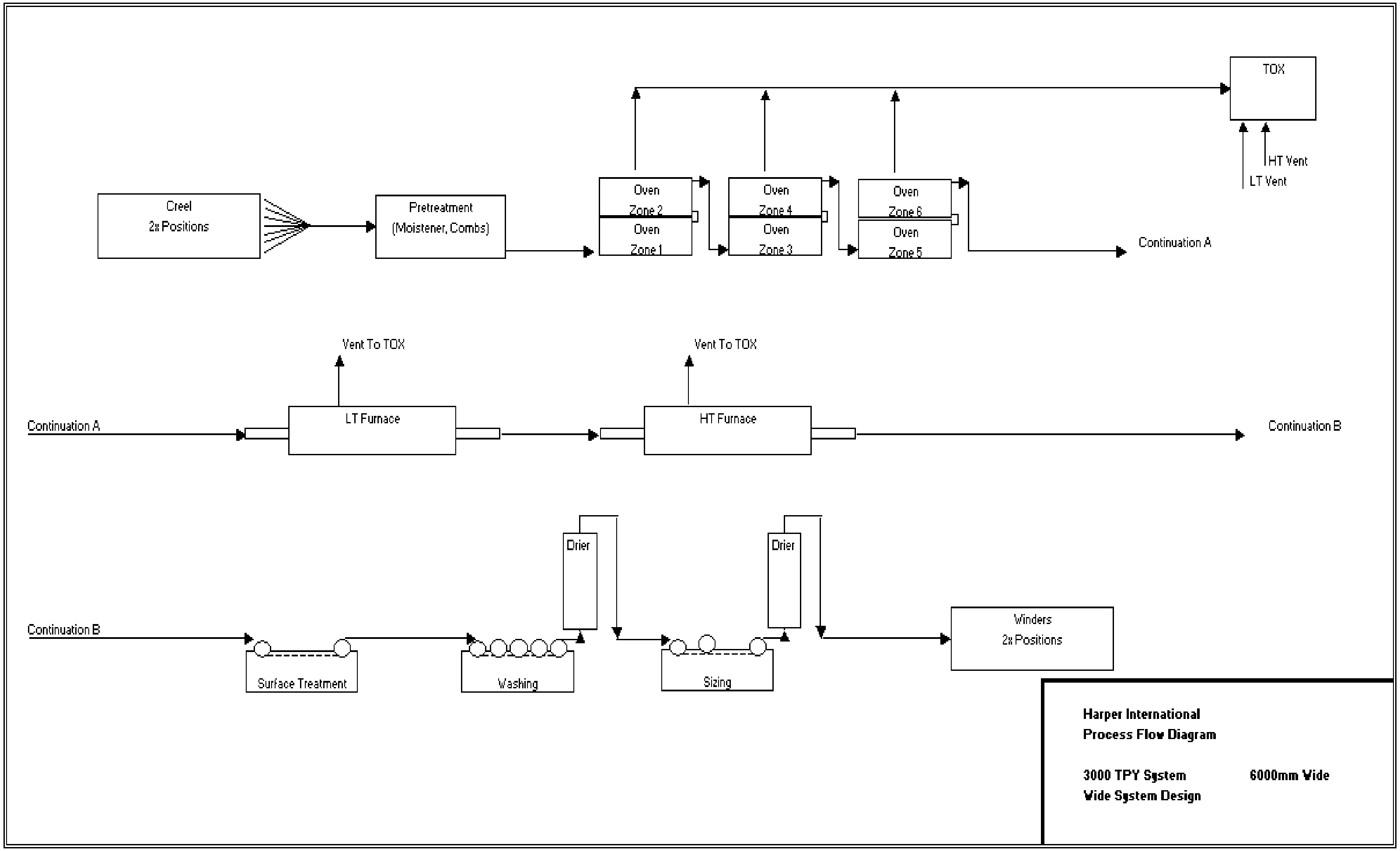
Block Diagram
30000 TPY – 6000mm Wide



System Design is Similar to 1500 TPY Plant, but Equipment is wider

Cost Model Output
Assumptions / Inputs

Capacity carbon fiber at HT exit (mton/yr):	3m Wide 1500 TPY	3m Wide x 2 Lines 3000tpy w / 2X	3m Wide - Faster 3000tpy	3m Wide x 2 Tow 3000tpy	6m Wide 3000tpy
Availability (hours/year):	7000	7000	7000	7000	7000
1000's of filaments per tow (K):	12	12	12	12	12
Tow spacing (mm):	6.0	6.0	6.0	6.0	6.0
Number of tows	475	475	475	475	950
Linear Density (gr / m tow)	1.66	1.66	1.66	1.66	1.66
Line speed (m/min)	9.1	18.2	18.2	9.1	9.1
Target Oxidation residence time (min)	90	90	90	180	90
Target LT residence time (sec)	90	90	90	90	90
Target HT residence time (sec)	90	90	90	90	90
Oxidation oven feed rate (kg/hr)	428.5	857.0	857.0	857.0	857.0
Oxidation exit mass rate (kg/hr)	407.1	814.2	814.2	814.2	814.2
LT exit mass rate (kg/hr)	252.4	504.8	504.8	504.8	504.8
Carbon fiber HT exit mass rate (kg/hr)	214.3	428.6	428.6	428.6	428.6
Number of Ovens	3	3	6	6	3
Estimated tow-band width (mm):	2850	2850	2850	2850	5700
Number of Control Zones in Oven Set	6	6	12	12	6
Design - Total Heated Length - (m):	840	840	1681	1681	840
Actual Oven Residence (@ system speed) (min):	93	46	93	185	93
LT Heated length (m)	14.3	14.3	28.6	14.3	14.3
LT Number of Control Zones	7	7	14	7	7
Actual LT Residence (@ system speed) (sec):	94	47	94	94	94
HT Heated length (m)	13.7	13.7	27.5	13.7	13.7
HT Number of Control Zones	8	8	16	8	8
Actual HT Residence (@ system speed) (sec):	91	45	91	91	91

Cost Model Output
Scale Up (3000 TPY) Scenarios - Utilities List

	3m Wide	3m Wide	3m Wide - Faster	3m Wide x 2 Tow	6m Wide
Power	1500 TPY	3000tpy w / 2X	3000tpy	3000tpy	3000tpy
CF Production (kg/hr)	214.3	428.6	428.6	428.6	428.6
Total Installed Power (Line Load)	**14683**	**29366**	**27540**	**24582**	**24903**
kw/kg (based on Installed)	68.5	68.5	64.3	57.4	58.1
Nominal Consumption Efficency	75.0%	75.0%	75.0%	75.0%	75.0%
Nominal Consumption (kW) with Recuperation	**7250**	**14501**	**13263**	**11045**	**11133**
kW/kg (Nominal) with Recuperation	**33.8**	**33.8**	**30.9**	**25.8**	**26.0**
Heat Recovery Present (1/0 = yes/no)	1	1	1	1	1
Heat Recuperation Possible (kW)	5016	10032	9856	9856	10059
kw/kg (Installed Net) with Recuperation	**45.1**	**45.1**	**41.3**	**34.4**	**34.6**
Creels (kW)	50	99	50	50	99
Pretreatment (kW)	5	9	7	7	14
Oxidation Ovens (kW)	5255	10510	10510	10510	6155
LT Furnace (kW)	1051	2102	1908	1051	1908
HT Furnace (kW)	2337	4674	4437	2337	4437
Surface Treatment - Elect., Wash, Dry (kW)	738	1477	1159	1159	1818
Surface Treatment - Sizing & Drying (kW)	771	1542	1210	1210	1899
Thermal Oxidizer 1 (kW)	4090	8181	7761	7761	7913
Thermal Oxidizer 2 (kW)	0	0	0	0	0
Winding (kW)	124	248	124	124	248
Tensioners (Assumed) (kW)	263	525	375	375	412
Total (kW) with Recuperation	**9667**	**19335**	**17684**	**14726**	**14844**

Cost Model Output
Scale Up (3000 TPY) Scenarios OPEX Est.

Operating Cost (OPEX)	3m Wide 1500 TPY	3m Wide 3000tpy w / 2X	3m Wide - Faster 3000tpy	3m Wide x 2 Tow 3000tpy	6m Wide 3000tpy
CF Production (kg/hr)	214.3	428.6	428.6	428.6	428.6
Operating Hours Per Year	7,000	7,000	7,000	7,000	7,000
Heat Recovery Present? (1/0 = Yes/No)	1	1	1	1	1
Nominal Consumption Efficency	75.0%	75.0%	75.0%	75.0%	75.0%
Nominal Consumption (kW) with Recuperation	7250.5	14501.0	13263.1	11044.8	11133.0
kW/kg (Nominal) with Recuperation	33.8	33.8	30.9	25.8	26.0
As Electricity (kW)	4684.8	9369.6	8221.4	6003.1	5987.8
As Natural Gas (kW)	2,565.7	5131.4	5,041.7	5,041.7	5,145.2
Electrical Cost (USD/kW)	$0.05	$0.05	$0.05	$0.05	$0.05
Natural Gas Cost (USD/kW)	$0.10	$0.10	$0.10	$0.10	$0.10
Nitrogen Consumption (Nm3/hr)	1,909.5	3819.0	2,700.0	2,700.0	3,818.3
Nitrogen Cost (USD/hr)	$74.94	$149.88	$105.97	$105.97	$149.85
Operators	59.0	118.0	66.0	101.0	101.0
Cost Per Operator (USD/year)	$100,000	$100,000	$100,000	$100,000	$100,000
Total Operator Cost Per Year (USD/year)	$5,900,000	$11,800,000	$6,600,000	$10,100,000	$10,100,000
Minutes Per Creel (Minutes)	2.8	1.4	1.4	1.4	1.4
Minutes Per Package (Product)	42.0	21.0	21.0	21.0	21.0
Kilograms Per Year	1,500,000	3,000,000	3,000,000	3,000,000	3,000,000
Cost Electricity (USD/year)	$1,639,676	$3,279,353	$2,877,487	$2,101,088	$2,095,726
Cost Natural Gas (USD/year)	$1,795,986	$3,591,972	$3,529,167	$3,529,167	$3,601,646
Cost Nitrogen (USD/year)	$656,485	$1,312,970	$928,259	$928,259	$1,312,712
Cost Operators (USD/year)	$5,900,000	$11,800,000	$6,600,000	$10,100,000	$10,100,000
Total Cost (USD/year)	$11,492,148	$22,984,295	$16,934,912	$19,658,513	$20,110,084
Cost Electricity (USD/kg)	$1.09	$1.09	$0.96	$0.70	$0.70
Cost Natural Gas (USD/kg)	$1.20	$1.20	$1.18	$1.18	$1.20
Cost Nitrogen (USD/kg)	$0.44	$0.44	$0.31	$0.31	$0.44
Cost Operators (USD/kg)	$3.93	$3.93	$2.20	$3.37	$3.37
Total Cost (USD/kg)	$7.66	$7.66	$5.64	$6.55	$6.70

Cost Model Output
Scale Up (3000 TPY) Scenarios Total Cost

Total Cost Model		3m Wide 1500 TPY	3m Wide 3000tpy w / 2X	3m Wide - Faster 3000tpy	3m Wide x 2 Tow 3000tpy	6m Wide 3000tpy
Cost PAN (USD/kg PAN)		$3.00	$3.00	$3.00	$3.00	$3.00
Cost Pan / kg CF (USD / kg CF)		$6.00	$6.00	$6.00	$6.00	$6.00
Cost PAN (USD/yr)		$8,998,902	$17,997,804	$17,997,804	$17,997,804	$17,997,804
Cost CAPEX (USD) / Per Line		$44,871,000	$89,742,000	$61,296,000	$79,343,000	$81,925,000
CAPEX Cost Factor (Over 1500 tpy line)			2.00	1.37	1.77	1.83
Systems Required for Desired Total Capacity		2	1	1	1	1
Infrastructure (fx CAPEX)		2.5	2.5	2.5	2.5	2.5
Infrastructure (USD)		$112,177,500	$224,355,000	$153,240,000	$198,357,500	$204,812,500
Building Dimensions Length (m) - Estimated		300	300	500	360	380
Building Dimensions Width (m) - Estimated		40	80	40	40	70
Building Dimensions Foot Print (m2) - Estimated		12,000	24,000	20,000	14,400	26,600
Cost PAN (USD/kg CF)		$6.00	$6.00	$6.00	$6.00	$6.00
Cost CAPEX (USD/kg CF)		$3.41	$3.41	$2.33	$3.02	$3.12
Cost Infrastructure (USD/kg CF)		$2.99	$2.99	$2.04	$2.64	$2.73
Cost OPEX (USD/kg CF)		$7.66	$7.66	$5.64	$6.55	$6.70
Total Cost (USD/kg CF)		$20.06	$20.06	$16.02	$18.21	$18.55

CUMMULATIVE Total Cost Model						
Total Cost (USD / kg CF)		$20.06	$20.06	$16.02	$18.21	$18.55
Cost PAN (USD/kg CF)		$6.00	$6.00	$6.00	$6.00	$6.00
Cost CAPEX (USD/kg CF)		$9.41	$9.41	$8.33	$9.02	$9.12
Cost Infrastructure (USD/kg CF)		$12.40	$12.40	$10.37	$11.66	$11.84
Cost OPEX (USD/kg CF)		$20.06	$20.06	$16.02	$18.21	$18.55
Cost PAN (%)		29.9%	29.9%	37.5%	32.9%	32.3%
Cost CAPEX (%)		46.9%	46.9%	52.0%	49.5%	49.2%
Cost Infrastructure (%)		61.8%	61.8%	64.8%	64.0%	63.9%
Cost OPEX (%)		100.0%	100.0%	100.0%	100.0%	100.0%

Future Line Capacity Evaluation

For Next Generation, Cost differential has been estimated via Cost Modeling:

	Capex	Total
• Multiple of Current State of the Art Line	(2x)	100%
• Faster Lines, Existing Widths	(1.37x)	79.8%
• Novel Configurations (Multiple Tow Bands)	(1.77x)	90.8%
• Wider Lines, Existing Speeds	(1.83x)	92.4%

Wider Lines and Stacking offer reduction of Consumed Energy, but large Benefits through Faster Velocities