Processing Advancements Within Reach for Achieving Significant Reductions in Carbon Fiber Cost of Manufacturing

JEC Europe 2013, Paris
ICS Carbon Conference

Agenda

- Introductions
- Historic Advancements of Scale & Integration
- A Different Approach: Rethinking Unit Operations
  - Reducing Environmental Losses
  - Reducing Purge Barriers
  - Reconfiguration
- Achievable Targets for the Future

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

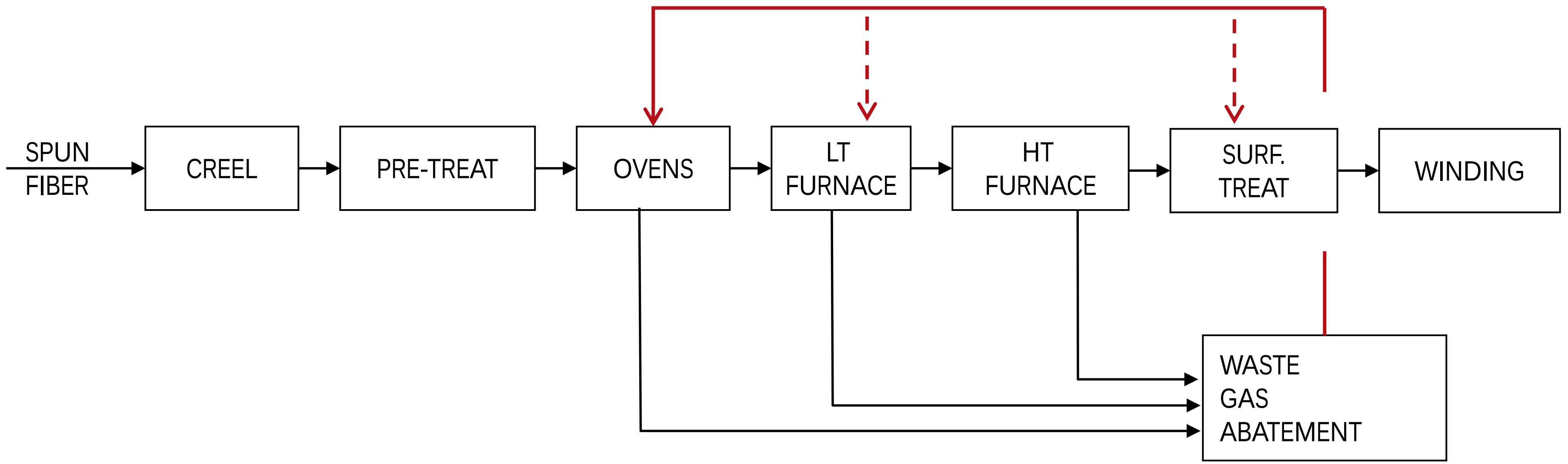
About Harper

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

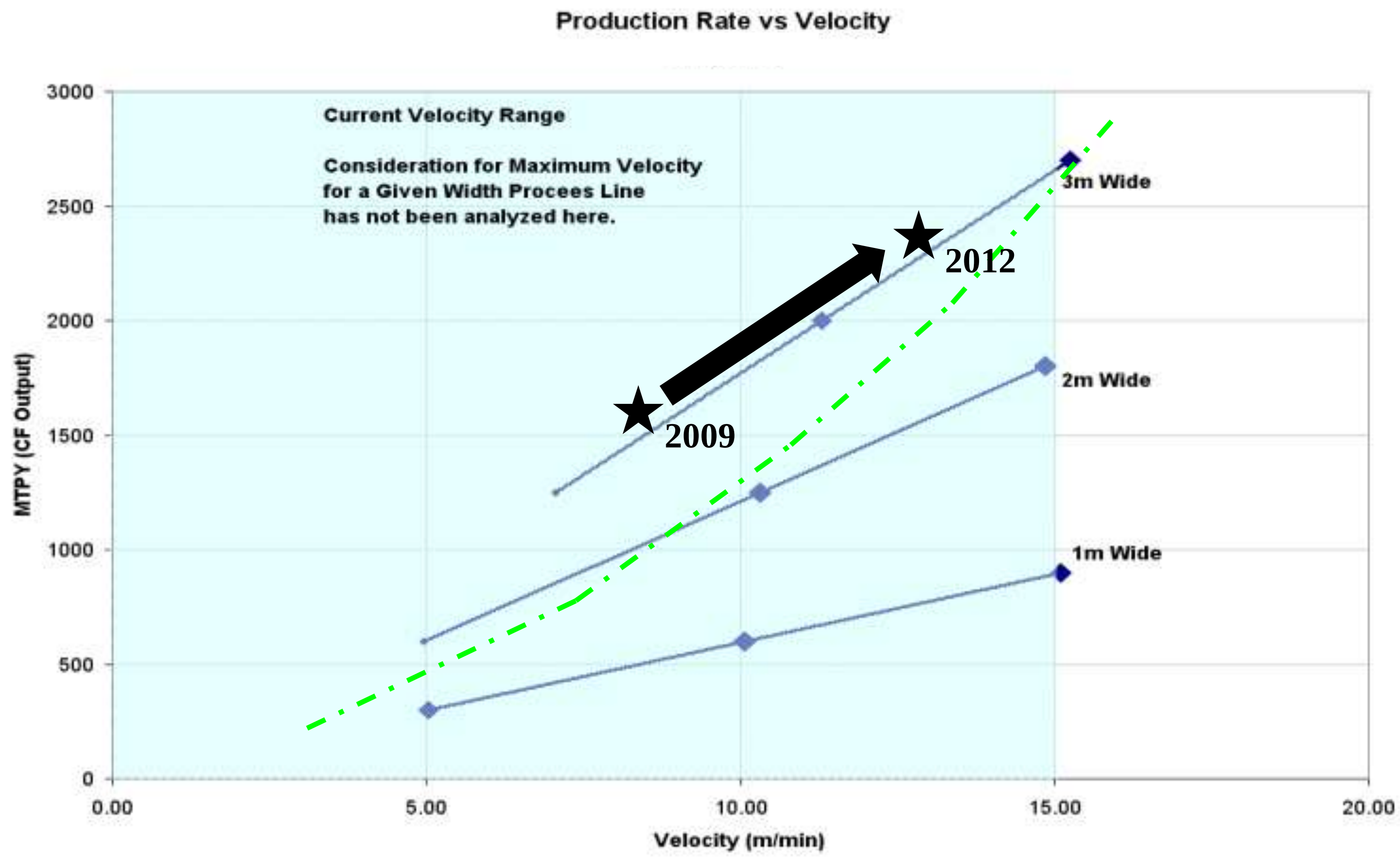
Historic Advancements of Scale and Integration

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

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 – 800 kg/hr feed of PAN

  More than 500 m – 1000m Overall Heated Length

  4 Zones Minimum; Typically 6 – 8 Zones

  3m wide designs are the prevalent state of the art design

  Unsupported Heated Lengths typically less than 15m

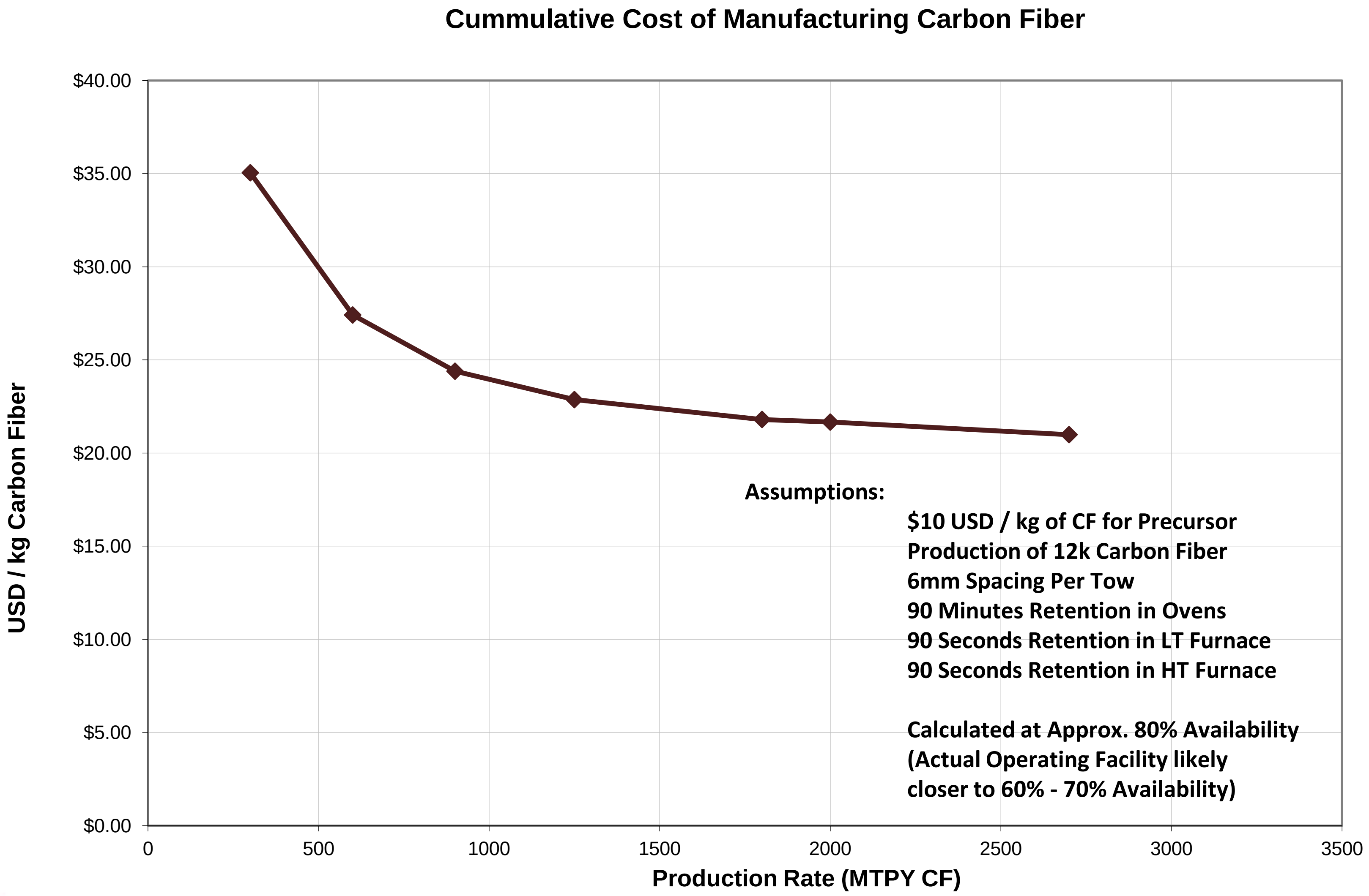
- LT and HT Furnaces Understand Your Process and the Impact of Technical Specifications

  3m wide designs wide are prevalent state of the art design

  Unsupported Heated Lengths 15 m – 20m

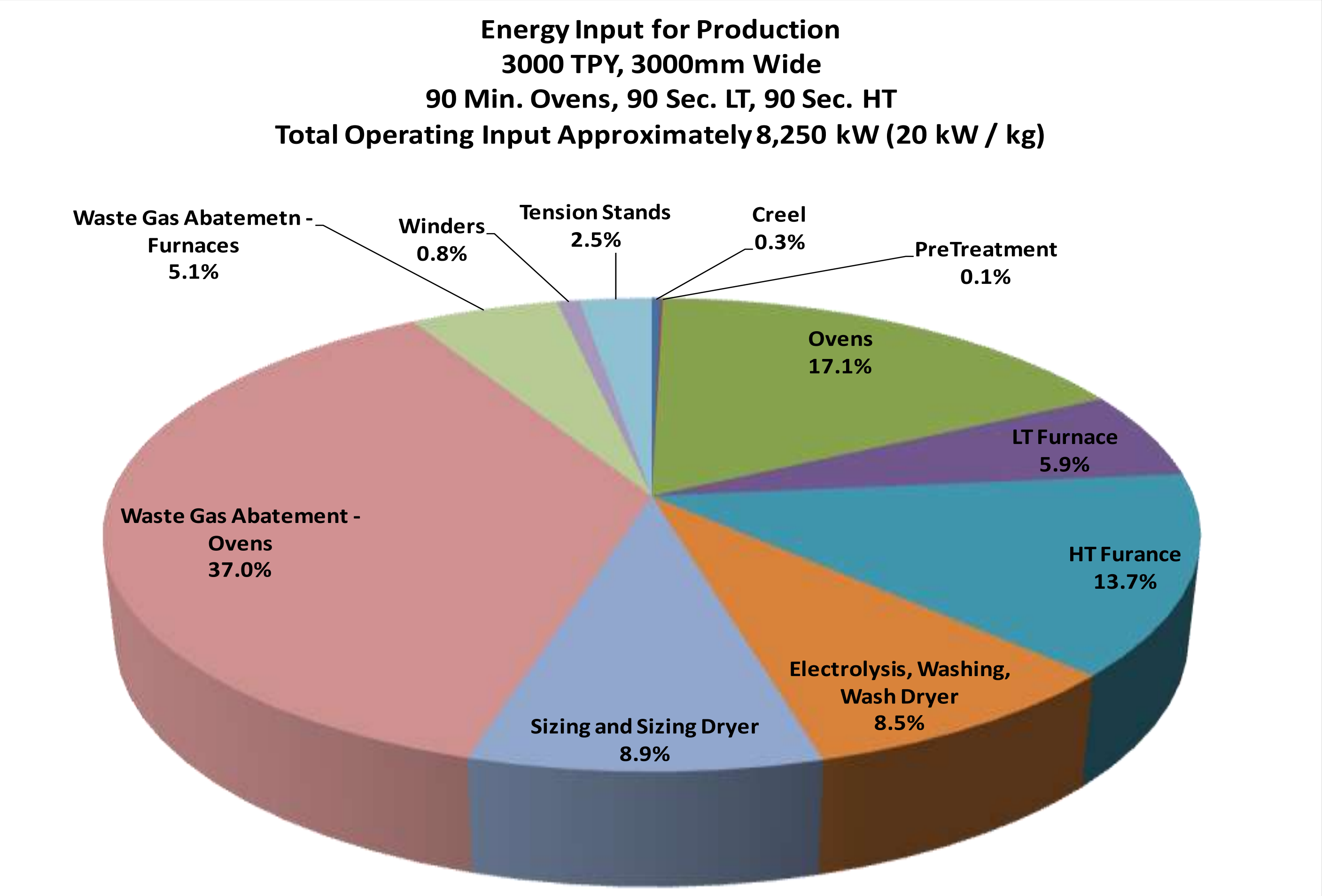
  HT Temperatures Regimes <1450C, 1600C, and 1800C or greater

Economies of Scale



Cost Dynamics as a Function of Scale-Up

Cost Structure Per Unit Operations



Total Conversion Process Cost: ~45 MM USD

Capital Depreciation of $2.14 USD / kg (with 7 yrs S.L.D.)

Exclusive of Facility, Utilities, Installation

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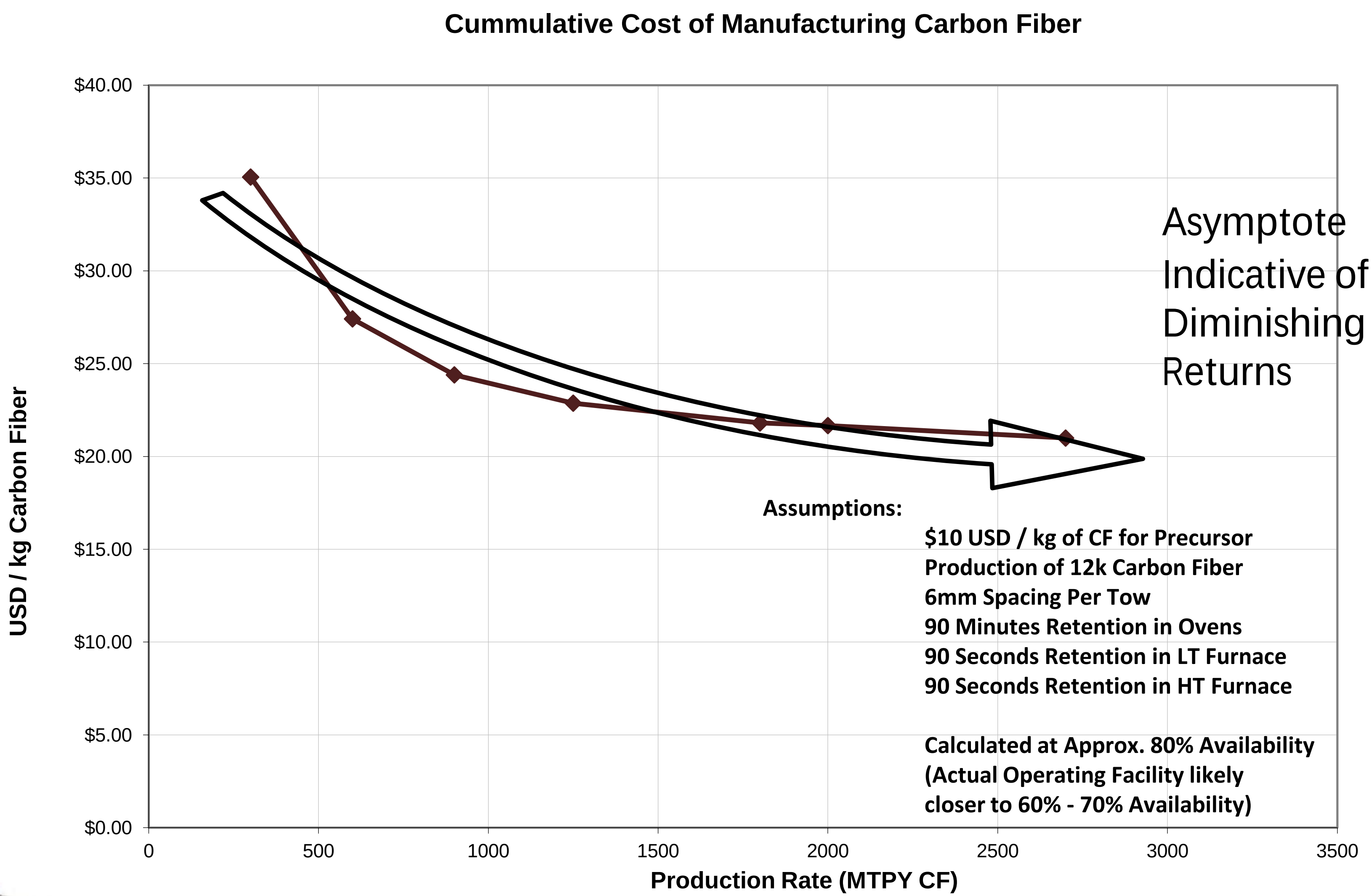
Challenges to Growth in Carbon Fiber Operations

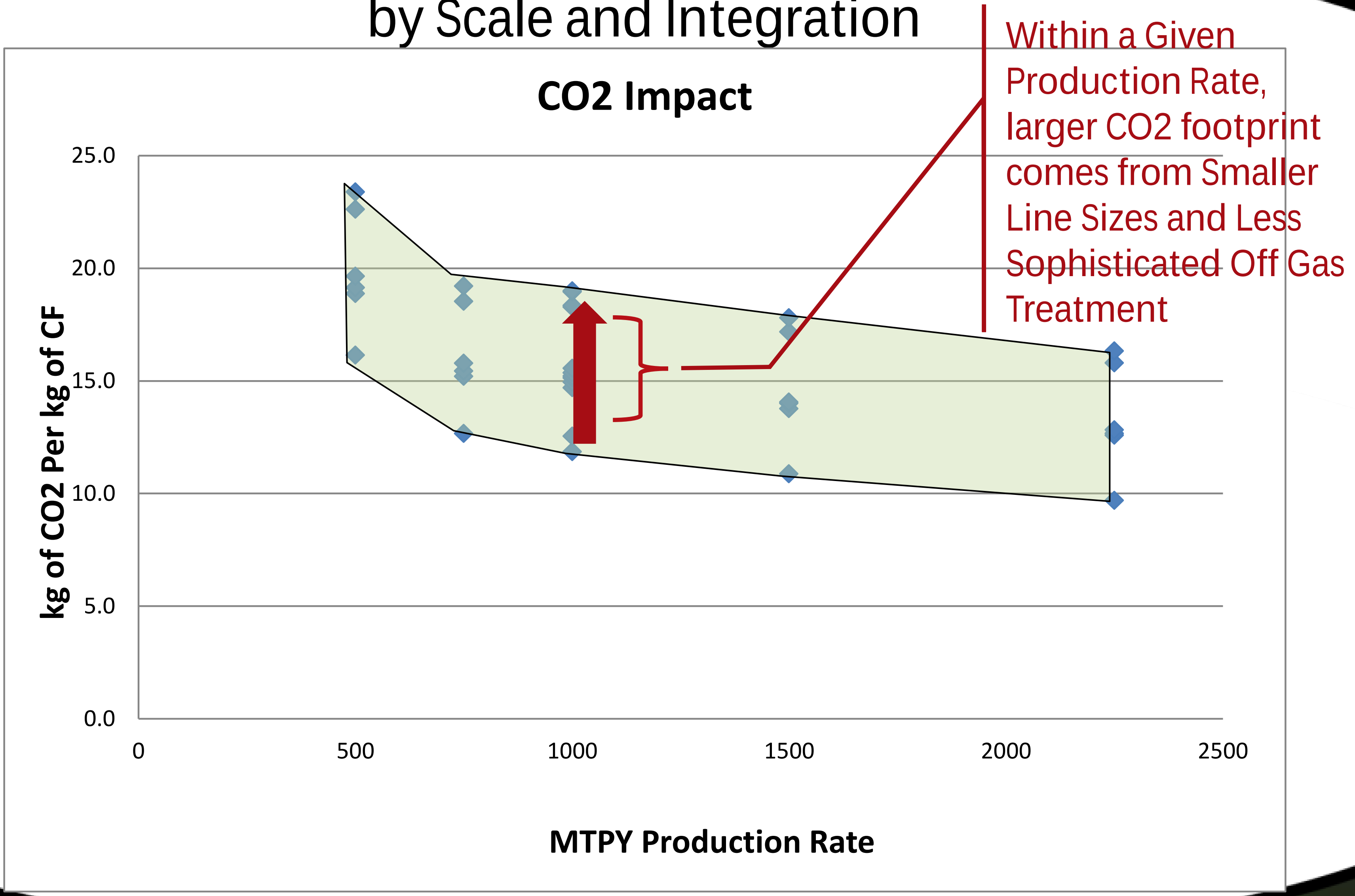
1. Diminishing Returns on Economies of Scale
2. The Carbon Fiber Footprint
3. Investment in Technology Advancements
4. Supply Chain Risks
5. Optimizing the Project Development Timeline

Diminishing Returns on Economies of Scale



Cost Dynamics as a Function of Scale-Up

CO2 Emissions Variation by Scale and Integration



Sample Data from *harperbeacon.com*

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*:	**23.4 – 9.7**	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*

State of the Art - Dynamics

- Larger capital expense for larger capacity lines

  (Of Course)

- But, Higher Capacity Lines achieve lower energy requirements (lower OPEX). Production requires less kilowatts per kg/hr of produced carbon fiber

  Large Capital Investment is Offset by Lower Operating Cost Over Payback over time, 3 year – 7 year Return On Investment (ROI).

Courtesy Of: Oak Ridge National Laboratory Carbon Fiber Technology Center

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Oxidation Oven Power Requirements

Oxidation Oven Heat Balance is driven by:

1. Exhaust Losses – Hot Air Leaving the Oven at Temperature, Replaced by Cold Air Flowing Into Oven Zone
2. Mechanical Energy (Mixing of Atmosphere, Fans)
3. End Losses (Heater Flowing Out of Furnace with Material Cooling at Turnaround Rolls) Air Seal Losses
4. Wall Losses – Heat Flowing Through the Insulated Walls

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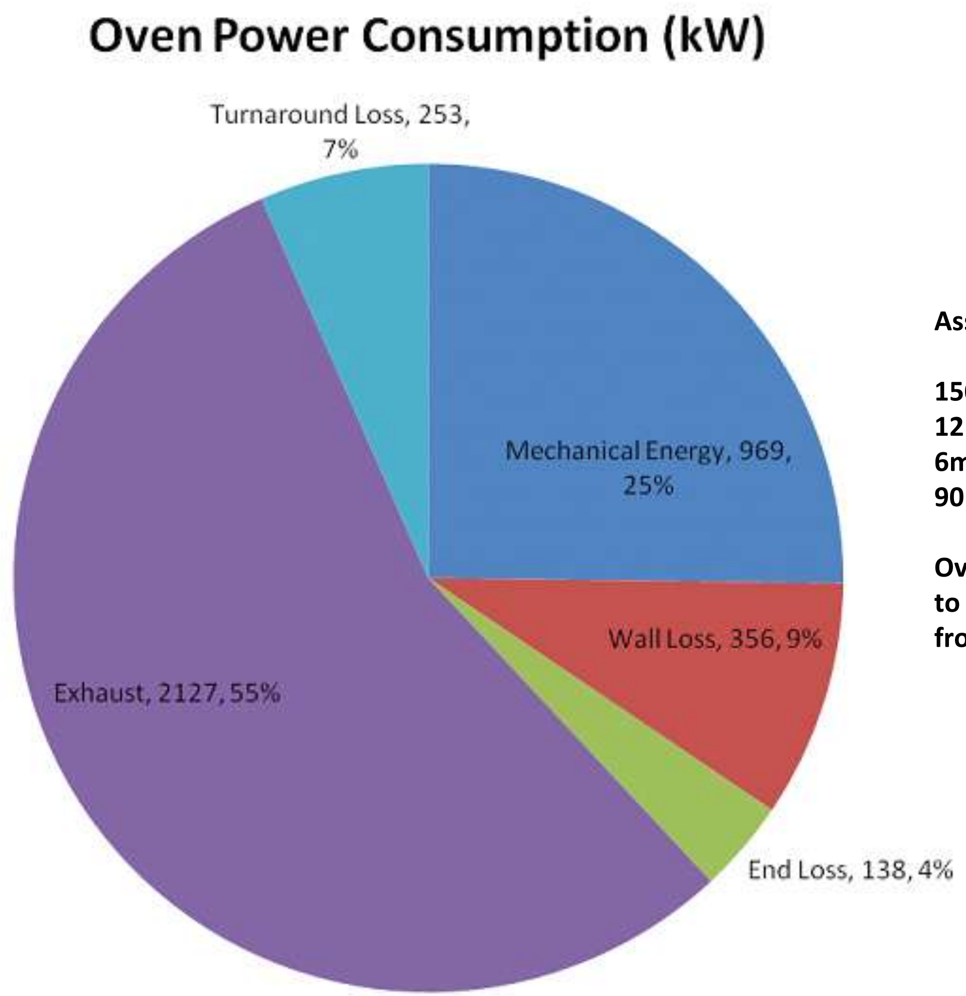
Oxidation Oven Power Utilization

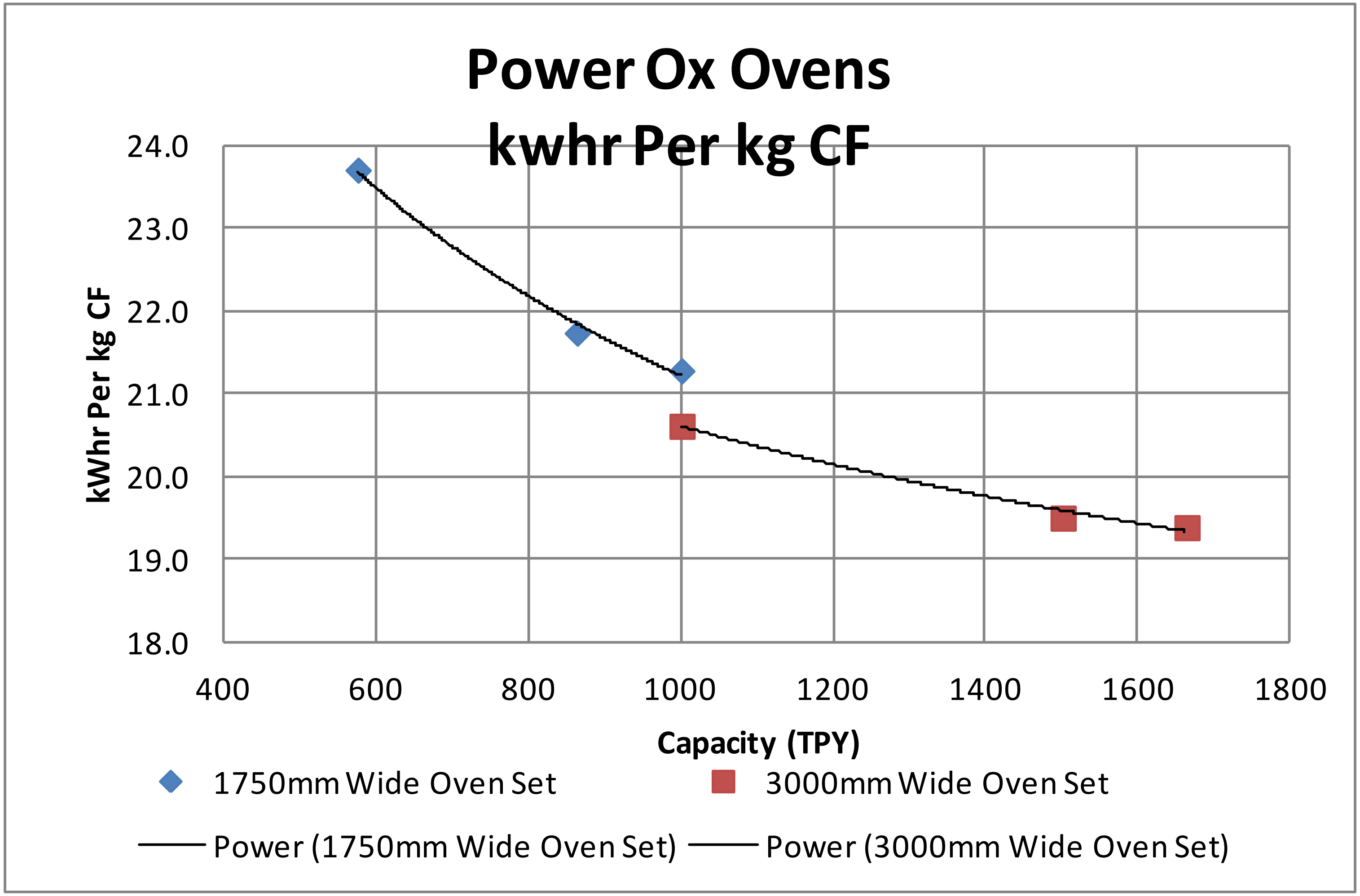


Assumptions:

1500 TPY Production
12k Carbon Fiber
6mm Spacing Per Tow
90 Minutes Retention in Ovens

Oven Operating with Minimum to Moderate Heat Recovery from Waste Gas

Oxidation Oven Power by Scale



LT & HT Furnace Power Requirements

Furnace Heat Balances are driven by:

1. Material Load (Heating of Fiber and Zone by Zone to Temperature – Much Greater Than Just the Sensible Heat of Carbon Fiber)

2. Energy Being Carried Out: by Exhaust Vent, by Vent Conduction, by Purging of Shell and by Purging of Process Atmosphere

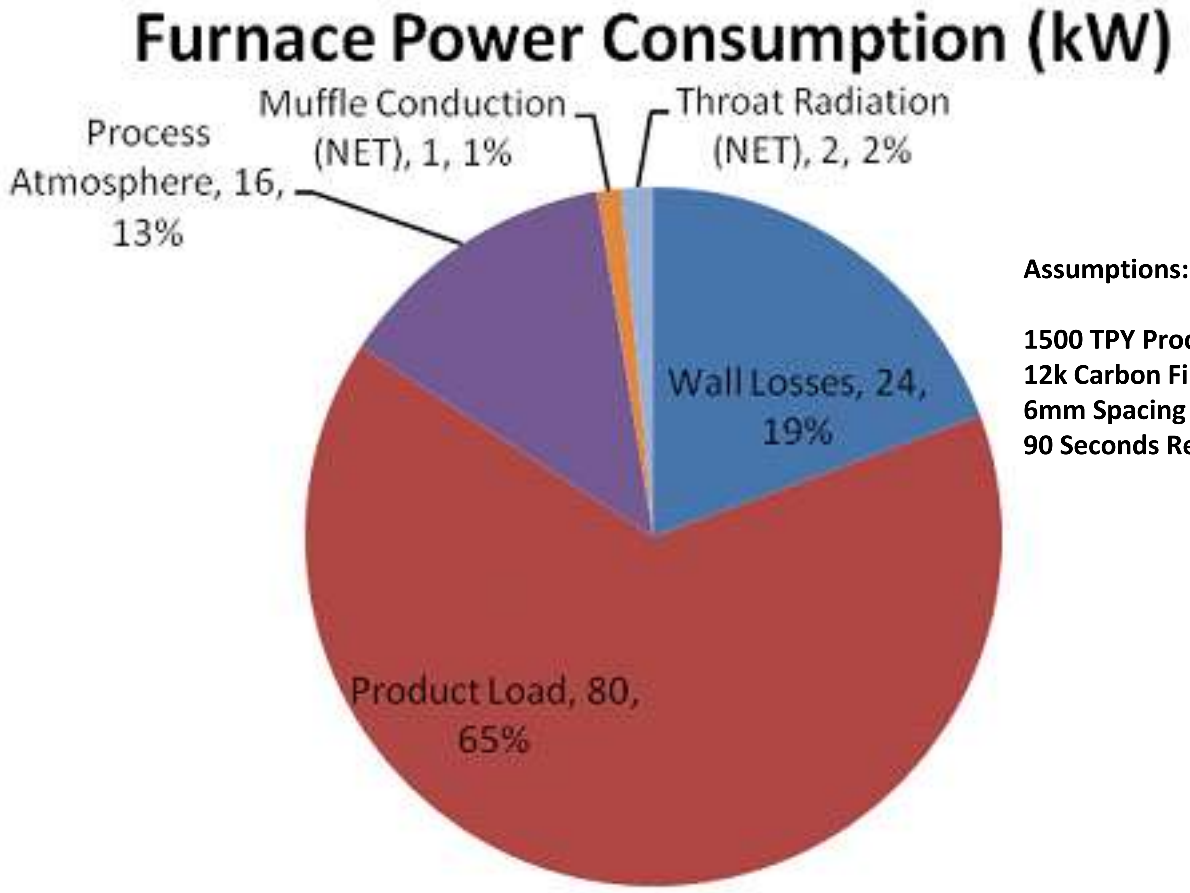
3. End Losses, Energy Flowing Out of Entrance and Exit End, Radiation from Ends. Sight Port Losses.

4. Wall Losses – Heat Flowing Through the Insulated Walls

5. Conduction of Energy through Muffle and Elements

6. Cooling Water Losses

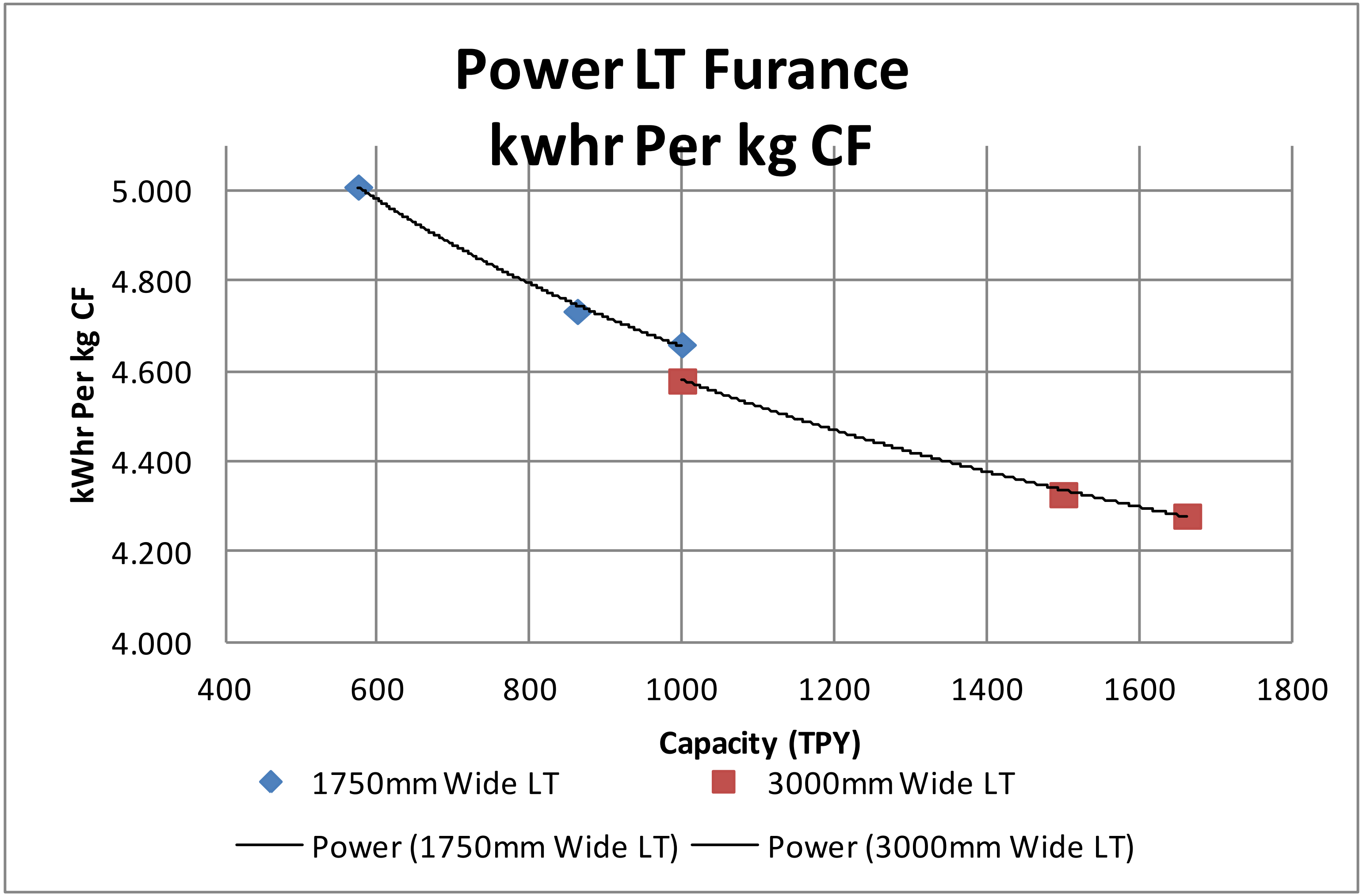
LT Furnace Power Utilization



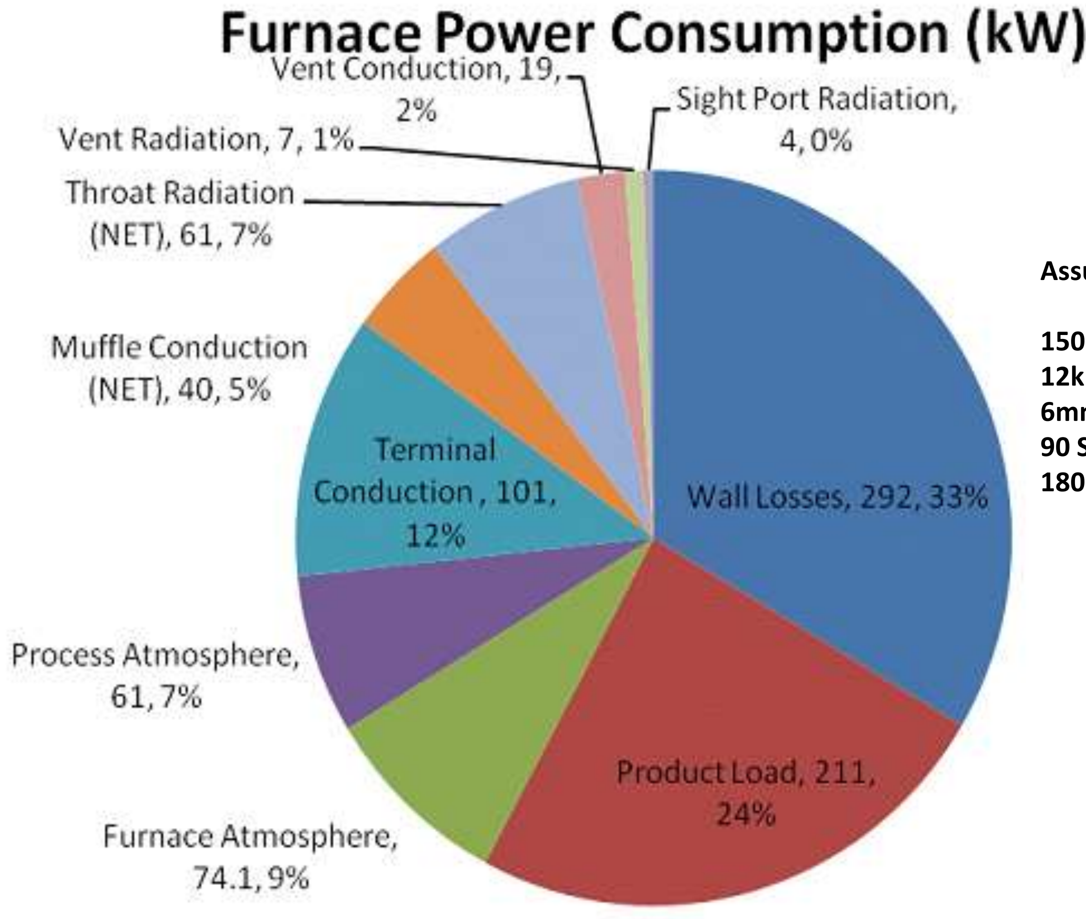
Assumptions:

1500 TPY Production
12k Carbon Fiber
6mm Spacing Per Tow
90 Seconds Retention in LT

LT Furnace Power by Scale



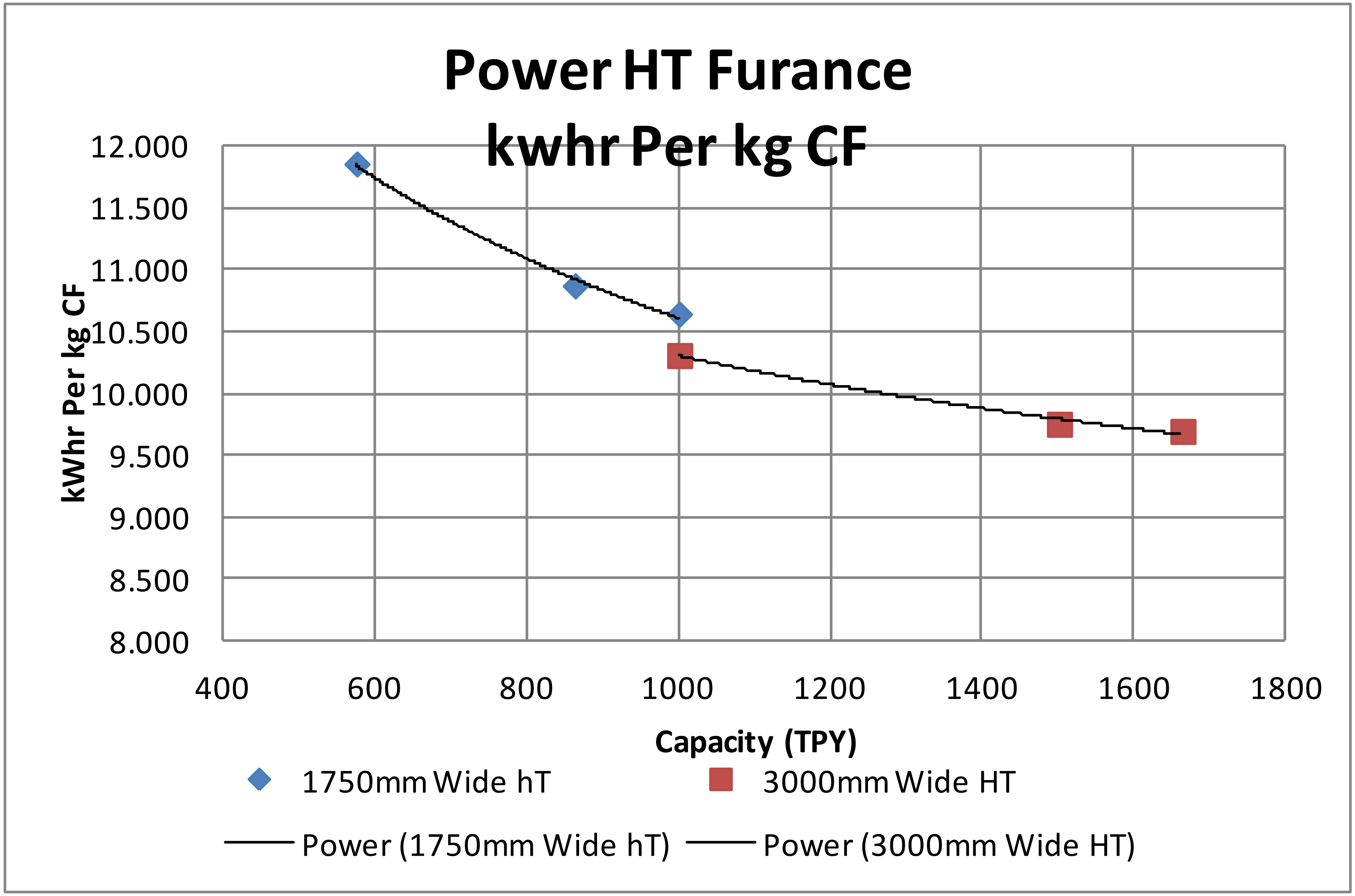
HT Furnace Power Utilization



Assumptions:

1500 TPY Production
12k Carbon Fiber
6mm Spacing Per Tow
90 Seconds Retention in HT
1800C Design of r HT

HT Furnace Power by Scale



Different Approach:
Rethinking Unit Operations

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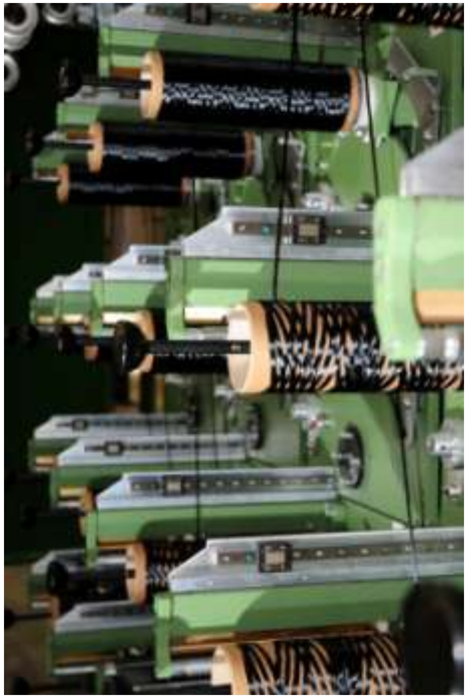
Efficiency Advances – Within Reach

- Don’t Try to Reinvent the Process – Optimize Existing Unit Operations
  Minimize the Timeline for Technology Development and Deployment

- Assess and Minimize Environmental Losses
  - Improved Insulation Profiles
  - Minimize Surface Area and Wall Losses
  - Minimize Exhaust Losses



Rethinking Oxidation Oven Advancements

- Use of Hot Make Up Air at Ovens – Recovered Energy from TOX

  (Of Course)

- Measurement of Atmospheric Concentration per Zone -- Allows for Higher Concentrations of Waste Gases within Oven and Reduction of Total Exhaust Flow From Oven – Can results in 50% or Greater Reduction in Exhaust Air From Oven

  Process Control Technique Exclusive to Harper International Oven Systems – Only Capable with Advanced Sealing

- Measurement of Total Air Room Air Ingress at Slots through the use of Flow Meters to measure Exhaust and Makeup air (Room Air Ingress at Slots is a result by Difference)

  Process Control Technique Exclusive to Harper International Oven Systems

Oven Advancements

		Traditional Line	Oven Improvements	Additional Insulation in Ovens	All Advancements, Combined
Capacity	TPY	1500	1500	1500	1500
Operating Hours Per Year	Hrs	7200	7200	7200	7200
Oven Operating Power		3843.0	**2682.6**	3765.0	**2604.6**
Recirculation	kW-hr	969.0	**872.1**	969.0	**872.1**
Exhaust	kW-hr	2127.0	**1063.5**	2127.0	**1063.5**
Wall Losses	kW-hr	494.0	494.0	**416.0**	**416.0**
Sensible Heat of Fiber	kW-hr	253.0	253.0	253.0	253.0

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Viable LT / HT Furnace Advancements

Three Primary Advancements to Yield Energy Reduction (In Order of Increase Developmental Risk

1. Increase Insulation in HT to Reduce Thermal Losses; Reduction of Cooling Water at HT; Reduction of Terminal Losses (Low / No Risk)

2. Use of an Interconnect Chamber --between LT and HT Furnaces; reduces Losses and Reduced N2 Usage; Further Reduces Number of Vent Lines and Vent Line Losses; (Moderate Risk)

3. Use of Fold Over Design to Reduce Wall (Roof to Floor) Losses between the LT and HT and / or allow power sharing from HT to LT (Equipment Development Risk – 'Ergonomics')

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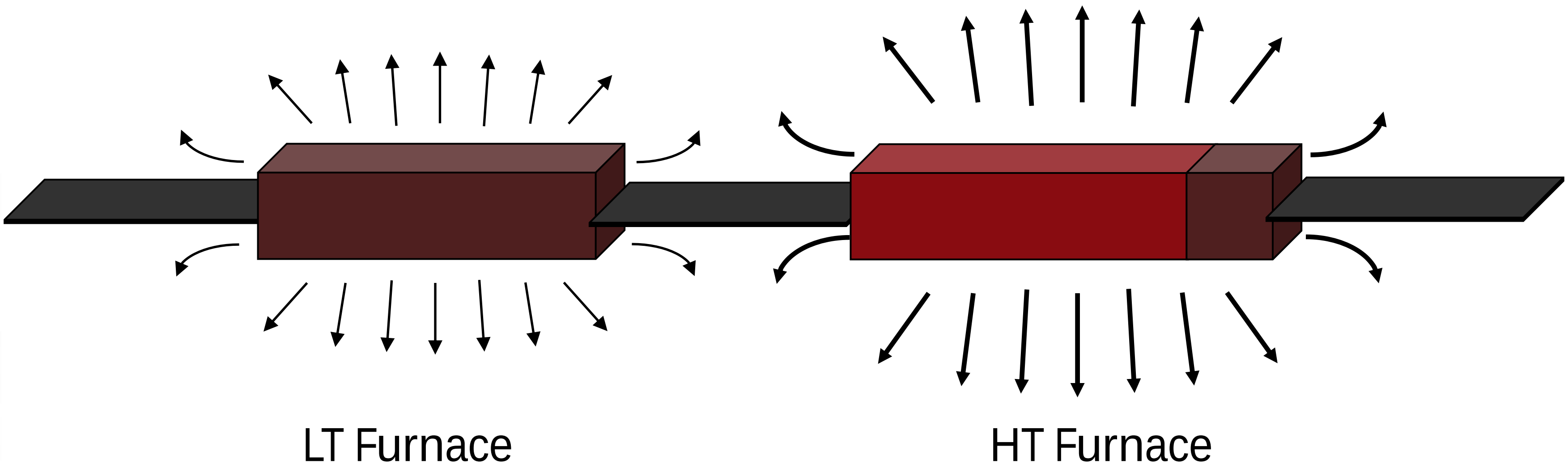
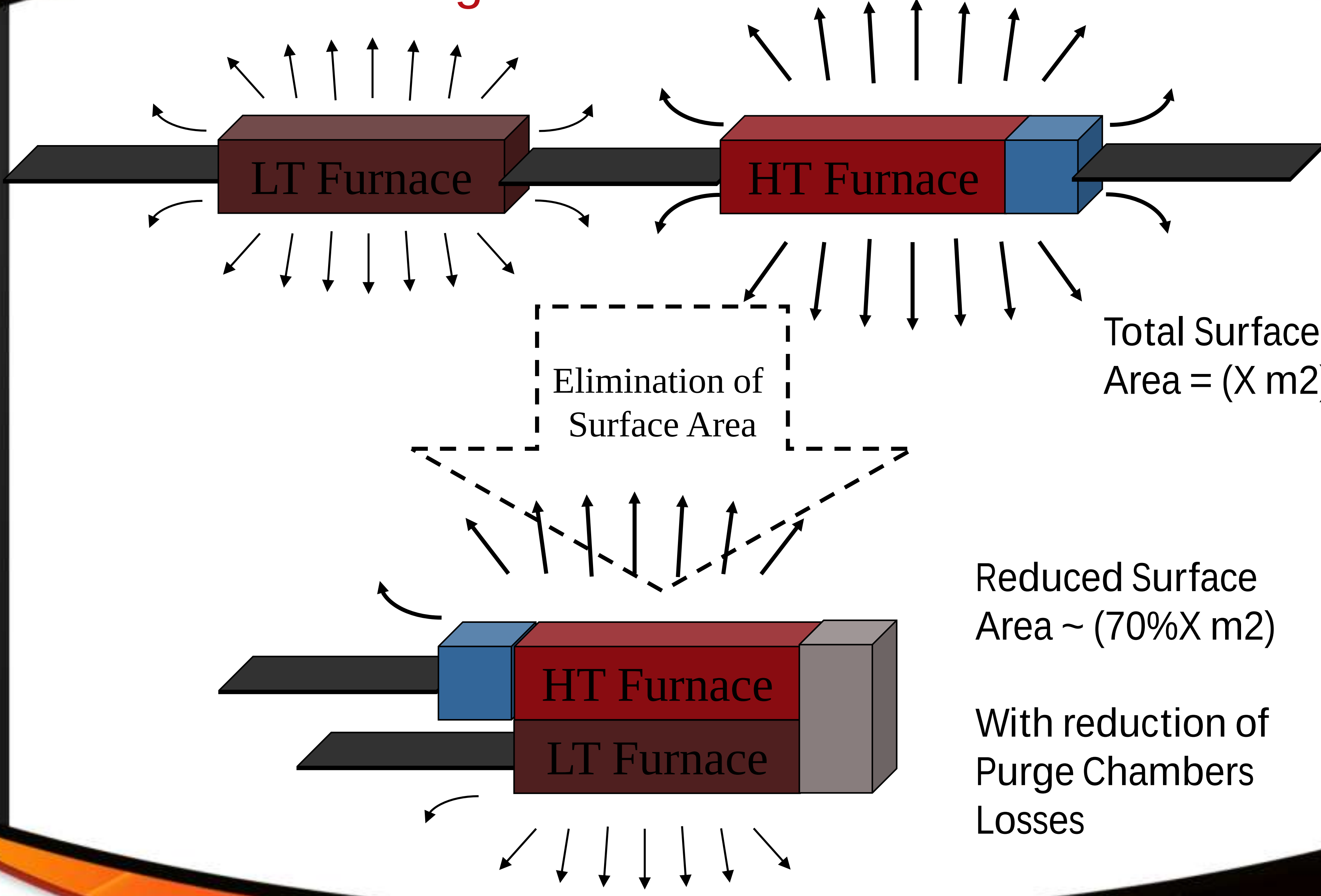
Rethinking LT HT Furnace Power Utilization



Effectively, Furnaces are Leaky Boxes Losing Energy Through:

- Wall Losses (Controlled by Insulation Profile)
- Slot Losses (Controlled by Purge Chamber Design)
- Exhaust Losses (Carried Away with Gases)

Rethinking LT HT Furnace Power Utilization



Total Surface Area = (X m2)

Reduced Surface Area ~ (70%X m2)

With reduction of Purge Chambers Losses

LT / HT Furnace Advancements

LT Furnace	**Slot Width**	**mm**	**300**	**1750**	**3000**
	Shell Width	mm	700	2150	3500
	Shell Length	mm	4465	9700	15200
	Shell Height	mm	1160	1370	1420
HT Furnace	**Slot Width**	**mm**	**300**	**1750**	**3000**
	Shell Width	mm	700	2150	3500
	Shell Length	mm	4465	9700	15200
	Shell Height	mm	1220	1370	1520
Surface Area LT		m2	18.2	74.2	159.5
Surface Area HT		m2	18.9	74.2	163.2
Total Surface Area		m2	37.1	148.4	322.8
Combined Unit Surface Area		m2	30.8	106.6	216.3
Percent Reduction from Traditional Design Surface Area		**%**	**83.1%**	**71.9%**	**67.0%**

LT / HT Furnace Advancements

		Traditional Line	Additional Insulation in HT	Combination Furnace Design	Furnace Purge Chamber	All Advancements, Combined
Capacity	**TPY**	1500	1500	1500	1500	1500
Operating Hours Per Year	**Hrs**	7200	7200	7200	7200	7200
LT Operating Power		**123.0**	**123.0**	**114.1**	**117.4**	**108.5**
Wall Losses	***kW-hr***	*27.0*	*27.0*	*18.1*	*27.0*	*18.1*
Exhaust	***kW-hr***	*16.0*	*16.0*	*16.0*	*10.4*	*10.4*
Sensible Heat of Fiber	***kW-hr***	*80.0*	*80.0*	*80.0*	*80.0*	*80.0*
HT Operating Power		**626.2**	**243.6**	**566.5**	**579.6**	**505.1**
Wall Losses	***kW-hr***	*267.6*	*243.6*	*207.9*	*267.6*	*193.1*
Exhaust	***kW-hr***	*103.6*		*103.6*	*57.0*	*57.0*
Element / Terminal Losses	***kW-hr***	*93.0*		*93.0*	*93.0*	*93.0*
Cooling Water Losses	***kW-hr***	*0.0*		*0.0*	*0.0*	*0.0*
Sensible Heat of Fiber	***kW-hr***	*162.0*		*162.0*	*162.0*	*162.0*

Peripheral Benefits to Waste Gas Abatement

- Possibility of >50% Reduction in Size of Waste Gas Abatement Unit due to reduction of Oven Exhaust (>50% Reduction in Exhaust Air From Oven)
- Reduction in Total Exhaust Flow from LT / HT Furnaces(s) due to advancements in Carbonization: Lower Line Losses, Fewer Vent Lines

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Achievable Targets for the Future

Achieving Future Improvements: Ovens

Evaluation Based On 1500 TPY Capacity - 3000mm Design	Priority	Impact kW-hr Saved	Investment Additions	Investment Reductions	Risks
Oven Insulation Thickness	2	78.0	Additional Insulation Costs	-	Low to No Risk
Oven Exhaust Control and Reduction	1	1360.4	Flow Controls at Oven, Atmosphere Monitoring	Smaller Exhaust Fans, Smaller, Waste Gas Abatement Unit, Smaller Waste Gas Abatement Exhaust Fans	Oven Sealing, Air Distribution and Process Control are Critical

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Achieving Future Improvements
LT Furnace

Evaluation Based On 1500 TPY Capacity - 3000mm Design	Priority	Impact kW-hr Saved	Investment Additions	Investment Reductions	Risks
Reduce Wall Loss - LT and HT Combination	3	68.6 Total	Investment Cost to Redesign Furnaces for Maintenance Access	-	Maintenance Access to Muffle must be Engineered.
Sealed LT and HT interconnect Chamber	4	52.2 Total	Investment and Development for Sealed Chamber, Investment and Development of Enclosed Drive Stand. R&D to determine impact of Intermediate Drive Operating Experience	Reduced Nitrogen Consumptions, Reduced Exhaust / Vent Infrastructure, Reduced Waste Gas Abatement	Risk of Enclosed Drive Stand and Operator Access.

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Achieving Future Improvements: HT Furnace

Evaluation Based On 1500 TPY Capacity - 3000mm Design	Priority	Impact kW-hr Saved	Investment Additions	Investment Reductions	Risks
HT Wall Loss Reduction - Insulation Profile	5	24.0	Additional Insulation Costs	-	Low to No Risk. Existing Designs
Reduce Wall Loss - LT and HT Combination	3	68.6 Total	Investment Cost to Redesign Furnaces for Maintenance Access	-	Maintenance Access to Muffle must be Engineered.

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The Near Future Targets

		Traditional Line	Oven Improvements	Additional Insulation in Ovens and HT	Combination Furnace Design	Furnace Purge Chamber	All Advancements, Combined
Capacity	TPY	1500	1500	1500	1500	1500	1500
Operating Hours Per Year	Hrs	7200	7200	7200	7200	7200	7200
Oven Operating Power		3843.0	**2682.6**	**3765.0**	3843.0	3843.0	**2604.6**
LT Operating Power		123.0	123.0	123.0	**114.1**	**117.4**	**108.5**
HT Operating Power		626.2	626.2	**606.2**	**566.5**	**579.6**	**505.1**
Balance of Unit Operations	kW-hr	1282.9	**1082.9**	1282.9	1282.9	1282.9	**1082.9**
Estimated Total	kW-hr	5875.1	4514.7	5414.5	5806.5	5822.9	**4301.1**
Specific Power Consumption	kW-hr / kg CF	28.2	21.7	26.0	27.9	28.0	20.6
Operating Power Compared to Traditional Line	%		76.8%	92.2%	98.8%	99.1%	73.2%
Cost of Electricity	USD / kW-hr	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05
Cost Per Year	USD / kW-hr	$2,115,050	$1,625,306	$1,949,234	$2,090,339	$2,096,250	$1,548,402
Cost Savings Per Kilogram Produced	USD / kg CF		$0.33	$0.11	$0.02	$0.01	$0.38
Reduction over traditional Line	USD Per Year		$489,744	$165,816	$24,710	$18,799	$566,647

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Thank you for your time!

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