ENABLING A STEP CHANGE IN SINGLE-LINE CARBON FIBER PRODUCTION CAPACITY THROUGH ADVANCED HIGH PRECISION LARGE SCALE THERMAL PROCESSING EQUIPMENT

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ABSTRACT

Carbon fiber applications for ground transportation exert market pressure towards increased capacity and lower cost. Both natural market forces and the NHTSA's rapidly rising CAFE mandates will push automotive manufacturers to use significantly more lightweight composite materials over the next 10 years.

Today large capacity carbonization lines for PAN precursor are in the range of 1500 – 2,500 tons per year. Much larger lines promise both investment and operating cost advantages due to the economies of scale. They also reduce the number of new lines and associated lead time required for adding large amounts of capacity.

This analysis focuses on 10,000 ton per year lines for PAN precursor. The physical space requirements are shown as functions of key variables such as tow band width, filament count, thermal residence times, and operability. Predictions of energy consumption are made using specific example configurations of 10,000 ton per year lines. The oxidation process energy consumption is shown to be chiefly a function of process exhaust requirements and the number of product turnarounds. For carbonization, the important factors are width-wise filament density and the peak temperature. Multiple flowsheets are presented to illustrate some of the possible configurations for fuel source, energy recovery heat exchange, and how the optimal selection is a complex choice that accounts for emission regulations, the price and availability of electricity and fuel gas, and piping complexity.

Finally the mechanical and process design challenges presented by a step change in capacity are discussed. The increasing importance of gas flow uniformity throughout the thermal processing steps as line width increases is demonstrated, and the ergonomic challenges posed by operating much larger equipment are discussed.

1. INTRODUCTION

Current state-of-the-art carbon fiber production lines are capable of producing 1500 to 2,500 tons of carbon fiber per year on a single line. Carbon fiber plant sizes are defined by their tow band processing width, and that width has grown continuously over the decades since carbon fiber became a commercial product. As of 2016 a normal full-sized production plant is 3 meters wide. Wider plants exist, but they are not common.

As of 2012 worldwide production nameplate production capacity of Polyacrylonitrile (PAN) based carbon fiber was approximately 96,000 tons.[1] This means that if every carbon fiber plant on Earth was running at full capacity, total production would be approximately 96,000 tons of carbon fiber.

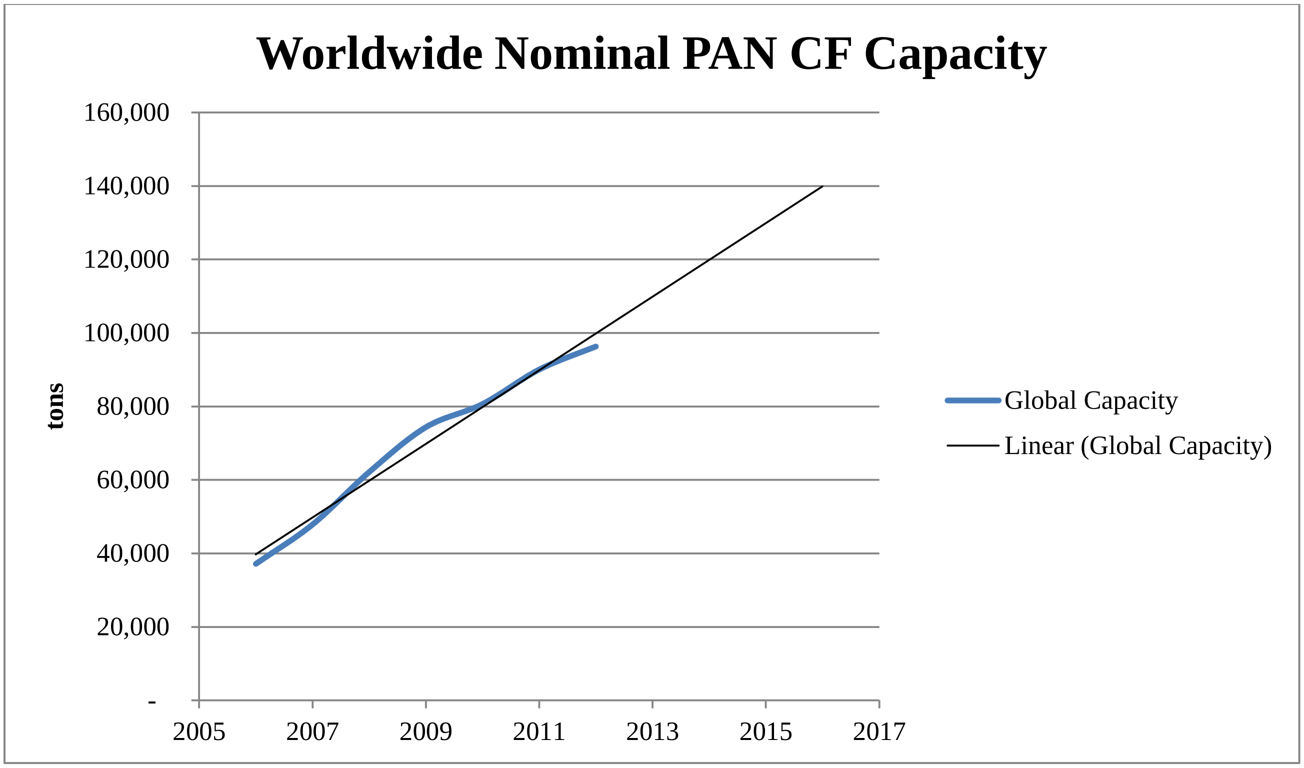

Figure 1: Worldwide nameplate capacity of PAN-based carbon fiber plants.[1]

If we extrapolate this data to today, we see that worldwide PAN-based carbon fiber capacity is approximately 140,000 tons per year.

1.1 Comparison to Current Automotive Materials

As the purpose of this paper is to explore the impact that demand from the automotive industry will have on the carbon fiber production industry, it is helpful to understand the volumes of established materials that are consumed by the global automotive industry. Knowing how much steel and aluminum is used globally by the automotive industry provides a frame of reference for understanding how much carbon fiber production capacity will have to increase when carbon fiber becomes a common material in the production of automobiles.

In 2015, the consumption of aluminum and steel by the global automotive industry was

- Aluminum – 20,245 kilotons[2]
- Steel – 80,000 kilotons[3]

When comparing the global capacity for carbon fiber production to the global consumption of materials by the automotive industry, it becomes clear that for carbon fiber to become a commonly used material in the automotive industry production is going to have to increase drastically.

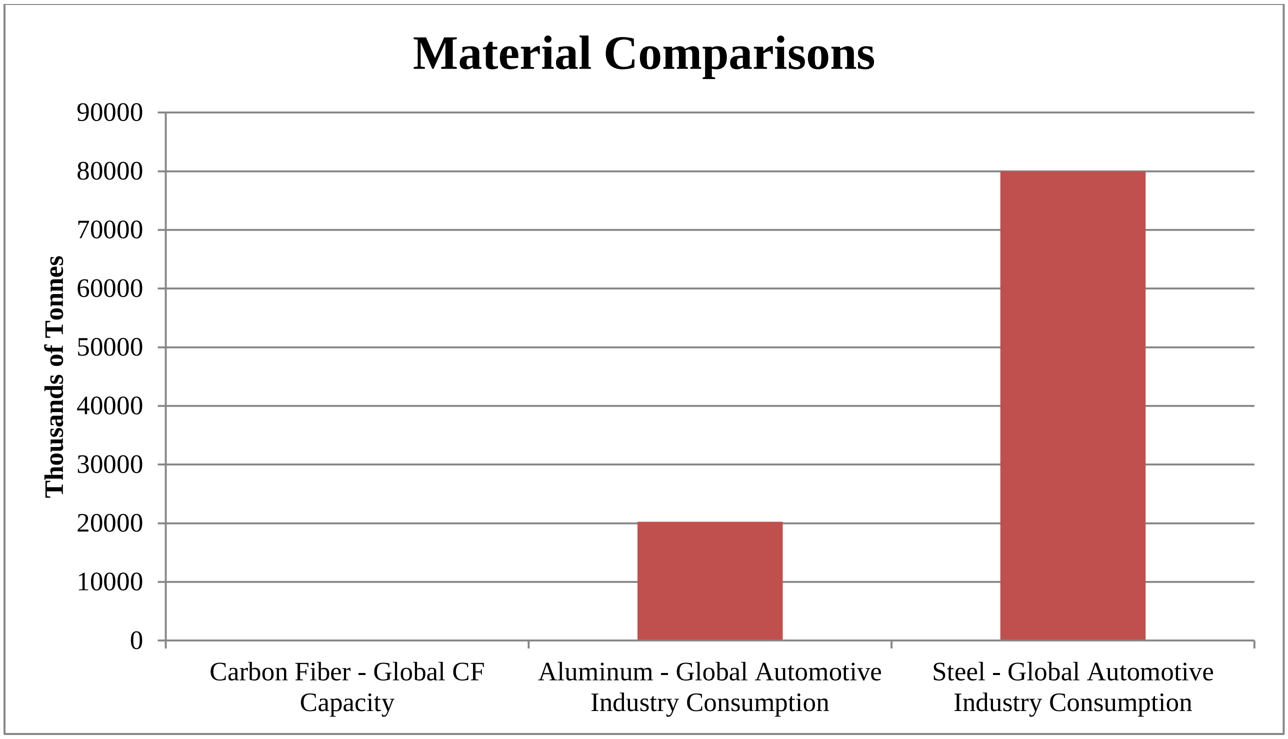

Figure 2: Carbon fiber production capacity compared to aluminum and steel consumption by the automotive industry.

1.2 Example Application of Carbon Fiber in Automobile Mass Production

Kilo for kilo comparisons of carbon fiber to conventional automotive materials (aluminum, steel) are interesting for gaining a frame-of-reference, but this is not a perfect analogy as one of the primary purposes for carbon fiber in the automotive industry is mass reduction. As such, it is useful to look at a real example of carbon fiber displacing conventional materials in an automobile.

General Motors builds every 7th Generation Corvette (2014+) with a carbon fiber hood and roof. This equates to approximately 8.2kg of carbon fiber per Corvette.[4] General Motors produced 37,288 Corvettes (29% were convertibles without carbon fiber roofs) in 2014[5] equating to a total consumption of approximately 261 tons of carbon fiber.

To further frame in gap between supply and demand that will exist if carbon fiber penetrates the automotive market in a meaningful way we can extend the Corvette example to all cars. Figure 3 shows much carbon fiber would be consumed by GM, Ford, and VW each of the cars they produced consumed 8.2kg of carbon fiber (i.e. if they each had a carbon fiber roof and hood like the corvette.

Manufacturer	2015 Production (millions of vehicles)	Theoretical CF Consumption (tons)
GM	6.0[6]	49,000
Ford	6.3[7]	51,000
VW	10.1[8]	82,000
Total	22.4	182,000

Figure 3: Carbon fiber consumption if GM, Ford, and VW used 8.2kg of carbon fiber in every vehicle they produced.

Given that global carbon fiber production capacity today is approximately 140,000 tons per year, if GM, Ford, and VW were to consume 8.2kg of carbon fiber with every vehicle they produced there is not enough carbon fiber production capacity in the world to meet that demand.

1.3 Light-Weighting for Fuel Economy

In 1975 the United States Congress enacted Corporate Average Fuel Economy (CAFE) standards. These standards mandate that the average fuel economy of an automobile manufacturer's fleet of vehicles for sale in the United States must meet a minimum value. From 1990 through 2010 this value was constant at 11.7 km/L (27.5 mpg). In 2011 the minimum CAFE value began rising rapidly, so that by 2025 the value will be 22.3 km/L (52.5 mpg).[9]

During that same time period, specifically from 1980 through 2015, the amount of aluminum used to build the average car tripled. In 1980 aluminum use averaged 60kg per vehicle and by 2015 average aluminum use had risen to 180 kg per vehicle.[10]

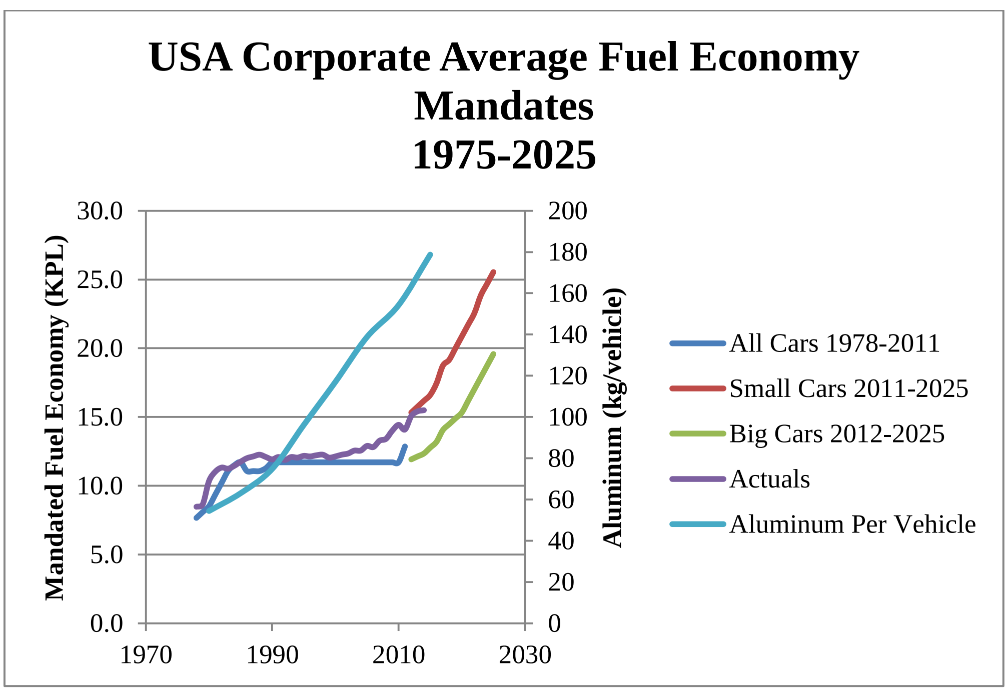

Figure 4: USA Corporate Average Fuel Economy – Mandates and Actuals. Also shown: Average aluminum use per vehicle.

As can be seen in Figure 4, actual fuel economy has historically tracked closely to CAFE mandated fuel economy, and there is a strong correlation between rising fuel economy and increasing use of light weight material. It is reasonable to believe that automotive manufacturers will meet the rapidly rising fuel economy standards of the next 10 years, and will do so through the use of light weight materials.

2. CURRENT STATE OF THE ART

2.1 Current State of the Art Plant

A current state-of-the-art high capacity carbon fiber production plant has a 3 meter wide processing width and is capable of producing 1500 to 2,500 tons per year of carbon fiber. Harper International has supplied larger carbon fiber production equipment, and every plant Harper builds is custom tailored to the client's unique precursor, process, and production goals. For the sake of discussion, it is fair to envision a "normal" current state-of-the-art plant as follows:

Creels→Oxidation Ovens (4 to 8 zones)→Low Temperature Furnace (4 to 8 zones)→High Temperature Furnace (4 to 8 zones)→Surface Treatment→Winders

This system will provide fiber residence times of 60 to 90 minutes in the oxidation ovens and 60 to 90 seconds in the carbonization furnaces. Overall plant length is in the range of 200 to 300 meters. Line speed (how fast the fiber is moving) is normally in the range of 6 to 12 m/min.

A plant producing 3K tow (3,000 filaments per tow) will produce less fiber in the same 3 meter processing width as a plant producing 48K tow (48,000 filaments per tow.) Depending on tow type, a current state of the art plant can produce between 1500 and 2,500 tons per year of carbon fiber. These production estimates include approximately 15% annual downtime for maintenance, repairs, and turnarounds. (A "turnaround" is when a production facility stops a production for a short time to clean the system and reload the creels. The time from one turnaround to the next is known as a "campaign.")

2.2 Current State of the Art Power Consumption

While actual power consumption depends on many factors such as fiber mass rates through the system, peak temperatures required in carbonization, and heat recovery methods, an average system such as described in 2.1 producing 1500 tons per year will consume approximately 6 MW of power. The approximate breakdown by process is shown in Figure 5.

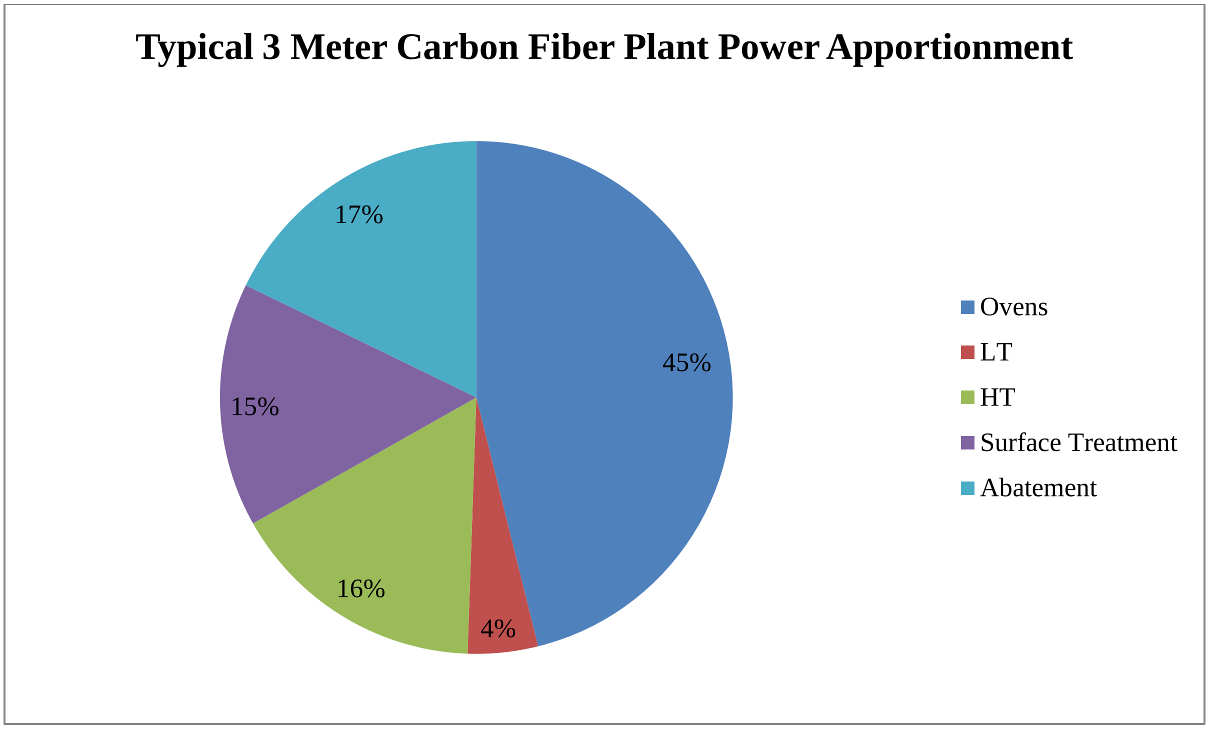

Figure 5: 3 meter carbon fiber plant power consumption by unit process.

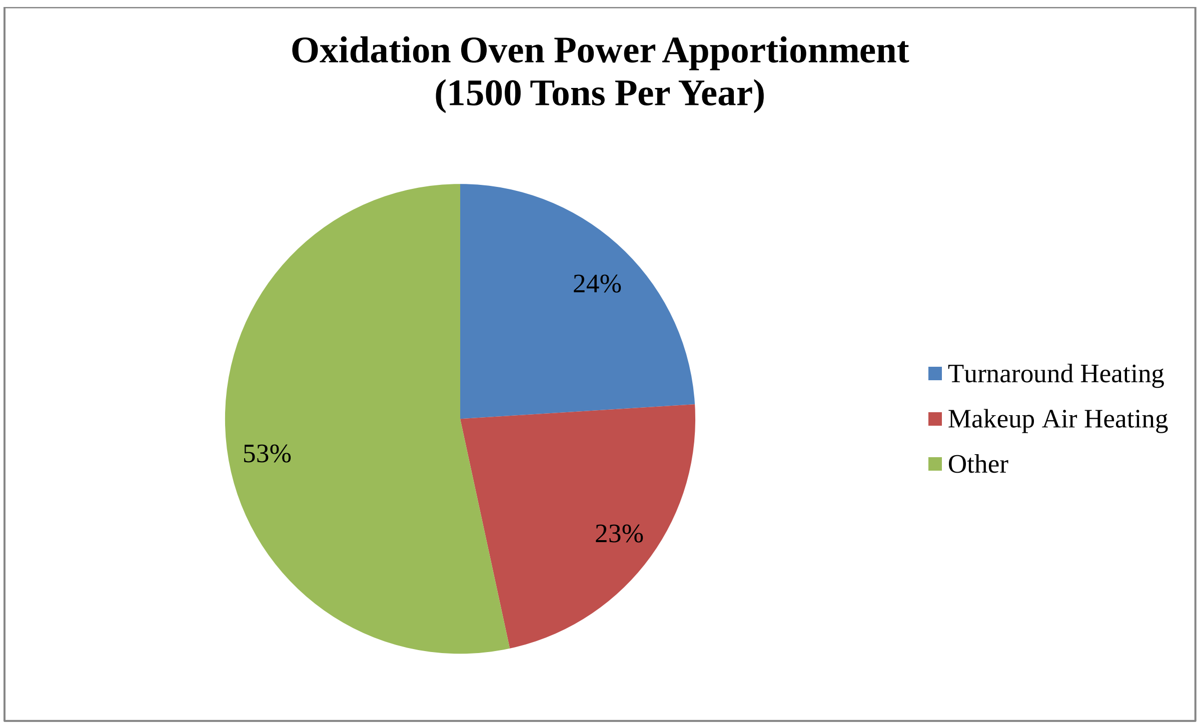

Figure 6: Power apportionment in a typical oxidation oven system from a 1500 ton per year carbon fiber line.

The oxidation ovens consume about half of the power in a carbon fiber line. Of that half, as shown in Figure 6 two terms account for half of the oven power consumption (25% of total power, or 12.5% each).

1. Oxidation requires very long residence times so effective oxidation heated lengths are approximately 500 to 1000 meters. To achieve this heated length the fiber passes back and forth in and out of the oven. Each time the fiber leaves the oven it cools as it turns around and then must be reheated when it re-enters the oven. This is known as turn-around heating.
2. Hydrogen Cyanide is produced during PAN oxidation, which is both toxic and explosive. To both keep the plant atmosphere safe to breathe and to prevent energy releases, huge amounts of exhaust must be removed and makeup air must be introduced and heated to dilute the oxidation oven process atmosphere.

The ovens are the largest pieces of equipment, both by physical size and effective heated length, and the most significant power consumers in a carbonization line. Because of this, the oxidation ovens should be the primary focus when considering a step-change scale up from 2,500 tons per year to 10,000 tons per year.

3. FUTURE STATE OF THE ART

In section 1.2 it was demonstrated that if just three major automakers were to build every car with just two carbon fiber body panels ala the C7 Corvette, there is not nearly enough carbon fiber capacity in the world to meet that new demand. That demand would be approximately 182,000 tons per year. Worldwide carbon fiber capacity is approximately 140,000 tons per year. Global capacity would have to more than double to accommodate the scenario in section 1.2.

Adding 182,000 tons per year of capacity with plants limited to 1500 to 2,500 tons per year capacity would require approximately 100 new carbon fiber production plants. If this were to happen over the next 5 to 10 years to meet the rapidly rising US CAFE mandates, this would require 10 to 20 new production plants per year. From 2006 to 2011, annual carbon fiber production capacity grew by 3,000 to 13,000 tons per year.[1] Meeting the increased capacity of section 1.2 in 5 to 10 years would require annual growth of 18,000 to 36,000 tons per year.

In addition to meeting a huge increase in demand from the automotive industry, it is also expected that a large reduction in price will be necessary to support carbon fiber adoption into the automotive industry. $9 to $11 US dollars per kilogram is expected to be necessary.[1] Current prices for industrial grade carbon fiber are approximately double that target. Aerospace grade carbon fiber is even more costly.

Both to meet a huge increase in demand and to meet a huge decrease in price, the adoption of carbon fiber into the automotive industry necessitates leveraging the economies of scale of mass production. The following sections will demonstrate how 10,000 ton per year carbon fiber lines can meet these requirements.

3.1 10,000 Ton Per Year Plant Layout

To move from 2,500 tons per year to 10,000 tons per year, a few changes will have to happen:

1. Plant width will have to increase from 3 meters to at least 5 meters.
2. Fiber line speeds (the rate at which fiber is produced) will have to increase to 20 m/min.
3. Width-wise filament density will have to increase from 2500 filaments/mm to 3500 filaments/mm (tows will have to be processed with less spread to get more production from the same size plant.)

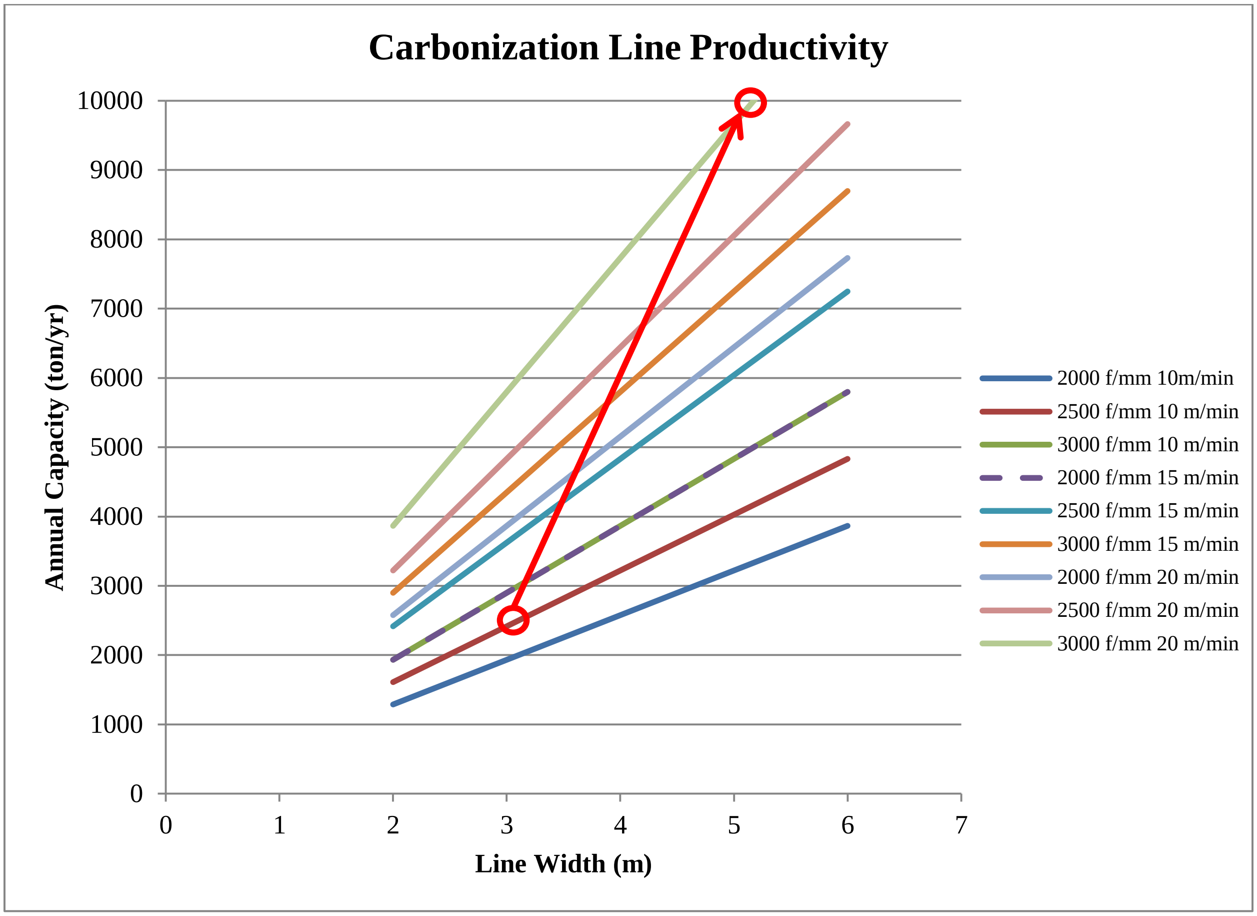

Figure 7: Increase in plant width, line speed, and filament density required to move from 2,500 to 10,000 tons per year.

Several factors affect the overall length of the carbon fiber plant. The heated length of thermal processing equipment is determined by line speed divided by residence time. The tow-type (number of filaments per tow) has a significant effect on the overall length of the plant: At a given production capacity, if the plant is producing fine tows (like 3K) more tows have to be processed than if the plant is producing heavy tows (like 48K.) More tows means more creels and more winders, which makes the plant significantly longer. Figure 8 shows this relationship between line length, tow type, and production capacity.

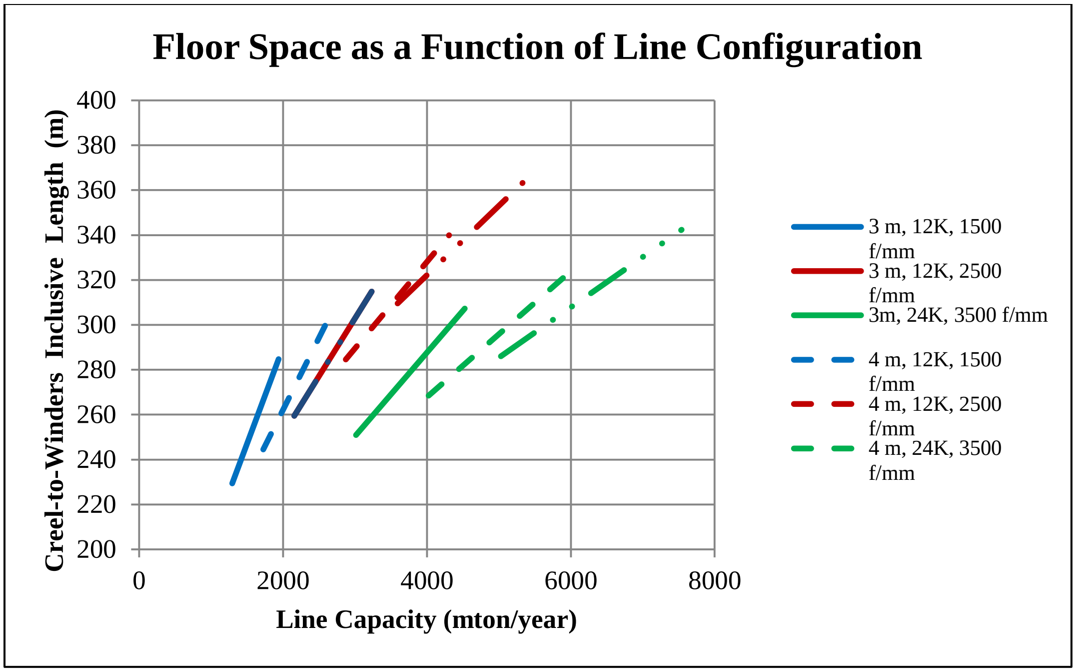

Figure 8: Examples of overall carbon fiber line length.

3.2 Example Plant – 10,000 Tons Per year, 48K Tow

The final configuration and performance of a carbon fiber plant depends on many assumptions. In order to explore a theoretical 10,000 ton per year plant in detail the following will focus on a specific example configuration.

Process Assumptions		**Resulting Equipment**	
Production	10,000 Tons Per Year	Plant Width	5 m
Tow Type	48K	Tow Spacing	15.2 mm
Tow Count	325		
Line Speed	20 m/min		
Filament Density	3000 to 3500 filaments/mm		
Oxidation Ovens Residence Time	60 min	Oxidation Heated Length	1170 m
		Oven Stacks	3
		Passes Per Stack	15
		Single Pass Heated Length	26m
LT Furnace Residence time	60 sec	LT Furnace Heated Length	20 m
		LT Zone Count	10
HT Furnace Residence Time	60 sec	HT Furnace Heated Length	20 m
		HT Zone Count	10

Figure 9: Example 10,000 ton per year plant configuration.

The overall length of the plant described in Figure 9 is approximately 310 meters.

3.3 Power Consumption – 10,000 Tons Per Year, 48K Tow

Section 3.2 demonstrates one way in which carbon fiber producers can support the increased demand anticipated from the automotive industry. Note that the process assumptions are aggressive but close to what world class carbon fiber producers are able to achieve today. The resulting equipment is within the capabilities of Harper International. Harper has produced carbon fiber slot ovens and furnaces >5 m wide, and >18 m long.

This section will look at the power consumption predicted by Harper thermal process models for this plant, to demonstrate how a 10,000 ton per year plant can drive down the cost to produce carbon fiber.

3.3.1 Power Consumption by Unit Process

Total power consumption for a 10,000 ton per year 48K carbon fiber line is predicted to be 17 megawatts of electricity. Figure 10 shows where all that power is going.

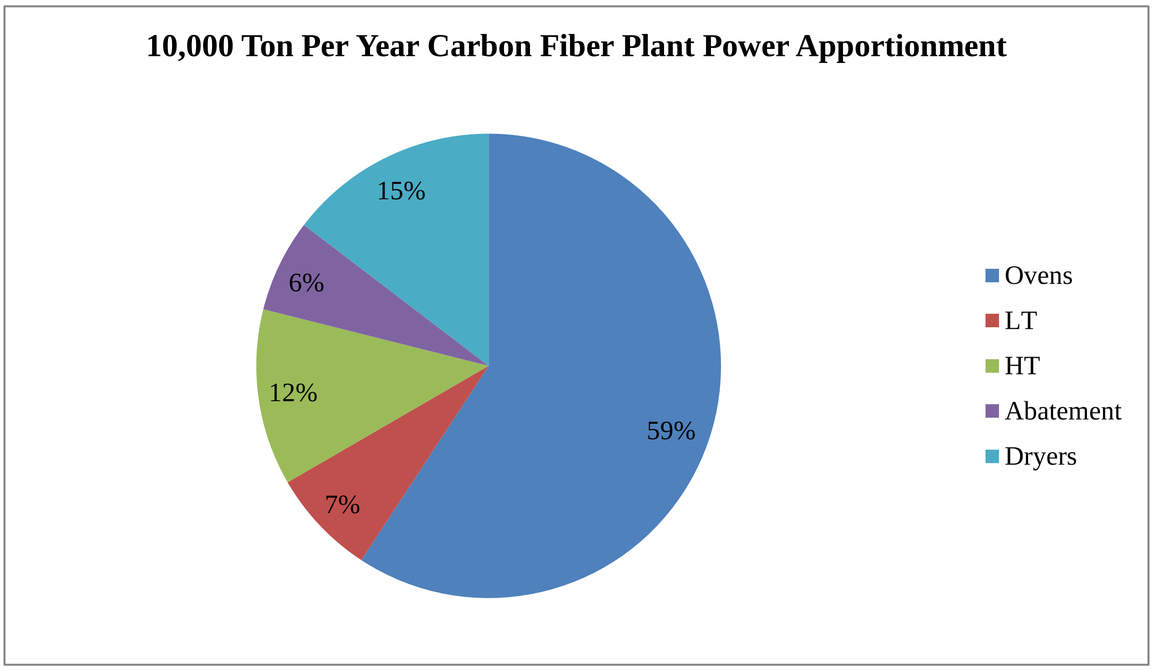

Figure 10: 5 meter, 10,000 ton per year carbon fiber plant power consumption by unit process.

In section 2.2 it was stated that a 1500 ton per year plant will consume approximately 6 MW of power, or 30 kw/kg of product (assuming 15% downtime). This 10,000 ton per year plant consuming 17 MW of electric power brings the specific power consumption down to 12.8 kw/kg of fiber. Reducing specific power consumption by 230% will contribute significantly to cutting the carbon fiber price target described in section 3.

3.3.2 Oxidation System Power Consumption

The oxidation oven system is now predicted to consume well over half of the power of the entire line. Fiber turnaround and makeup air heating now accounts for over 75% of the power consumed by the oxidation ovens.

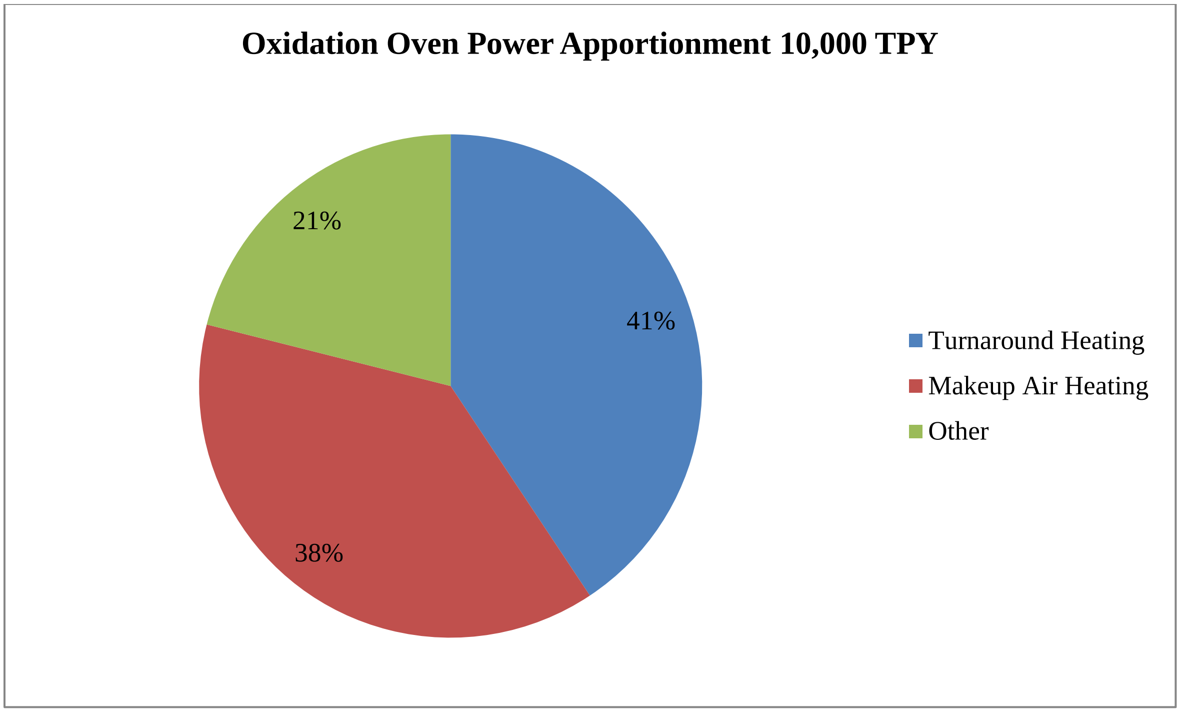

Figure 11: Power consumption in the oxidation system is dominated by fiber turnaround and makeup air heating in a 10,000 ton per year plant.

Fiber turnaround and makeup air heating each consume about 4 megawatts of power in this plant. Careful oven design is crucial to the economics and overall success of a large plant. 15 pass oven stacks were selected for this plant to minimize the number of fiber turnarounds. More passes per stack would reduce the overall size of the oxidation oven system (by reducing the pass length) but increasing the number of passes fails a cost:benefit analysis when operating expense is considered.

Makeup air heating is minimized through advanced oven end seal technology. The primary driver of makeup air volume is keeping the process atmosphere dilute enough that a small amount of inevitable fugitive emissions does not create a toxic environment on the plant floor. Advanced end seals like those found on Harper's production ovens minimize fugitive emissions which in turn minimizes makeup air requirements.

Oxidation ovens typically operate around 250 °C. At that temperature natural gas heating is efficient, and in many regions where natural gas is inexpensive gas-fired ovens may be preferable.

3.3.3 Surface Treatment (Dryers)

After the oxidation oven system, the next largest power consumer in the carbon fiber line are the surface treatment dryers. Traditional surface treatment systems consist of the following process steps:
Electrolysis→Water Wash→Drying→Sizing Application→Drying

On a plant with a huge mass rate vaporizing all of the water that becomes entrained in the fiber during water washing and sizing application consumes a huge amount of power, approximately 2.5 megawatts. Dry surface treatment technologies have not been proven on a production basis, and so cannot be recommended for inclusion on a plant of this scale. Unproven technology presents too much risk for a plant of this scale. At 10,000 tons per year and $10 US dollars per kg, an hour of downtime costs almost $14,000 dollars.

3.3.4 HT Furnace Power Consumption

The third largest power consumer in this line is the HT furnace. The main heating term, accounting for over 50% of power consumed the HT furnace this scale, is the material sensible heat – heating the fiber from ambient to over 1400 °C. As such, peak temperature is the primary variable in HT furnace power. An 1800 °C furnace consumes 500 kW more than a 1450 °C Furnace.

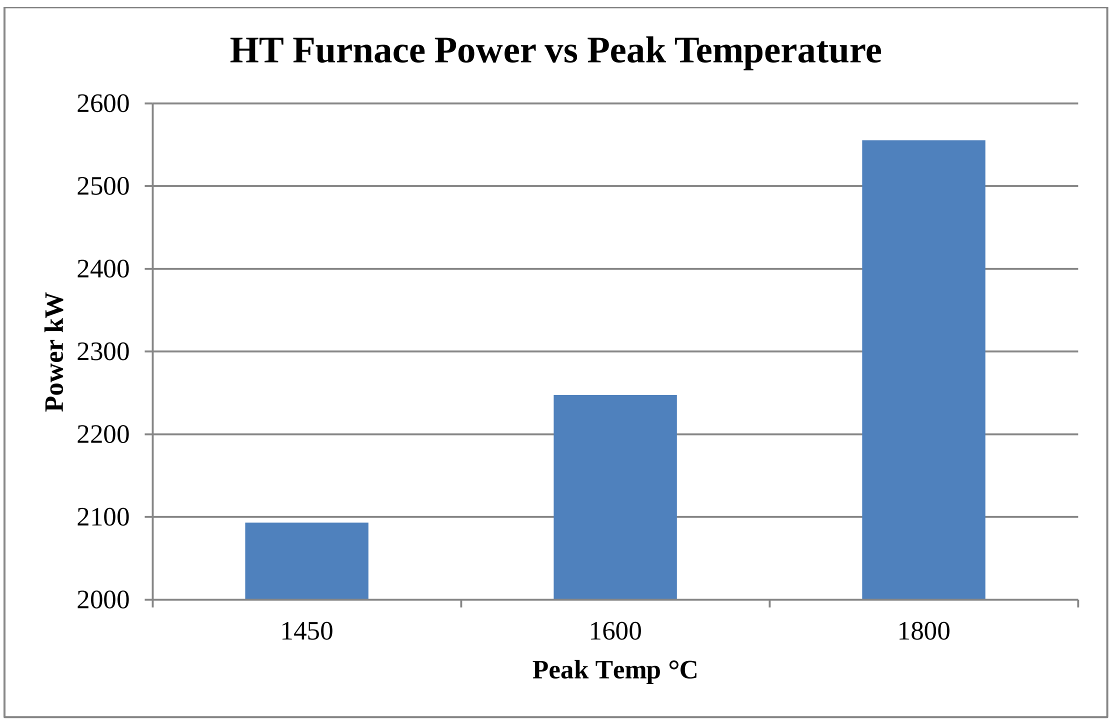

Figure 12: Power increases with peak temperature in the HT furnace.

3.3.5 LT Furnace and Abatement

The LT furnace and the abatement system are the smallest power consumers of the major unit processes in this line. Most of the energy consumed by the LT is split between product load and process atmosphere heating.

The electric energy consumed by the abatement system is for fan power to pull waste gases from the ovens and furnaces, and to drive the abatement system waste stream out of the vent stack. The system will abate 216 tons per hour of total flow from the ovens and furnaces. 95% of that is the process exhaust from the oxidation ovens. Any reduction in makeup/exhaust at the ovens will reduce both oven power consumption and abatement system power consumption. The abatement system is predicted to consume 22 megawatts of natural gas, or 1995 Nm^3/h at a heating content of 38 MJ/m^3.

The LT and abatement systems combined consume the remaining 2300 kW of power in the 10,000 ton per year carbon fiber line.

3.4 Performance

Oxidation is the slowest and most energy intensive step in the conversion of PAN to carbon fiber. As such it is considered the bottleneck to carbon fiber production and should be the primary focus when scaling up to 10,000 tons per year.

Oxidation is an exothermic process. A good analogy to the process is toasting a marshmallow on a camp fire: The material has to get just hot enough to start the reaction, but if it gets just a little too hot it catches fire. This is known as a runaway exotherm. Airflow on the fiber is used to sweep away excess heat and suppress the exotherm.

On this 10,000 ton per year plant many tows are packed very tightly together across a very wide tow band. Thus having uniform airflow across the entire width of the tow band is critical to successful oxidation. Without uniform airflow there will be cold tows that under-stabilize and eventually break, or hot tows that catch fire. Fires are the worst-case scenario, as the HCN laden process atmosphere can ignite and lead to a deflagration event, putting personnel at risk.

Harper’s production ovens have achieved airflow variance of under 3%. Other typical production ovens have been measured at 25% to 40% variance. Harper’s oven airflow technology will be necessary to enable these high production capacities.

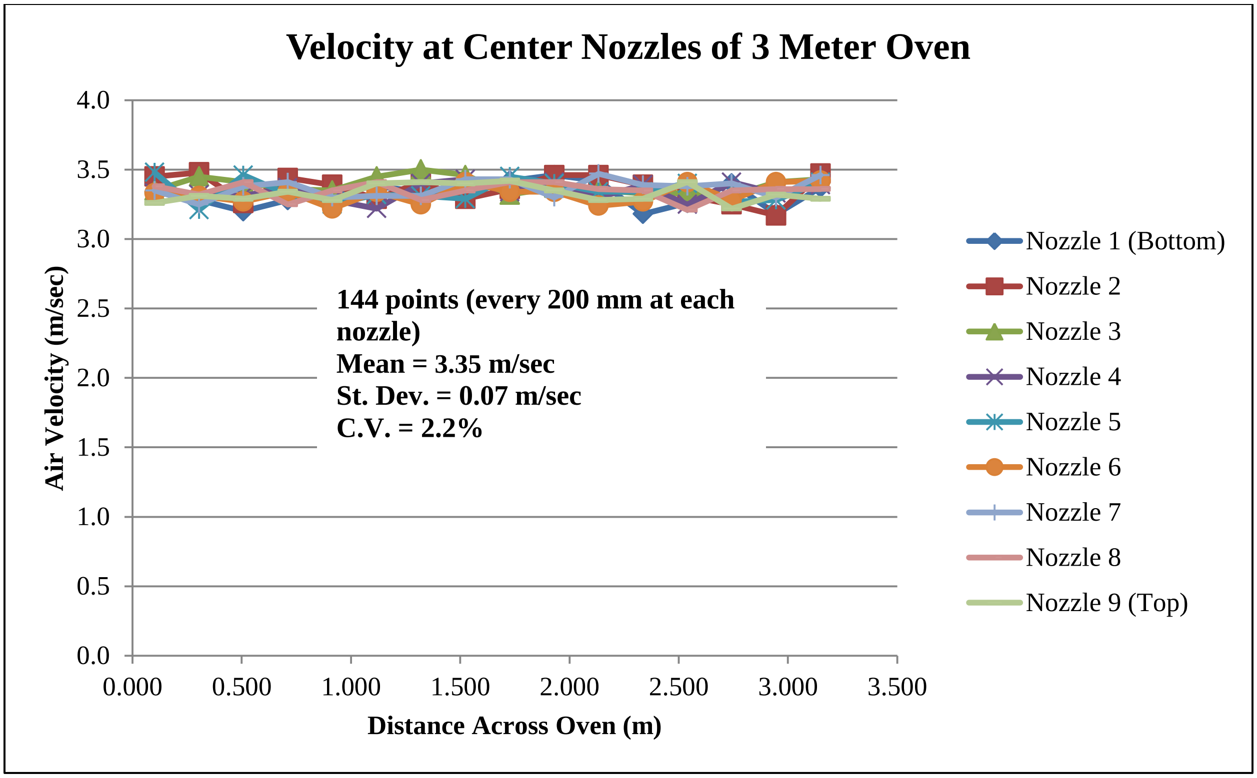

Figure 13: Harper production oxidation oven airflow uniformity, as measured in a 3 meter wide Harper production oven.

3.5 Operation Size Considerations

The equipment described in section 3.2 is large, but not of a different order of magnitude than what exists today. Harper has supplied carbon fiber equipment over 5 meters wide in the past. The 26 meter oven length is large but feasible. The furnaces are 20 meters long, but Harper has supplied many furnaces over 18 meters long that have been operating successfully for many years. While there are many ways to increase carbon fiber plant capacity as an academic exercise, the equipment described in 3.2 was selected carefully to still fit in the envelope of what can be maintained and operated.

4. CONCLUSIONS

Corporate Average Fuel Economy is mandated to increase to 22.3 km/L (52.5 mpg) by 2025. This is an increase of almost 200% in 15 years. One of the ways that automobile manufacturers will meet this economy mandate is through the use of lightweight materials like carbon fiber.

If three major automobile manufacturers such as Ford, GM, and VW were to use 8.2kg of carbon fiber in every vehicle they produce (such as is currently being done with the 7th Generation Corvette) worldwide carbon fiber production capacity would have to more than double. It is anticipated that to become viable for the automotive market, the price of carbon fiber will have to decrease by half.

Much larger “mass production” carbon fiber plants can meet this double mandate for increased capacity and decreased cost. A 10,000 ton per year carbon fiber plant is four times the capacity of current typical “large” carbon fiber plants and would consume less than half the power per kilogram of carbon fiber as a current large plant.

High precision equipment will be necessary for these large plants. As production rates rise higher and higher, so does the cost of downtime. Stable processes will be necessary to avoid downtime. Specifically, this means oxidation ovens with advanced airflow uniformity will be necessary for cost, performance, and safety at this scale.

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