Presentation Overview

Advancements in Carbon Fiber Research & Development

- Industrial Scale
- Micro Scale Processing Lines – Enabling Rapid Cycle Research
- Going Smaller?

Industrial Scale Carbon Fiber Advancements

- MultiFlow Oxidation Oven Technology
- Benchmarking the Next Generation of Advanced Oxidation Ovens
Carbon Fiber Systems Experience

- Multiple references for complete CF line supply
- Pilot scale (<100 TPY)
- Production scale (up to >1500 TPY)
- Research Scale – micro (<1 TPY)
- Hundreds of LT furnace, HT furnace and surface treatment systems worldwide
Carbon Fiber Systems
Scale of Operations

Scale of Operations
- Industrial Production
- Industrial Research (Pilot Plant)
- Research (Non-Industrial Scale)

Considerations
- Capacity
- Feed Stock Requirements
- Frequency of Use & Staffing
- Investment Costs
# Carbon Fiber Systems
## Scale of Operations

<table>
<thead>
<tr>
<th>Scale</th>
<th>Size Range (mm Width)</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>1000mm - 4200mm</td>
<td>100 tpy to More Than 2000 tpy</td>
</tr>
<tr>
<td>Industrial Scale Pilot</td>
<td>300mm - 1000mm</td>
<td>20 tpy - 100 tpy</td>
</tr>
<tr>
<td>Micro Scale (University, Institute)</td>
<td>&lt;100mm</td>
<td>Less Than 1 tpy</td>
</tr>
</tbody>
</table>
## Carbon Fiber Systems Scale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Size Range (mm Width)</th>
<th>Capacity</th>
<th>Function</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>1000mm - 4200mm</td>
<td>100 tpy to More Than 2000 tpy</td>
<td>Continuous, Industrial</td>
<td>15MM USD - 45 MM USD</td>
</tr>
<tr>
<td>Industrial Scale Pilot</td>
<td>300mm - 1000mm</td>
<td>20 tpy - 100 tpy</td>
<td>Continuous, Pilot (Mimics Industrial)</td>
<td>Up to 15MM USD</td>
</tr>
</tbody>
</table>
Carbon Fiber Systems
Scale of Operations

System Investment

Industrial Scale
Pilot Plant Range

Non-Industrial Users

Capacity (TPY)

$100,000,000

$10,000,000

$1,000,000

$100,000

MM USD
Carbon Fiber Systems
Scale of Operations

System Investment

Harper Developed
Micro Line

Capacity (TPY)

MM USD

$1,000,000

$10,000,000

$100,000,000
Carbon Fiber Systems
Scale of Operations
Carbon Fiber Systems
Micro Scale Research System

- Fits within a Reduced Foot Print 72’L (22m) x 12’W (3.15m) x 10’H (3.05m)
- Capable to Extremely Low Load Control (grams)
- Enables Processing of Sub 1k Filament Bundles
- Continuous Process
- Equivalent to an Industrial System w.r.t. Number of Material Handling Systems
- Some Variation in Retention Time and Zone Count from an Industrial System

Lower (Lowest?) Practical Limit for Continuous Fiber Draw?
## Carbon Fiber Systems
### Scale of Operations

<table>
<thead>
<tr>
<th>Scale</th>
<th>Size Range (mm Width)</th>
<th>Capacity</th>
<th>Function</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>1000mm - 4200mm</td>
<td>100tpy to More Than 2000 tpy</td>
<td>Continuous, Industrial</td>
<td>15MM USD - 45 MM USD</td>
</tr>
<tr>
<td>Industrial Scale Pilot</td>
<td>300mm - 1000mm</td>
<td>20tpy - 100 tpy</td>
<td>Continuous, Pilot (Mimics Industrial)</td>
<td>Up to 15MM USD</td>
</tr>
<tr>
<td>Micro Scale (University, Institute)</td>
<td>&lt;100mm</td>
<td>Less Than 1 tpy</td>
<td>Continuous (Some Variance, Zones, Times. Less Feed Stock Required)</td>
<td>Less than 5MM USD</td>
</tr>
</tbody>
</table>
Carbon Fiber Systems
Scale of Operations

Need for Even Smaller Systems
???
Carbon Fiber Systems
Micro Scale Research System

Potential Table Top Research System

- Continuous or Batch?
- Multiple Cycles of Combined Heating, Atmosphere and Loading within a Single Machine
- Scale-Ability? How to Benchmark performance and Track to Industrial Scale Research
- Enables a Broad Research Community
Advancements in Carbon Fiber Research & Development

- Industrial Scale
- Micro Scale Processing Lines – Enabling Rapid Cycle Research
- Going Smaller?

Industrial Scale Carbon Fiber Advancements

- MultiFlow Oxidation Oven Technology
- Benchmarking the Next Generation of Advanced Oxidation Ovens
Harper Oxidation Technology
Harper International
MultiFlow Research Oven

MultiFlow Research Ovens

- Pertains to Industrial Scale Facilities
- Capable of Operating in Multiple Industry Standard Flow Distributions
- Meets or Exceeds Best In Class for Each Flow Regime
- Allows for True Evaluation of Different Flow Techniques with Balance of Line under Similar Conditions
Harper Oven
Technology Focused Areas for Technology Advances

- Most Technologies focus only on Temperature Uniformity
- Harper Oxidation Technology offers Improvements in:
  - Velocity Uniformity
  - Velocities Range Capability
  - Modular Construction Technique
  - Advanced Instrumentation and Control
  - Superior Atmospheric Seals
Concrete Guarantees in Performance

- Temperature Uniformity

![Temperature Uniformity Graph]

- Mean temperature: 236.0 °C
- Standard deviation: 1.3 °C
- Average variance: 1.2 °C
Concrete Guarantees in Performance

- Wider Range of Operational Velocities

---

**Harper Oxidation Oven**

**Cold Flow Test - Velocity Uniformity Across Width**

*Fig 1. Velocity Uniformity Data – 3 m/s to 5 m/sec Mean Airflow (Passes are counted from the Bottom of the Chamber Upward)*
Concrete Guarantees in Performance

- Velocity Field Uniformity

**Equivalence Uniformity at Higher Velocity = Faster Oxidation**
Harper Oven Technology Nozzle Development

Lower Energy in Recirculation Through Optimization of Nozzle Delta P (Pressure Loss)
Harper Oven
Technology Focused Areas for Technology Advances

Concrete Guarantees in Performance
- Velocity Field Uniformity – Vibration Testing

- Parallel Flow - Air Velocity
- Vibration Testing Results Show Low Fiber Disruption, at 2x to 3x Typical Velocities
Harper Oven
Technology Pilot System Modular Construction

Full Line Pilot System (300mm) by Harper International

- Harper MultiFlow Oven, Field Erect ~1,000 Manhours
- 90% Reduction in Labor versus similar Field Erection Time
Harper Oven
Technology Focused Areas for Technology Advances

Modular Construction for Optimal Installation Time
- Actual Install Time ~ 1,000 Man-hours
Instrumentation & Controls

- System Flow Control
- Two-Tier Balancing Methodology
- Responsive Quench System and Rapid Cool Down System
- Emissions Monitoring
- Inherently Safer Pressure Relief System
Unique Seal Design

Motorized Seal Slots

Side Venting of Slot Passes and Vertical Collection of Exhaust Gases

Technology Focused Areas for Technology Advances
Harper Oven Technology End Seal Function
Harper International
Oven Seals and Energy Recovery

Why is Improved Seal Technology Important?
- Reduced Fugitive Emissions
- Increase Active Volume of Oven
- Reduced Energy Consumption
Ideal Situation is Preheated Make-Up Flow is Approximately Equal to the Exhaust Flow (MU/E ~ 1)
Harper International
Oven Seals and Energy Recovery

But… As Make-Up Flow Approaches Exhaust Flow Fugitive Emissions Increase
Harper International
Oven Seals and Energy Recovery

To Reduce Fugitive Emissions, Typical Seals Depend on Ingress of Cold Air at the Seal Face
Harper International
Oven Seals and Energy Recovery

Air Into the Seal Results in Less Preheated Makeup
Harper International
Oven Seals and Energy Recovery

The Ratio of Make Up / Exhaust is Critical for Energy Efficiency
Harper International
Oven Seals and Energy Recovery

Harper’s Seal Results in Reduced Fugitive Emissions and Higher Energy Reutilization. Guarantee Performance w.r.t. M/E Ratios
Harper Oven
Technology Focused Areas for Technology Advances

Concrete Guarantees in Performance
- Greater Active Volume Due to Seal Advances
Concrete Guarantees in Performance

- Greater Active Volume Due to Seal Advances
Harper International

Summary

- Emergence of Research Systems for Non-Industrial Users
- Product Development for Further Reduction of R&D Systems
- Emergence of MultiFlow Research Ovens
- Advancement of Oven Technology
Thank You for Your Attention

The greatest laboratory in the world is the human mind.