



*Ensuring the future of carbon  
fiber in automotive and beyond*

JEC Americas 2012: Carbon Forum,  
Wednesday November 7, Boston

# Agenda

- Introductions
- State of The Industry
- Challenges to Automotive Market
  - Diminishing Returns on Economies of Scale
  - The Carbon Footprint of CF
  - Time and Investment for Technology Advancements
  - Supply Chain Risks
  - Optimizing the Project Development Timeline



# Introduction: About Harper

# About Harper

## 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



# About Harper

## Advanced Thermal Systems for Fiber Processing

- PAN based C-fiber
- Pitch based C-fiber
- Rayon based C-fiber
- Alternative Precursor Development
- Carbon Nano Tubes / Fibers
- Carbon Fiber Recycling



A Broad Experience Base in a Range of Carbon Processes

# About Harper

## Services to the Carbon Fiber Market

- Equipment Supply (~40 Years)
  - LT Furnaces, HT Furnaces and UHT Furnaces
  - Atmospherically Controlled 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



# State of the Industry

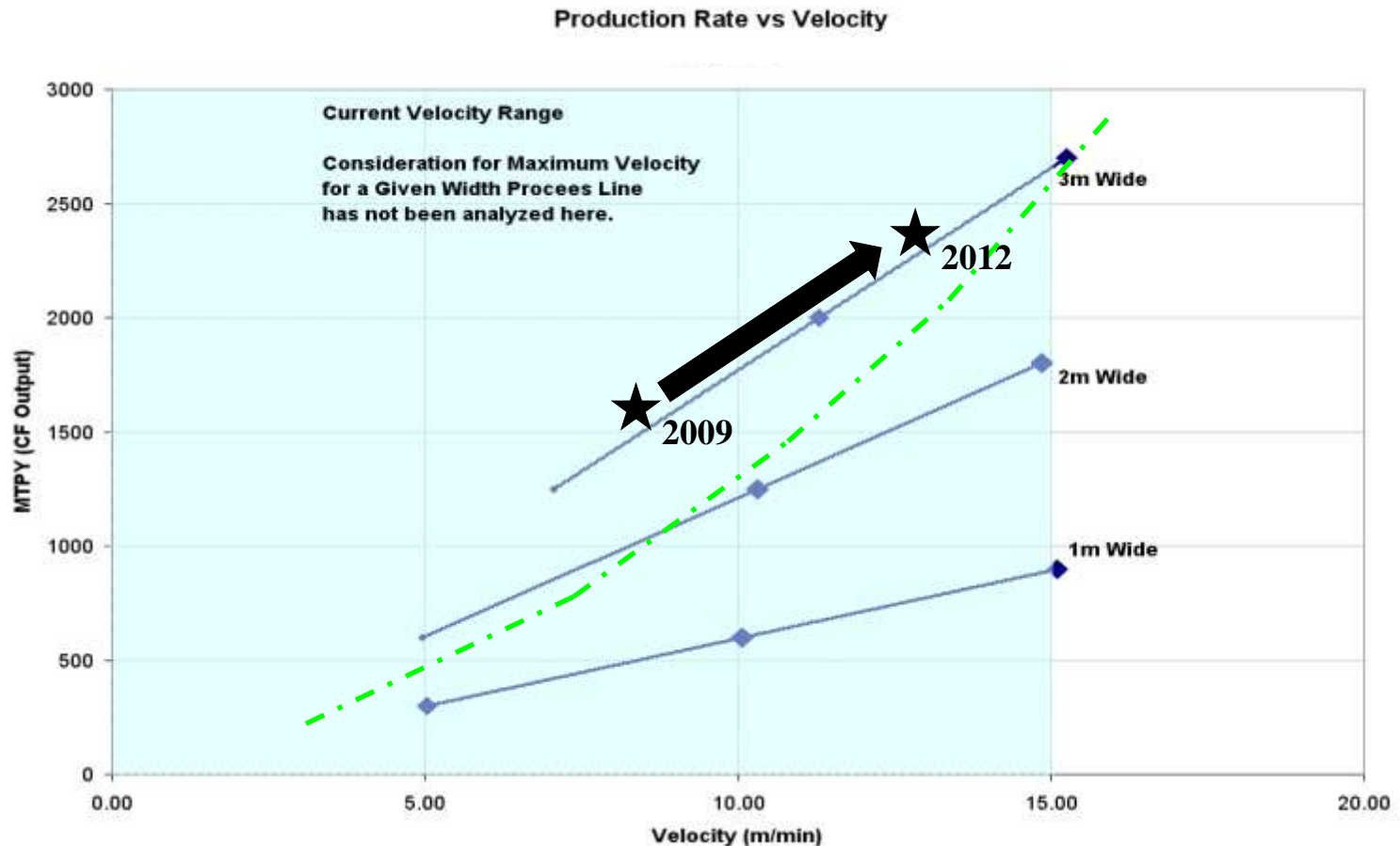
# State of the Industry: Review of Scales of Operations

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 3 tpy





# State of the Industry: Review of Scales of Operations



Capacity Expansion 2011 - 2012 Based on Faster Line Velocities;  
Higher Production Rates from 3m Single Muffle

# State of the Industry: Review of Scales of Operations

- Modern Line Speeds

At 10m/min – 20 m/min for a state of the art line

- Oxidation Oven Capacities

More Than 500 – 750 kg/hr feed of PAN

More than 500 m – 1000m Overall Heated Length

4 Zones Minimum; Typically 6 – 8 Zones

Widths up to 4m -- 3m wide designs are becoming more common

Unsupported Heated Lengths typically less than 15m

- LT and HT Furnaces Understand Your Process and the Impact of Technical Specifications

Widths up to 4m -- 3m wide designs wide are dominant state of the art

Unsupported Heated Lengths 15 m – 20m

HT Temperatures Regimes <1450C, 1600C, and 1800C or greater

# Recent Production Capacities (2010)

**GLOBAL CARBON FIBER PRODUCTION** (ESTIMATED ANNUAL CAPACITY IN 2010)

Manufacturer	Small tow (metric tonnes)	Small tow (lb)	Large tow (metric tonnes)	Large tow (lb)	ID#*
AKSA	1,800	4,000,000			27262
Cytec Industries	2,300	5,000,000			24960
Dalian Xingke Carbon Fiber	600	1,320,000			27750
Formosa Plastics	7,300	16,000,000			27264
Grafil	2,000	4,400,000			26890
Hexcel	7,300	16,000,000			25238
Kemrock	650	1,430,000			26142
Mitsubishi Rayon	6,150	13,530,000	2,750	6,060,000	27836
SGL Carbon			6,500	14,300,000	25642
Toho Tenax	13,500	29,620,000			26204
Toray Industries	17,900	39,440,000	300	660,000	26964
Yingyou Group	220	484,000			72402
Zoltek Corp.			8,750	19,300,000	26150
<b>TOTAL</b>	<b>59,700</b>	<b>131,240,000</b>	<b>18,300</b>	<b>40,320,000</b>	

A list of the world's current carbon fiber manufacturers, compiled by HPC. Capacity estimates for the year 2010 are based on public information about ongoing expansions that was available to HPC in December 2008. Source: CompositesWorld

2010 Total Capacity Estimated at 78,000 MTPY

With 10% - 15% Growth Per Year Since

# Challenges and Expectations for Automotive Market

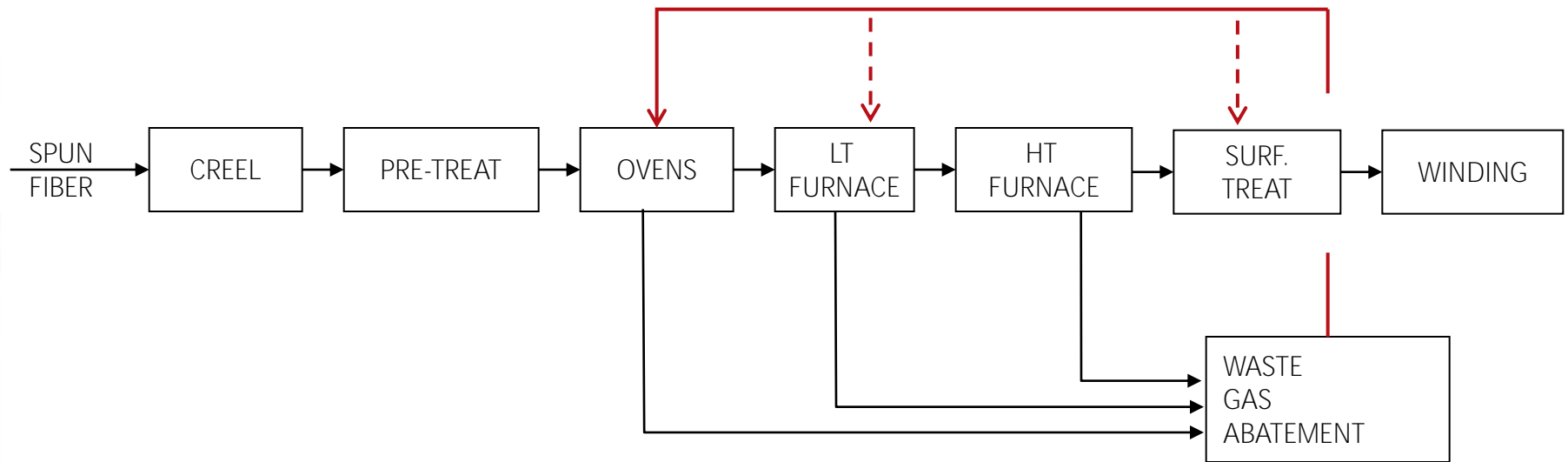
# Challenges in Carbon Fiber Operations to Growth for Automotive Market

1. Diminishing Returns on Economies of Scale
2. The Carbon Footprint of CF
3. Investment in Technology Advancements
4. Supply Chain Risks
5. Optimizing the Project Development Timeline



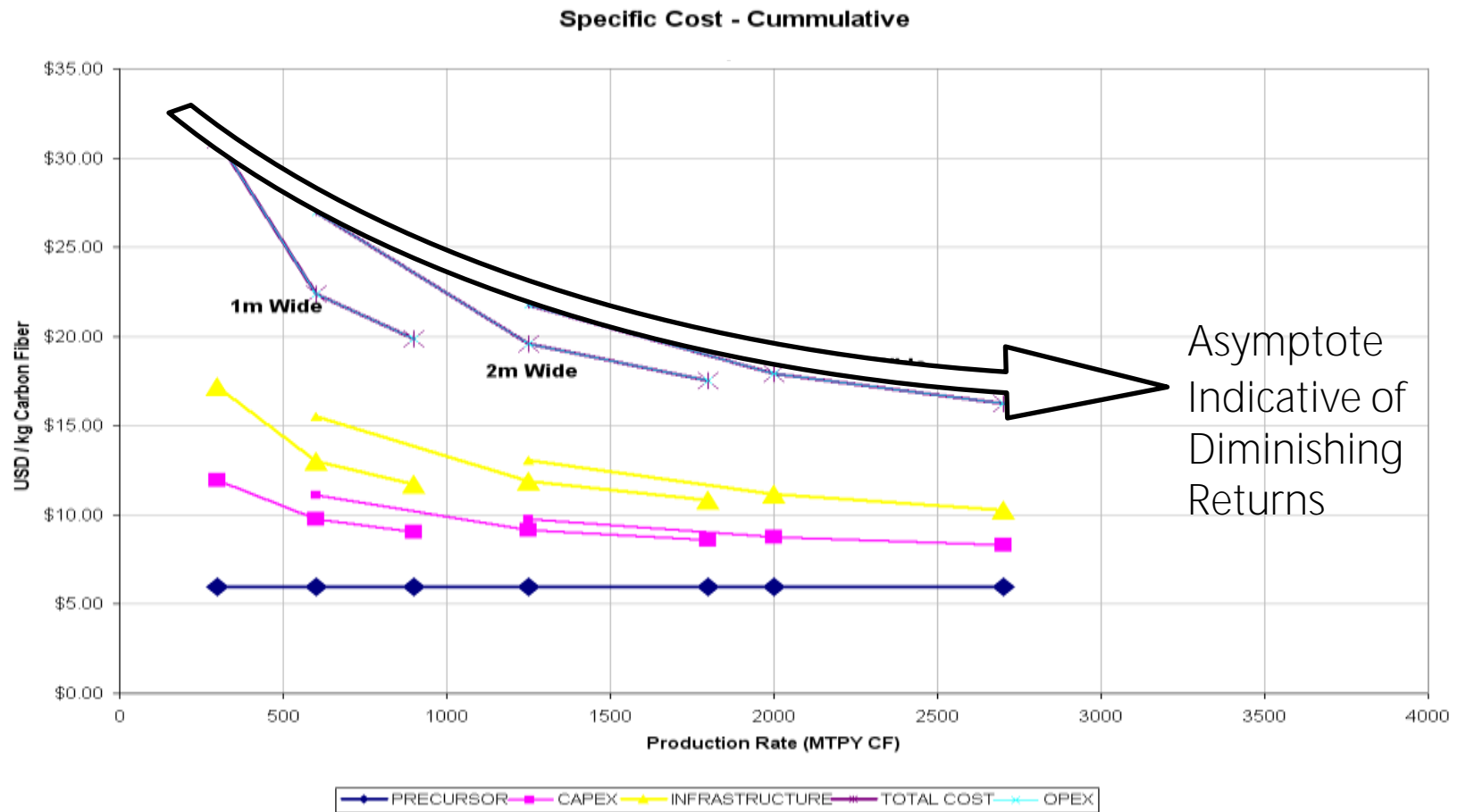
Challenges and Expectations for Automotive Market:  
1) Diminishing Returns on Economies of Scale

# Diminishing Returns on Economies of Scale: Carbon Fiber Conversion Process



- Complexity and Cost added through Waste Gas Treatment
- Significant Opportunity for Energy Recovery and Cost Reduction; through further Flowsheet sophistication
- A State of the Art Integrated Plant yields 15 – 25 kW / kg CF

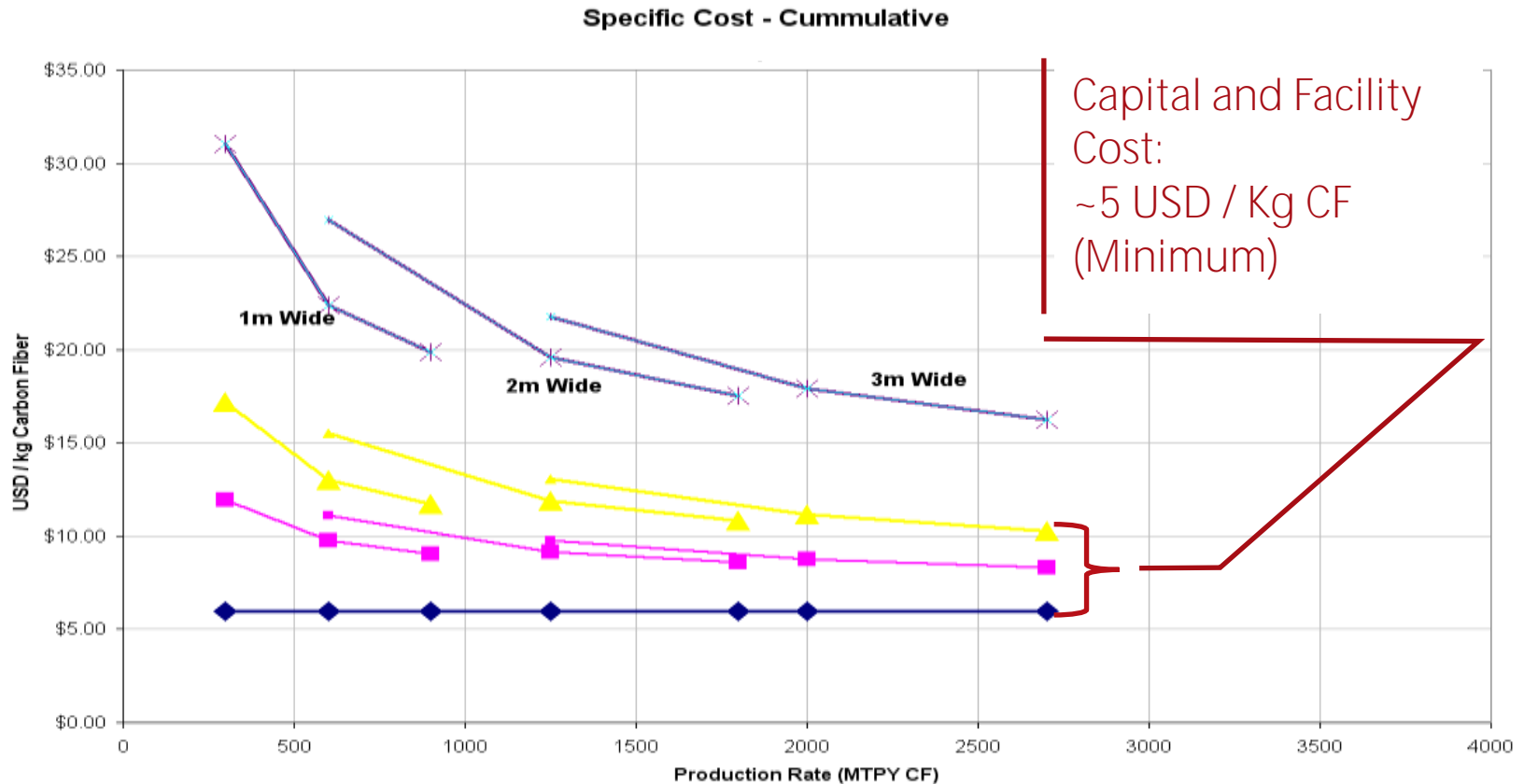
# Challenges to Capturing Growth: Diminishing Returns on Economies of Scale



Cost Dynamics as a Function of Scale-Up

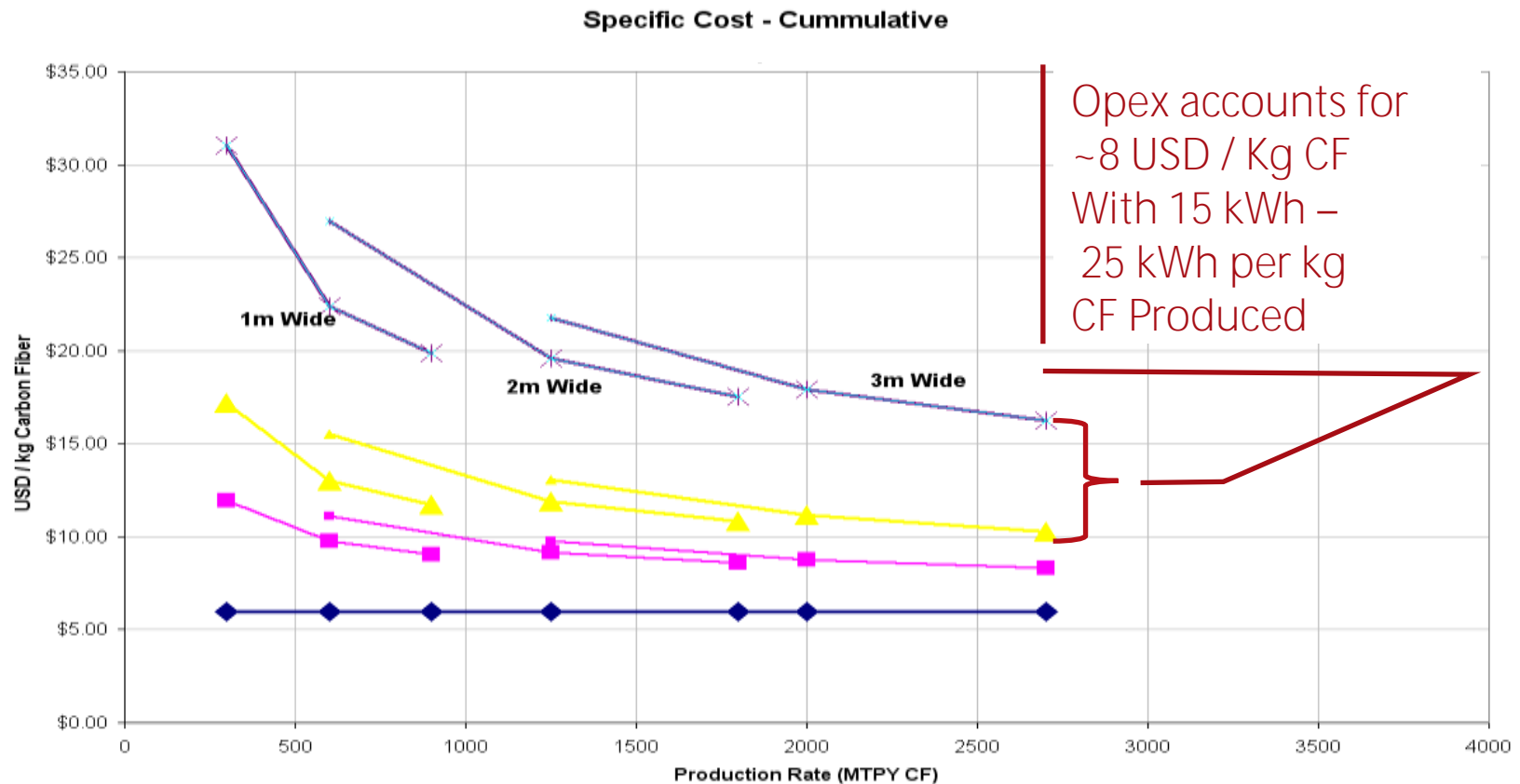


# Challenges to Capturing Growth: Diminishing Returns on Economies of Scale



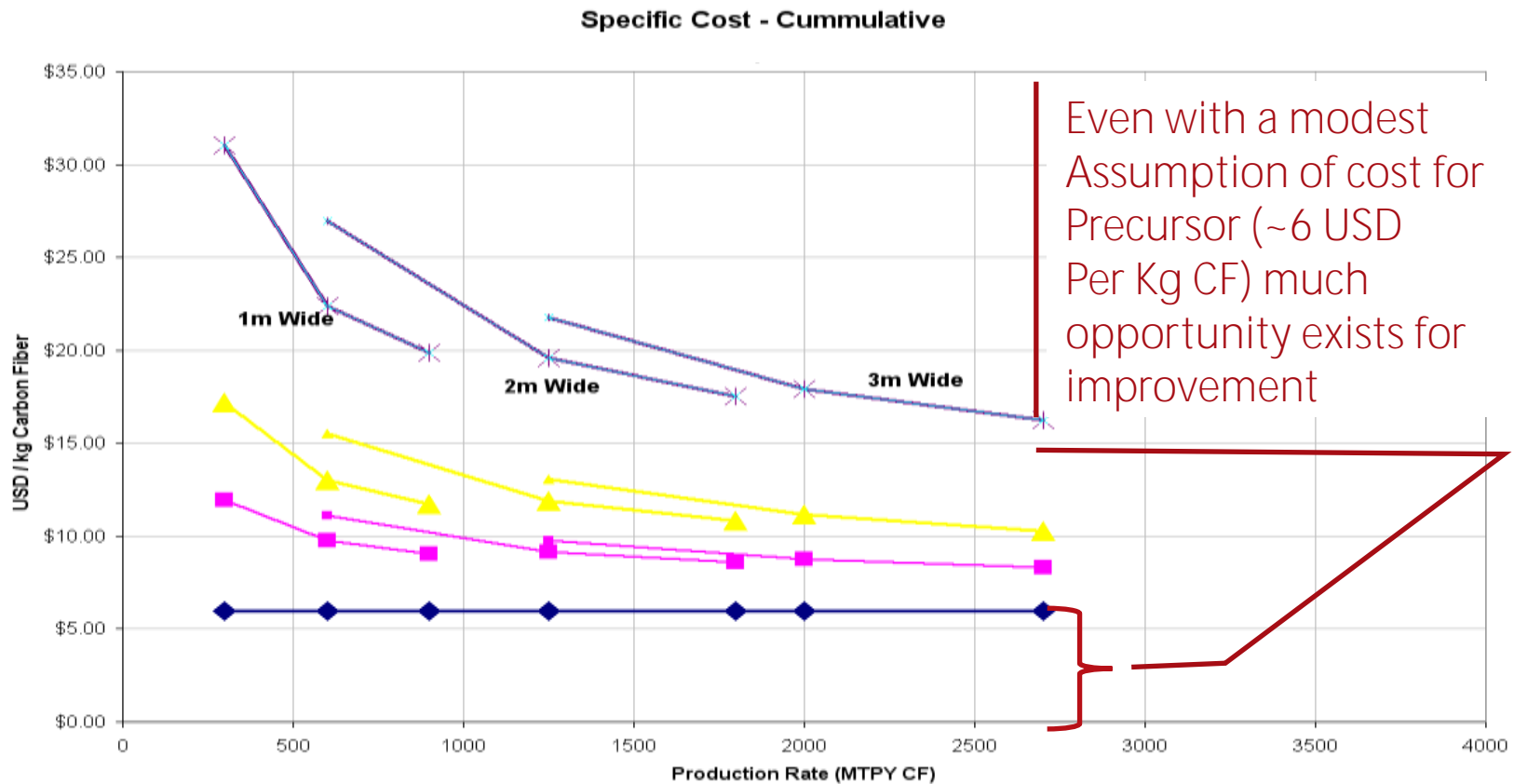
Even by removing the Capital and Facility Cost, you do not arrive at a LCCF Benchmark of \$10 USD / kg

# Challenges to Capturing Growth: Diminishing Returns on Economies of Scale



A 50% Reduction in Energy Consumption would yield a savings of  
\$0.53 - \$0.88 Per Kg of CF (at \$0.07 Per kWh)

# Challenges to Capturing Growth: Diminishing Returns on Economies of Scale



Precursor costs and precursor chemistry should be a major target for future cost improvements and process optimizations

Challenges and Expectations for Automotive Market:  
2) The Carbon Footprint of CF

# Challenges to Capturing Growth: The Carbon Fiber Footprint

## 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



# Challenges to Capturing Growth: The Carbon Fiber Footprint

CO2  
Emissions  
Modeling

Theoretical CO2 Emission for CF Production\*:

Polymer Losses (Footprint of Polymer Production Ignored)

Sensible Heat of Reaction (Polymer and Purge Gases)

Source of Energy

Actual CO2 Emission for CF Production\*:

Polymer Losses(Footprint of Polymer Production Ignored)

Sensible Heat of Reaction (Polymer and Purge Gases)

Energy Summarized by Unit Operation

Thermal Losses

- Heat Rejected to Atmosphere

- Heat Rejected To Cooling Water

Waste Gas Abatement Technology (Major Schemes Considered)

Source of Energy

\* Energy Requirement to Produce Purge Gas Ignored

# Challenges to Capturing Growth: The Carbon Fiber Footprint

## CO2 Emissions Modeling

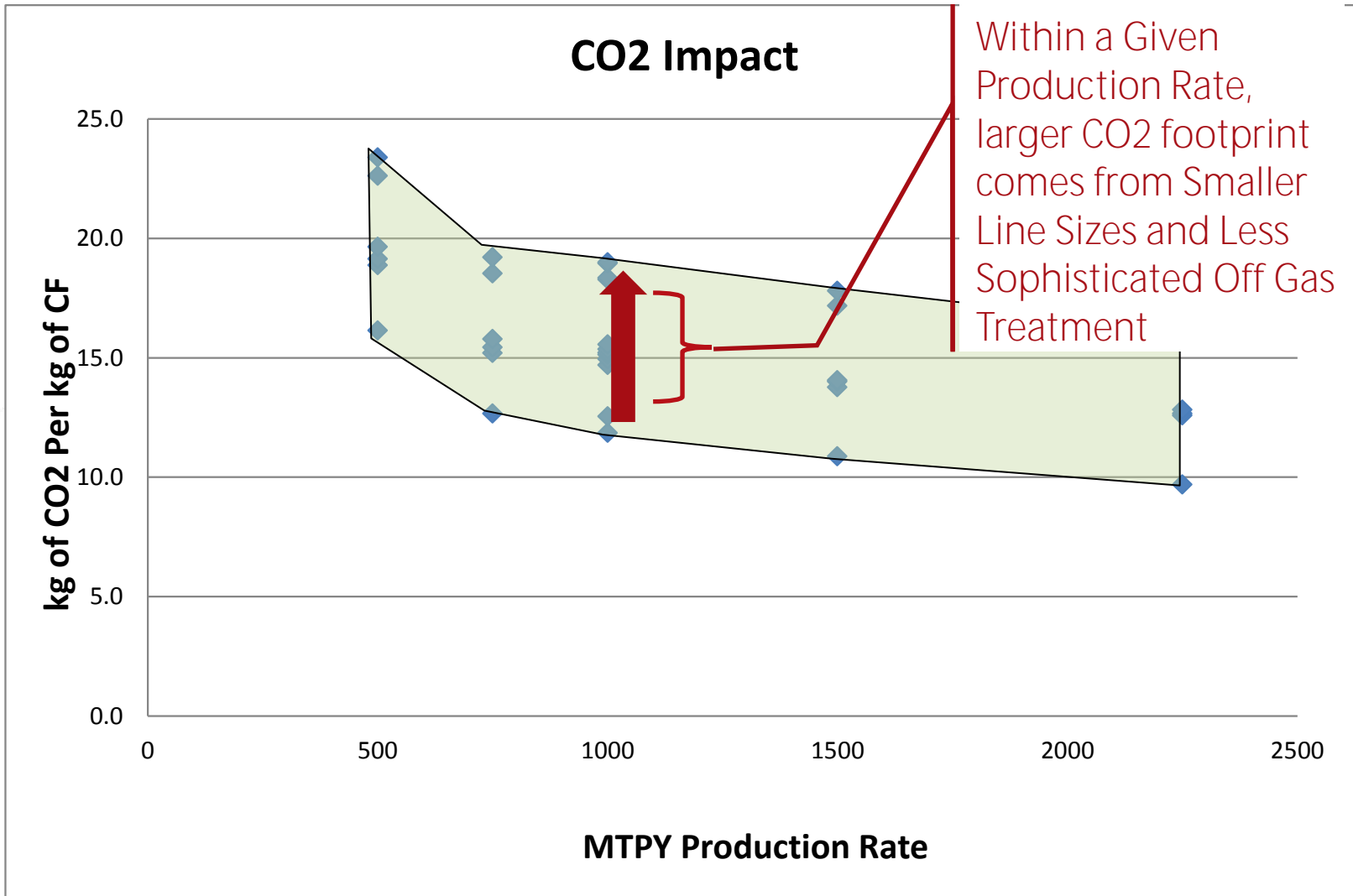
### Primary Results from Sample Evaluation:

Production Rates:	500 – 2250	TPY
Line Sizes:	1750 & 3000	mm Wide
CO2 Emissions*:	9.7 – 23.4	kg CO2 Per kg CF
Theoretical CO2*:	2.7 (average)	kg CO2 Per kg CF
(*Energy to Produce Purge Gas Ignored)		
CAPEX	\$2.17 – \$4.55	USD / kg of CF
OPEX	\$6.27 – \$14.58	USD Per kg CF

- A CO2 Foot Print that is 3x – 9x the theoretical value leaves much room for improvement and optimization.
- The practical consequence of a lower CO2 footprint will be reduced operating costs (per kg of CF)

Sample Data from [harperbeacon.com](http://harperbeacon.com)

# CO2 Emissions Modeling



Sample Data from [harperbeacon.com](http://harperbeacon.com)



# Challenges to Capturing Growth: The Carbon Fiber Footprint

## CF Precursors & Recovery

<u>Chemistry</u>	<u>Maximum</u> <u>C- Recovery</u>	<u>Typical</u> <u>C-Recovery</u>
■ PAN	68% max	(50% typical)
■ Cellulose	44% max	(20% - 30% typical)
■ Lignin	67% max	(typical ?)
■ Pitch	85% max	(w/o solvent) (25% - ?? w/ solvent)
■ Polyethylene	85% Max	(typical ?)
■ Polypropylene	85% Max	(typical ?)

The Precursor can have a significant impact  
on Plant Economics and CO2 Footprint.

# Challenges and Expectations for Automotive Market:

## 3) Investment in Technology Advancements

# Investment in Technology Advancements

Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:



1. Increase of Scale (Wider and Longer)
2. Treatment of Oxidation Oven Exhaust & Potential for Energy Recovery
3. Closed Pipe Treatment of Furnace Exhausts & Potential for Energy Recovery
4. Low Profile Furnace Muffles for Reduced Gas Consumption
5. Movement Towards Sealed Oxidation Oven Design

# Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:

Step 1:  
Increase of Scale

## Increase of Scale Trends, as Led by Harper International

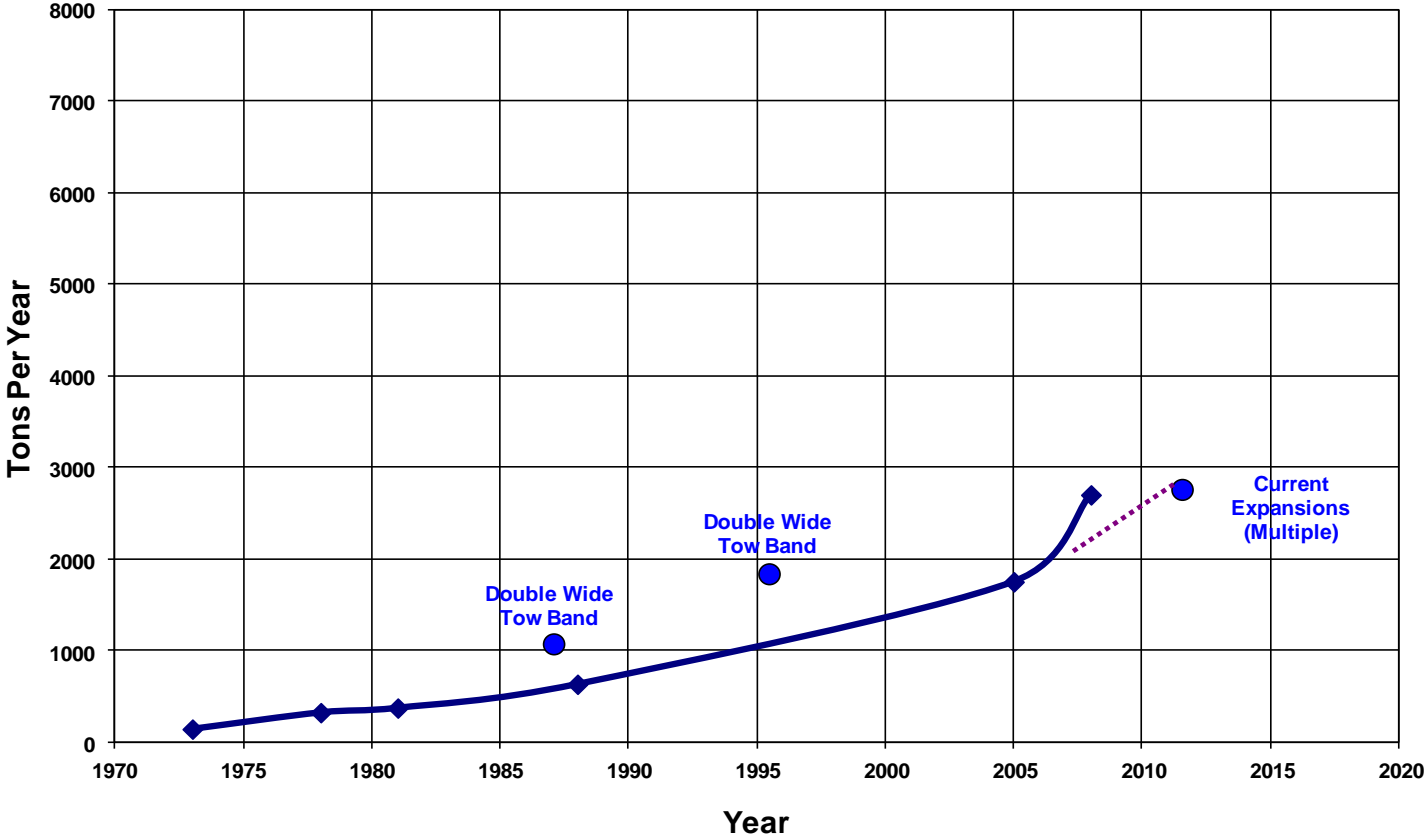
- First System in 1973 still in operation: **36"** Wide (915mm)
- First System > 1m in 1978: 40" wide (1015mm) with 2 of 3 systems still in operation
- 1981: 46" wide (1200mm wide)
- 1988: 68" (1750mm wide)
- 1997: 72" wide (1800mm wide)
- 1997: **163" wide (4141mm wide)**
- 2005: 120" wide (3000mm wide)
- 2008 to Today: >12 systems @ 3000mm wide



> 100 Units Carbon Fiber Projects to date

# Trend of Increase in Scale

## Single Line Capacity



# Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:

Step 2:  
Treatment of  
Oxidation Oven Exhaust

# Treatment of Oxidation Oven Exhaust: Integration & Heat Recovery 2m and 3m (6 Zone Designs)

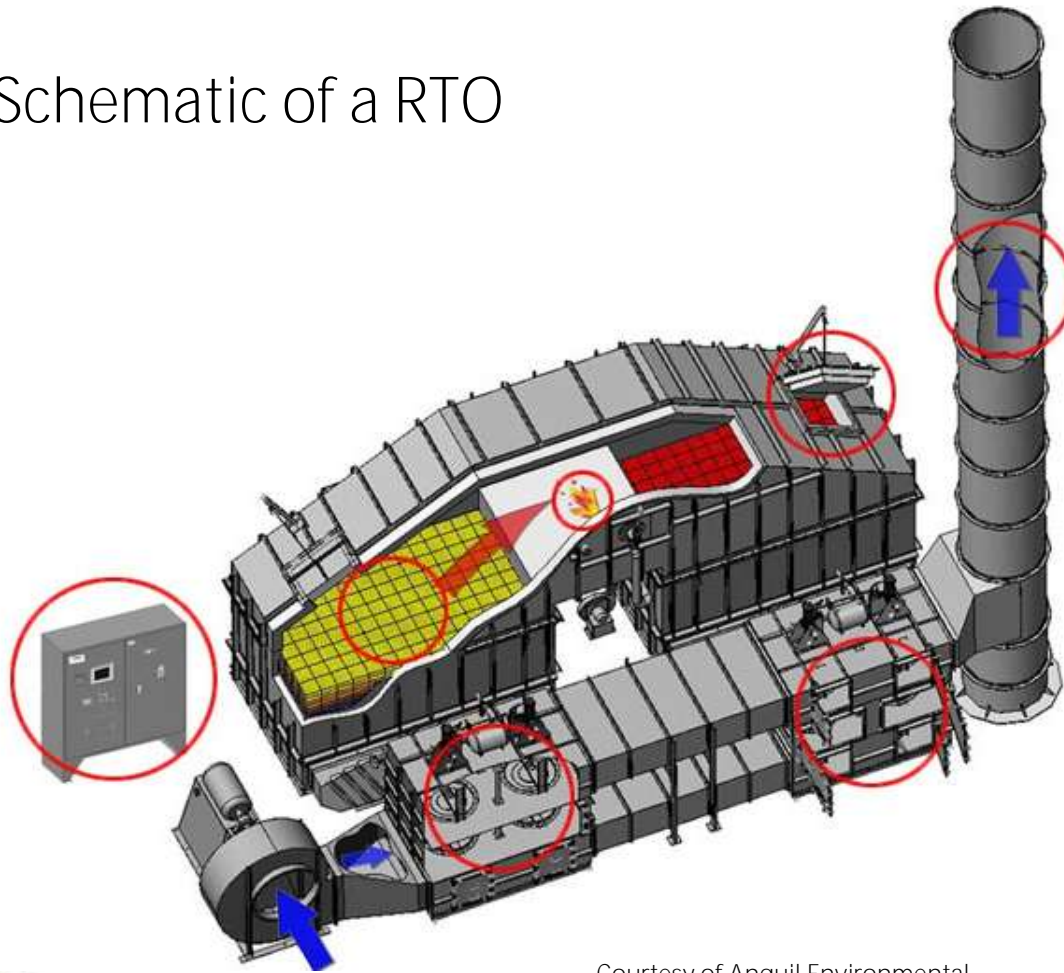
Line Width	m	2m Wide	3m Wide
Oxidation Oven Zones	#	6	6
Exhaust Rate	Nm <sup>3</sup> /hr	20760	43200
Exhaust Temp	C	260	260
Ambient Temp	C	25	25
Delta T	C	235	235
Energy Lost	kw	1633	3399





# Treatment of Oxidation Oven Exhaust: Waste Gas Treatment Systems

## Schematic of a RTO



Courtesy of Anguil Environmental

### RTO Pros / Cons

- Lower Capital Cost
- Lower Operating Cost
- Relies on in Media to Store / Transfer Energy
- Media Susceptible to Fouling - Not Ideal for Fouling Streams
- Some Techniques Exist for Reduction of Maintenance Cleaning (Sacrificial Fouling Surfaces)
- Self Contained Energy Recovery

# Treatment of Oxidation Oven Exhaust

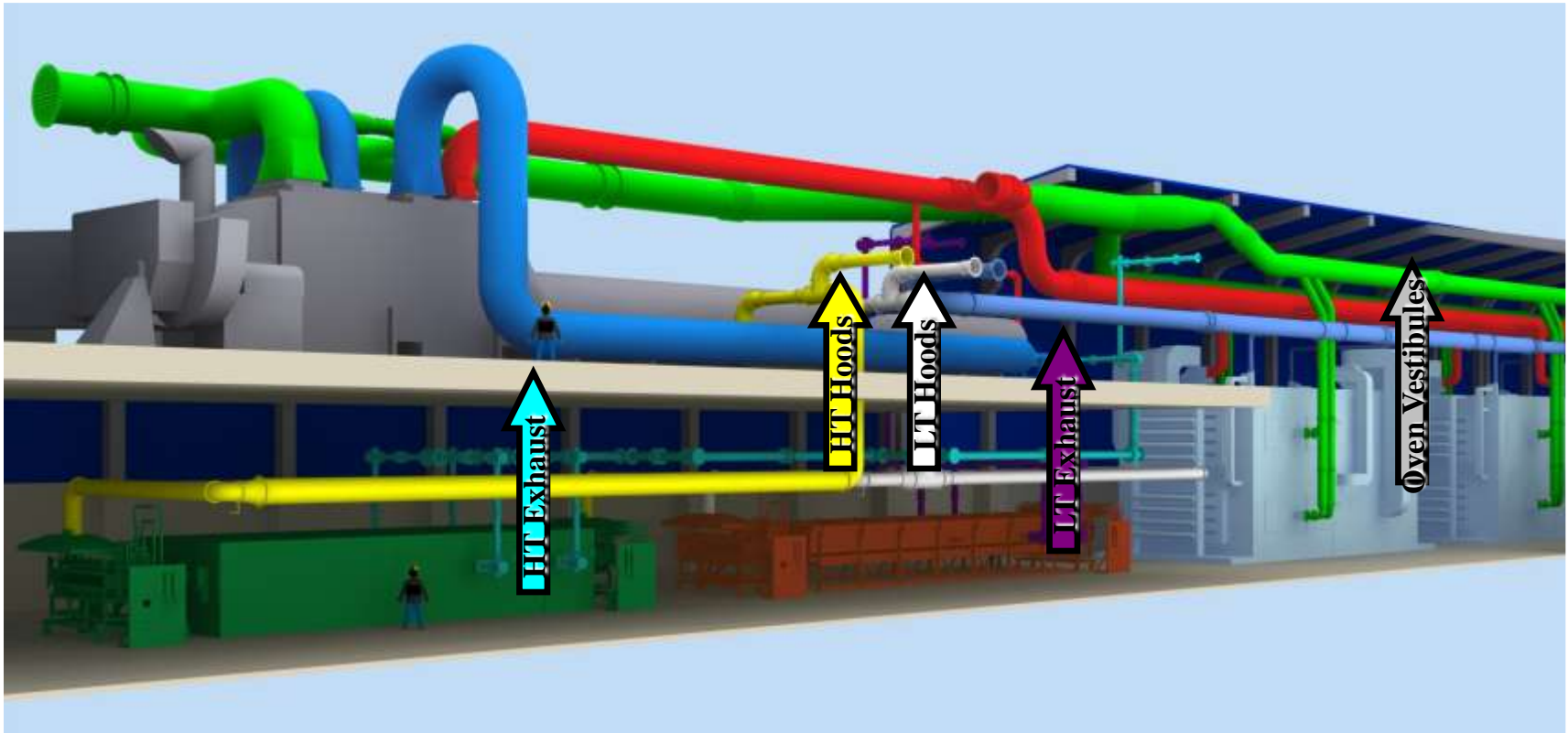


Oven Make Up Air Preheated to  $>200^{\circ}\text{C}$  in the 2<sup>nd</sup> Stage Preheater

# Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:

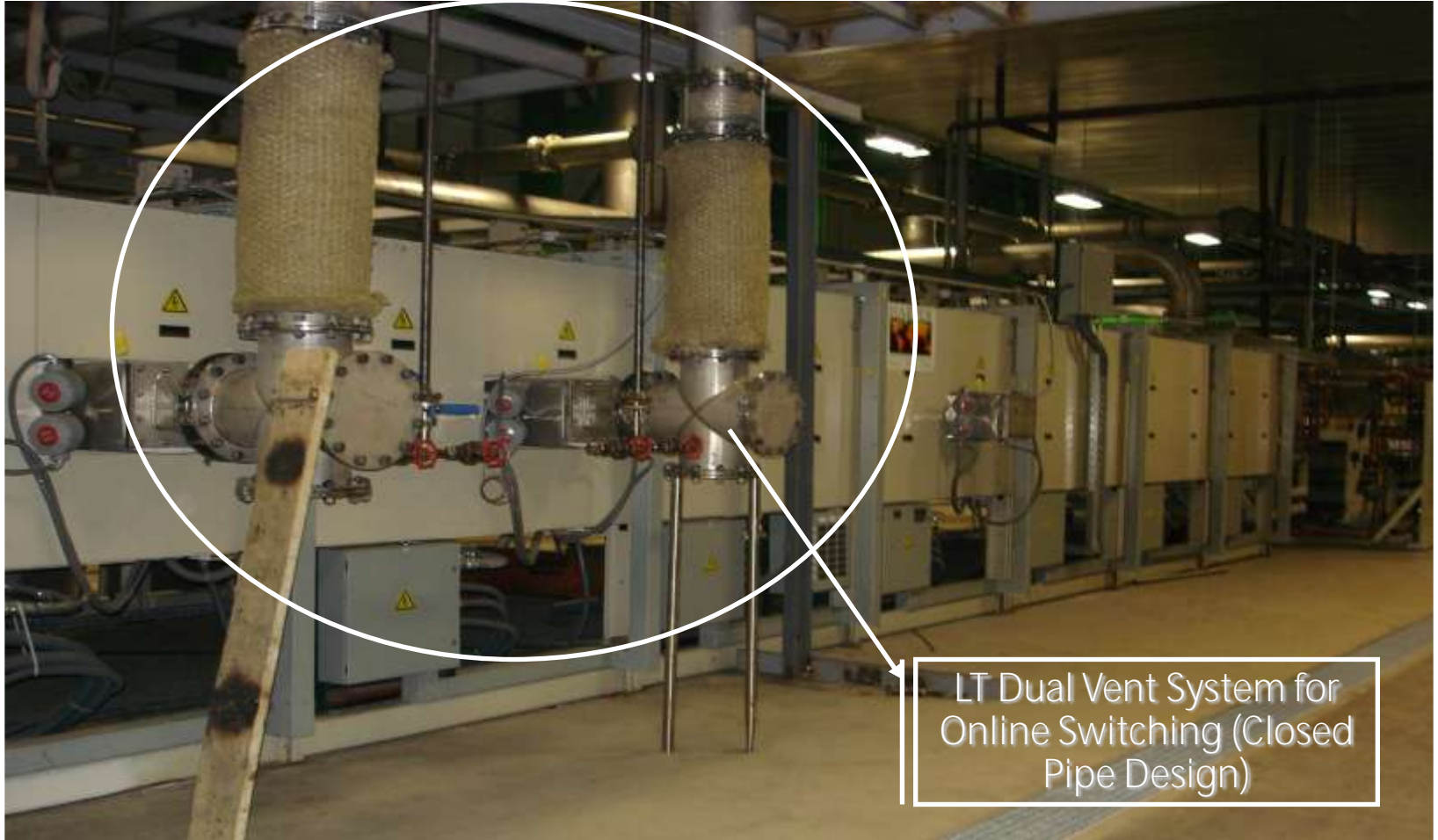
Step 3:  
Closed Pipe Treatment  
of Furnace Exhaust

# Closed Pipe Treatment of Furnace Exhaust



TOX capable of also treating LT & HT Process Exhausts as well the Ventilation Hoods (LT Hoods, HT Hoods, Oven Vestibules)

## Closed Pipe Treatment of Furnace Exhaust



LT Dual Vent System for  
Online Switching (Closed  
Pipe Design)

Gas Abatement - Collection

Five Important Technology Advancements focused on  
Efficiency for Carbon Fiber Capacity Expansion:

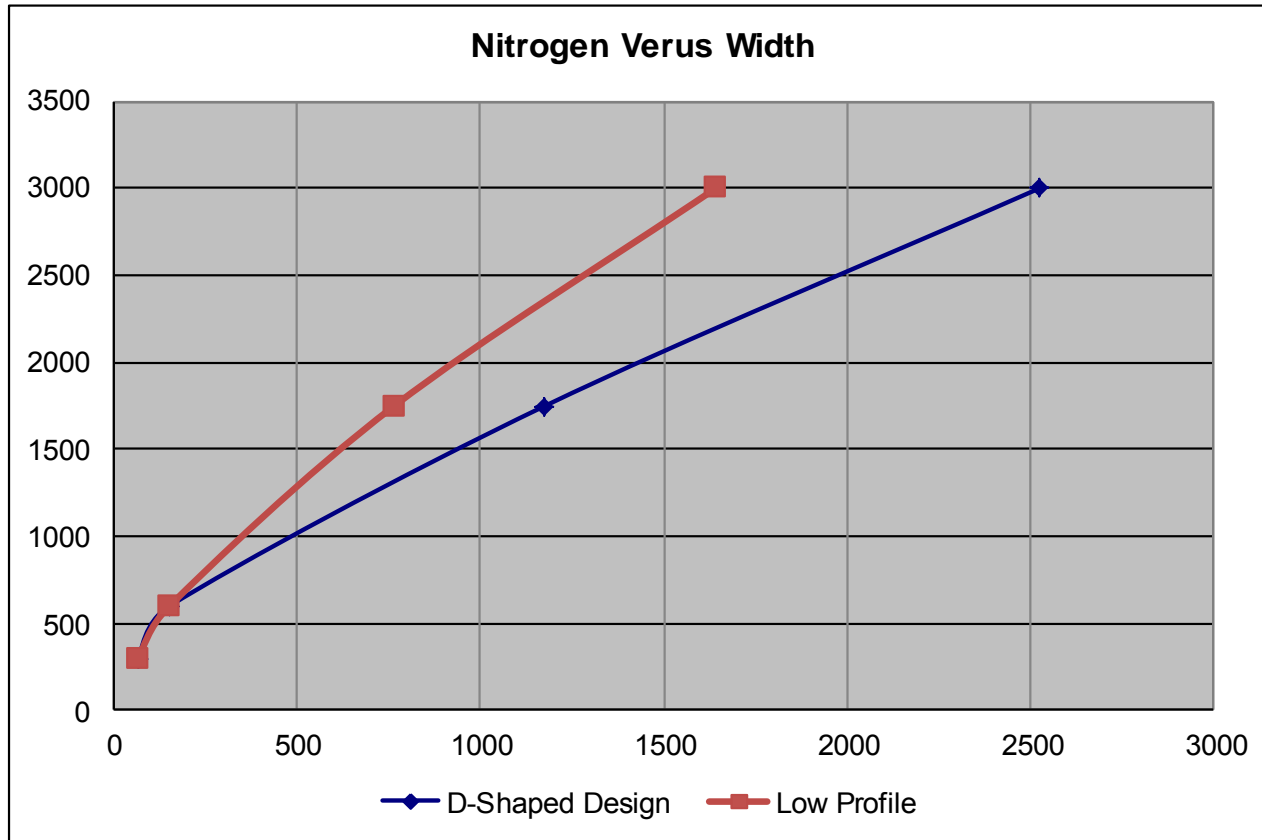
Step 4:  
Low Profile Muffle Design  
To Reduce Nitrogen  
Consumption

# Low Profile Muffle Design To Reduce Nitrogen Consumption



Harper LT Furnace  
3 meter wide low-profile muffle

# Low Profile Muffle Design To Reduce Nitrogen Consumption



Nitrogen Consumption Model Reduction Based on Muffle Design



# Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:

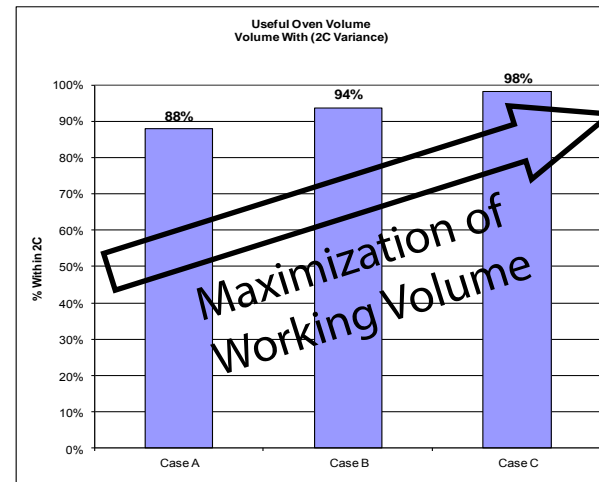
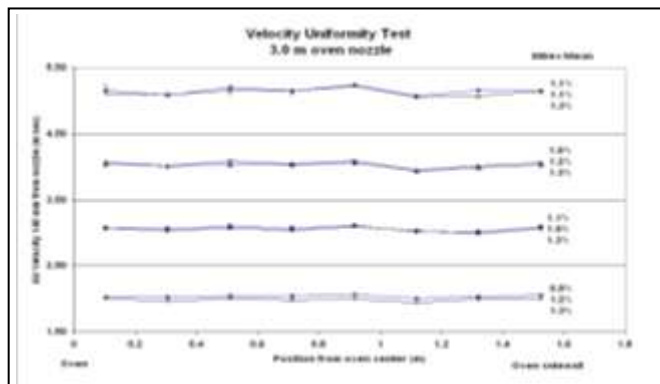
Step 5:  
Shift Towards Sealed  
Oxidation Oven Design

# Shift Towards Sealed Oxidation Oven Design



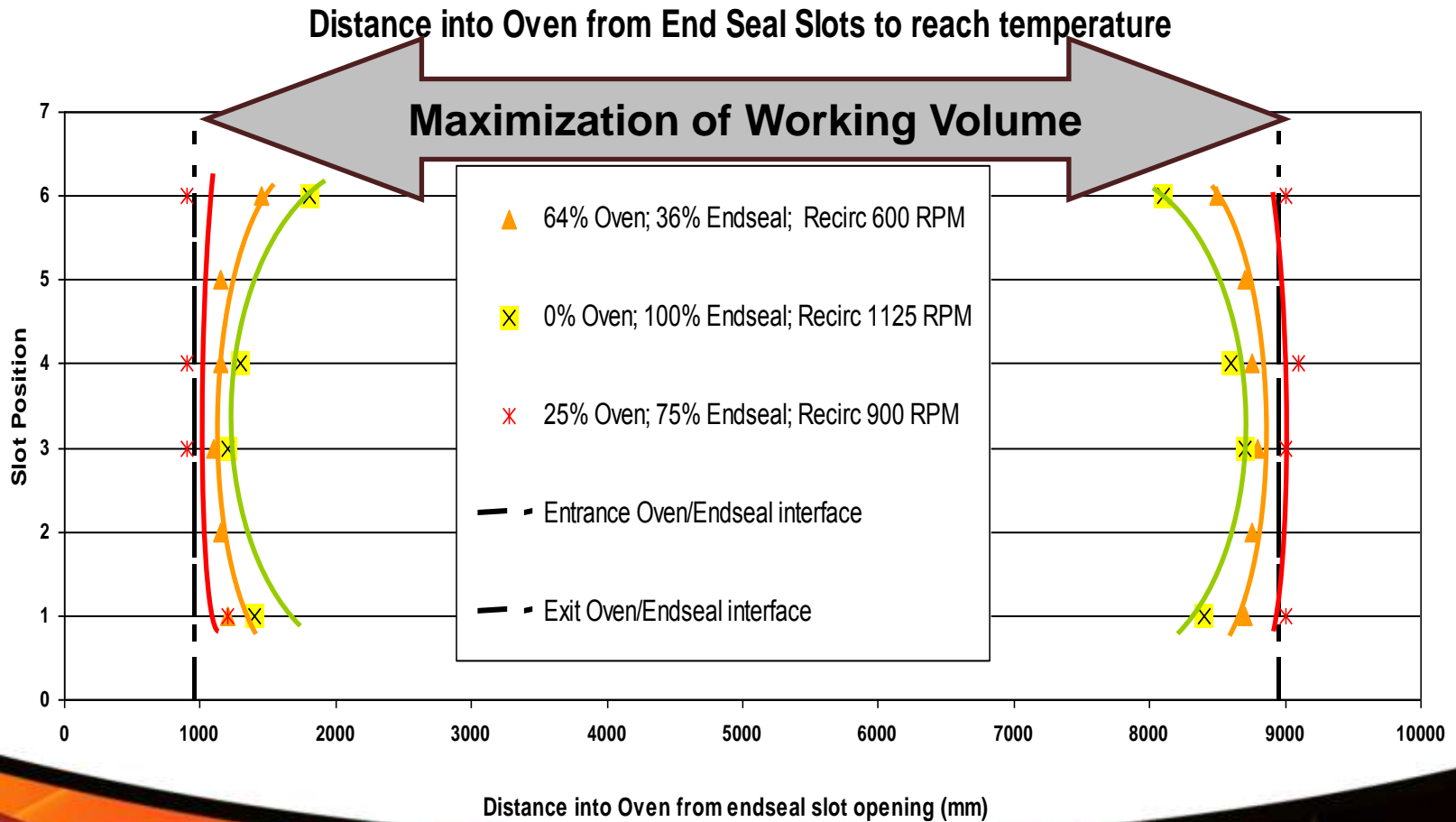
## Performance Metrics

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



# Shift Towards Sealed Oxidation Oven Design

Greater Active Volume Due to Seal Advances



# Shift Towards Sealed Oxidation Oven Design

## Integration & Heat Recovery 2m and 3m (6 Zone Designs)

Line Width	m	2m Wide	3m Wide
Oxidation Oven Zones	#	6	6
Total Exhaust Rate	Nm <sup>3</sup> /hr	20760	43200
Exhaust Temp	C	260	260
Ambient Temp	C	25	25
Delta T	C	235	235
Energy Lost	kw	1633	3399

% MakeUp to Exhaust	%	0.75	0.75
Preheated Make Up	Nm <sup>3</sup> /hr	15570	32400
Make Up Temperature	C	260	260
Ambient Temp	C	25	25
Offset	kw	1225	2549
Hours Per Year	kw	>7000	>7000
USD\$ / kw-hr	\$	\$0.10	\$0.10
USD\$ / year	\$	\$903,150	\$1,879,385

# Investment in Technology Advancements

Five Important Technology Advancements focused on Efficiency for Carbon Fiber Capacity Expansion:

1. Increase of Scale (Wider and Longer)
2. Treatment of Oxidation Oven Exhaust & Potential for Energy Recovery
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=> As we reflect on these advancements which have enabled the current state of capacity, we must consider what additional advancements will be necessary to support growth at the economics needed for automotive.

Challenges and Expectations for Automotive Market:  
4) Supply Chain Risks

# Current Supply Chain Status

- Modern Production Rates

1500 TPY – 2750 TPY Per Line

- Production Capacity Growth Rate

4 - 6 Line Major Industrial Fiber Expansions Per Year

12 Months – 18 Months Per Line Execution

Current Industry Capability to Support 6000 TPY – 16,500 TYP Expansion

- Line Availability

Most Lines are rated for 7200 hours / year or less (82% Availability)

Most lines operating at less than nameplate capacity, due to:

- Operational Experience

- Material Packing Efficiency

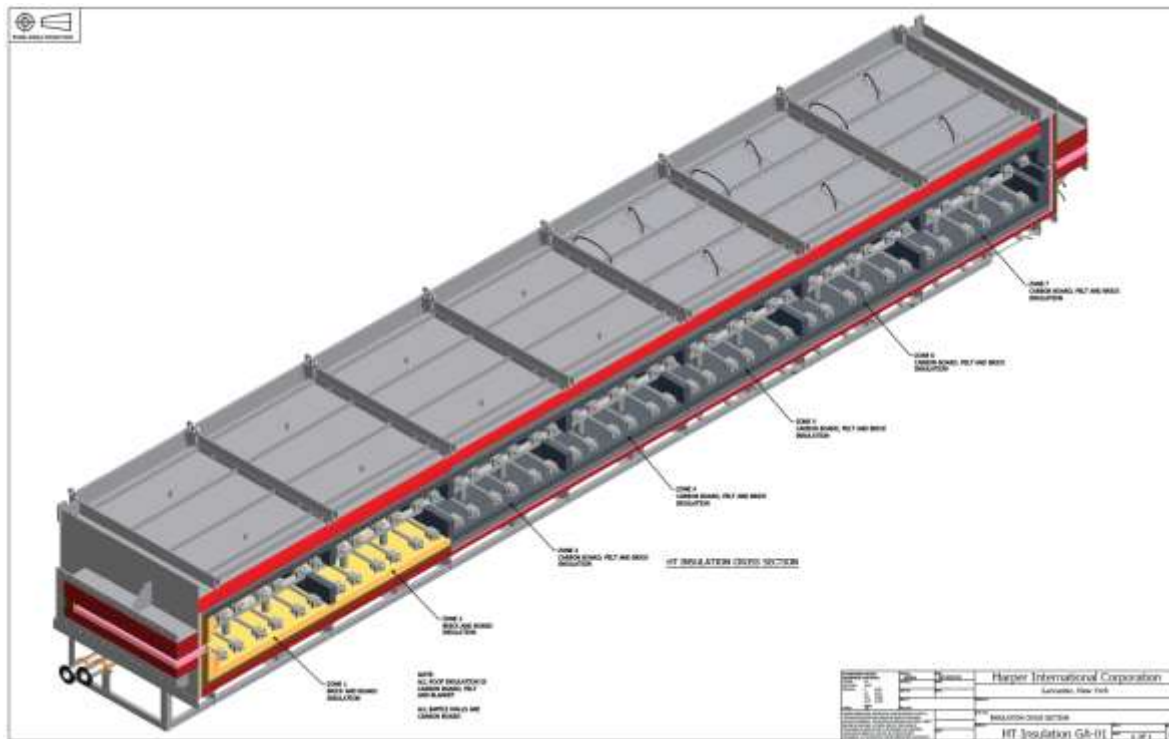
- Online Availability

Forthcoming expansions should consider the supply capacity within the market place and partner with suppliers for dedicated capacity.

Opportunities exist for debottlenecking as well.

# Supply Chain Risk Mitigation

- Module Standardization (Platform Design) yields Fast-Cycle Manufacturing and Delivery



## Harper's Platform Design HT Furnace

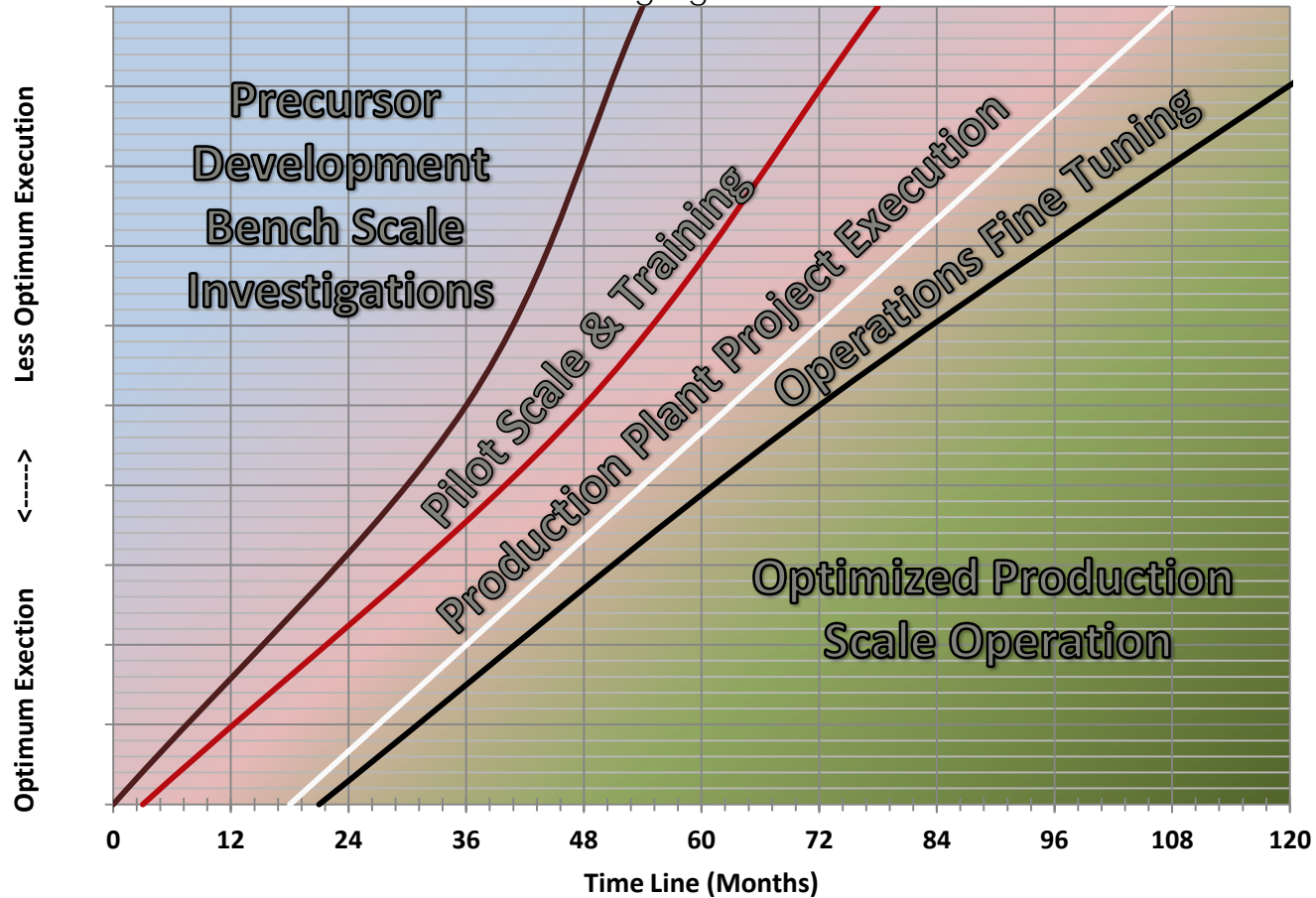
- ✓ Custom Design Provided through Assembly of Standardized Modules of Varying Design and Capabilities
- ✓ Each Module Optimized for delivery with Standard Shipping Containers
- ✓ 20% - 30% Reduction in Manufacturing Time



Challenges and Expectations for Automotive Market:  
5) Optimizing the Project Development Timeline

# Optimizing the Project Development Timeline

Timeline to Production Scale Operations  
for Emerging Producers



— Bench Scale Investigations — Pilot Scale — Production Scale — Optimized Operations (Nameplate)

# Optimizing the Project Development Timeline

- Precursor Development & Bench Scale Investigation  
0 – 60 Months in Duration (Buy, Develop, License)
- Pilot Scale Investigation, Scale Up, Validation & Training  
3 – 24 Months in Duration (Test at Harper Facility –vs- Own)
- Production Scale Project Execution  
15 – 30 Months in Duration (Experience & Execution Plan)
- Operations Fine Tuning  
3 – 24 Months in Duration (Oper. Experience & Training)
- Production Scale Operation: Total Time Line

Total Time Line for Reaching Production Scale Operation  
20 Months to More than 10 Years

# Optimizing the Project Development Timeline

- How to Establish a Technology Position

Buy, Joint /Venture, License Technology, Develop Technology  
What about a Process Design Package

- First Target Fiber Uses; then Type, Properties and Capacity

Led By Business Planning and Market Development Efforts

- Understand Your Process and the Impact of Technical Specifications

Empirical Investigation of Material Packing Density (Tow Spacing is Critical)  
Empirical Investigation of Residence Time and Each Process Step

Market Size and Empirical Data Will Determine Line Size and Unit Op. Design

- Consider Capacity and Other Needs – Is a Single Line Enough?

Capacity Limitations of Single Lines

How is Product Development Handled

How Is Training and Staff / Operations Development Handled

Partnerships, Industrial Pilot Plants and MicroLine Options

# Summary of Challenges for Automotive Adoption

## 1. Diminishing returns in optimization of current scale systems

Further Expansion beyond 3,000 TYP Line is within Reach

Modest Reductions on Cost of Production from Scale

## 2. Reducing carbon footprint

3x – 9x the Theoretical CO2 footprint is unacceptable

## 3. Development costs associated with next generation technology

Need to Focus on Technology advancements

Opportunity for Reduction of CO2 footprint is Key

## 4. Supply Chain Risks

Major expansion plans should be coordinated with Supply Chain to avoid bottle necks

## 5. Optimizing the Project Development Timeline

Various paths to commercialization that players may take must be considered as automotive adoption is forecasted

Thank you for your time!



*Spark the future.™*

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