Agenda

- About Harper International
- Historical Growth & Expansion Trends
  - Review of Scales of Operations
  - Five Important Historical Steps
- Challenges to Capturing Growth
- A Path to Achieve Greater Capacities
About Harper

- Headquartered outside of Buffalo, NY
- Established in 1924
- 45,000 ft² manufacturing facilities
- 5,500 ft² dedicated Technology Center
- Multi-disciplined engineering talent
  - Chemical
  - Ceramic
  - Mechanical
  - Electrical
  - Industrial
  - Process & Integration
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
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**
# Carbon Fiber Historical Growth & Expansion Trends

## Review of Scales of Operations

<table>
<thead>
<tr>
<th>Scales</th>
<th>Size Range (mm Width)</th>
<th>Capacity</th>
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<tbody>
<tr>
<td>Production</td>
<td>1000mm-4200mm</td>
<td>100tpy to more than 4000tpy</td>
</tr>
<tr>
<td>Industrial Scale Pilot</td>
<td>300mm-1000mm</td>
<td>20tpy-100tpy</td>
</tr>
<tr>
<td>Micro Scale (University, Institute)</td>
<td>&lt;100mm</td>
<td>Less than 1tpy</td>
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Carbon Fiber Historical Growth & Expansion Trends

Five Important Historical Steps Towards Efficiency that have Supported 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 Historical Steps Towards Efficiency

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: Carbon Fiber Conversion Cost Model

Cost Dynamics as a Function of Scale-Up
Five Important Historical Steps Towards Efficiency

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

<table>
<thead>
<tr>
<th>Line Width</th>
<th>m</th>
<th>2m Wide</th>
<th>3m Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation Oven Zones</td>
<td>#</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Exhaust Rate</td>
<td>Nm3/hr</td>
<td>20760</td>
<td>43200</td>
</tr>
<tr>
<td>Exhaust Temp</td>
<td>C</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>Ambient Temp</td>
<td>C</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Delta T</td>
<td>C</td>
<td>235</td>
<td>235</td>
</tr>
<tr>
<td>Energy Lost</td>
<td>kw</td>
<td>1633</td>
<td>3399</td>
</tr>
</tbody>
</table>
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

Schematic of a RTO

Treatment of Oxidation Oven Exhaust: Waste Gas Treatment Systems

Courtesy of Anguil Environmental
Oven Make Up Air Preheated to >200C in the 2\textsuperscript{nd} Stage Preheater
Five Important Historical Steps Towards Efficiency

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

Gas Abatement - Collection

LT Dual Vent System for Online Switching (Closed Pipe Design)
Five Important Historical Steps Towards Efficiency

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 Historical Steps Towards Efficiency

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)

![Graph showing useful oven volume and volume with 2°C variance for cases A, B, and C.]

Maximization of Working Volume
Shift Towards Sealed Oxidation Oven Design

Greater Active Volume Due to Seal Advances

Distance into Oven from End Seal Slots to reach temperature

Maximization of Working Volume

- 64% Oven; 36% Endseal; Recirc 600 RPM
- 0% Oven; 100% Endseal; Recirc 1125 RPM
- 25% Oven; 75% Endseal; Recirc 900 RPM

Slot Position
Distance into Oven from endseal slot opening (mm)
### Shift Towards Sealed Oxidation Oven Design

#### Integration & Heat Recovery

2m and 3m (6 Zone Designs)

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<tr>
<td>Oxidation Oven Zones</td>
<td>#</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total Exhaust Rate</td>
<td>Nm3/hr</td>
<td>20760</td>
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<tr>
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<td>1633</td>
<td>3399</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% MakeUp to Exhaust</th>
<th>%</th>
<th>0.75</th>
<th>0.75</th>
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<td>Preheated Make Up</td>
<td>Nm3/hr</td>
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<td>32400</td>
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<tr>
<td>Make Up Temperature</td>
<td>C</td>
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</tr>
<tr>
<td>Ambient Temp</td>
<td>C</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Offset</td>
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<tr>
<td>Hours Per Year</td>
<td>kw</td>
<td>&gt;7000</td>
<td>&gt;7000</td>
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<tr>
<td>USD$ / kw-hr</td>
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<td>$0.10</td>
<td>$0.10</td>
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<tr>
<td>USD$ / year</td>
<td>$</td>
<td>$903,150</td>
<td>$1,879,385</td>
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</table>
Historical Growth & Expansion Trends – Why are These Steps Important?

1. Increase of Scale (Wider and Longer)  
   -> Over 40 years, scale of operation has reduced costs by half

2. Treatment of Oxidation Oven Exhaust & Potential for Energy Recovery  
   -> At modern production scales, more than 12 kW-hr / kg of CF can be removed through energy reuse (35 kw-hr / kg -> 20 kw-hr / kg)

3. Closed Pipe Treatment of Furnace Exhausts & Potential for Energy Recovery  
   -> Reduces NOx discharge from plants, allows for greater single site capacity  
   -> Opportunity for kw-hr / kg energy reduction through recovered fuel value

4. Low Profile Furnace Muffles for Reduced Gas Consumption  
   -> Change of Furnace muffle design has allowed for 40% - 50% reduction in Nitrogen Consumptions (kg N2 / kg CF)

5. Movement Towards Sealed Oxidation Oven Design  
   -> Further energy reductions in oxidation and abatement are possible
Carbon Fiber Expansion: Challenges to Capturing Growth
Challenges in Carbon Fiber Operations to Capturing Projected Growth

- Diminishing returns in optimization of current scale systems
- Development costs associated with next generation technology
- Need for increased efficiency of chemical reaction
- Reducing carbon footprint
Challenges in Carbon Fiber Operations to Capturing Projected Growth

Asymptote Indicative of Diminishing Returns

Cost Dynamics as a Function of Scale-Up
A Path to Achieve Greater Capacities
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
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
Harper Beacon: Outputs
Quantifies Environmental and Energy Efficiency

152 Variable

Beacon Model

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

152 Variable

Beacon Model

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 Lower HCN and Higher CO2

Thermal Losses:
kWh of Losses as a function of Scale & Operating Parameters
Allows for Quantification of Anticipated Thermal Losses and Design Optimization

For a Full List of Capabilities Consult Harper
Carbon Dioxide Emissions:

- Expressed in total kg/hr of CO2 Emitted and kg/hr of CO2 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
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)
- 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
Carbon Dioxide Emissions:

![CO2 Emission from Different Control Equipment](image)

Process Assumptions:
- 10,000 SCFM
- 70°F Inlet Temperature
- 5% Lower Explosive Limit
- Toluene Emissions

Courtesy of ANGUIL Environmental
CO2 Emissions Modeling

Sample Data from www.harperbeacon.com
### Primary Results from Sample Evaluation:

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rates:</td>
<td>500 – 2250</td>
<td>TPY</td>
</tr>
<tr>
<td>Line Sizes:</td>
<td>1750 &amp; 3000</td>
<td>mm Wide</td>
</tr>
<tr>
<td>CO2 Emissions*:</td>
<td>9.7 – 23.4</td>
<td>kg CO2 Per kg CF</td>
</tr>
<tr>
<td>Theoretical CO2*:</td>
<td>2.7 (average)</td>
<td>kg CO2 Per kg CF</td>
</tr>
<tr>
<td>CAPEX</td>
<td>$2.17 – $4.55</td>
<td>USD / kg of CF</td>
</tr>
<tr>
<td>OPEX</td>
<td>$6.27 – $14.58</td>
<td>USD Per kg CF</td>
</tr>
</tbody>
</table>

(*Energy to Produce Purge Gas Ignored)

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

Plan to capture greater opportunities ahead must include continued equipment improvements with a holistic operating economics perspective.
Thank you for your time!

Visit us at harperintl.com and harperbeacon.com

Spark the future.™