Carbon Nanotubes Plant

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Ilze Veidemane
Presentation Outline

- Carbon nanotube history
- Production methods
- Economic Forecast
- HiPCO plant design
- CoMoCat plant design
- Plant Capacity and Location
- Business Plan
History

- The discovery of nanotubes comes from the Buckyball in 1980
- Nanotubes discovered in 1991 by S. Iijima

(http://www.slb.com)
Types of CNT’s

- Single wall (SWNT)
  - single layer wall
  - diameter 0.7-5 nm

- Multi-wall (MWNT)
  - concentric tubes
  - inner diameter: 1.5-15 nm
  - outer diameter: 2.5-30 nm
Orientation and Properties

All possible structures of SWNTs can be formed from chiral vectors.
Bond Types

- Armchair (conductor)
- Zigzag (semiconductor)
- Chiral (semiconductor)
Properties

- The chart compares the tensile strength of SWNT's to some common high-strength materials.
- Electrical conductivity is as high as copper.
- Thermal conductivity is as high as diamond.
- Strength 100 times greater than steel at one sixth the weight.
### SWNT Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Diameter (nm)</th>
<th>Length (μm)</th>
<th>Desired Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium batteries</td>
<td>0.7 - 1.4</td>
<td>5. -40.</td>
<td>Defects</td>
</tr>
<tr>
<td>Chemical sensors</td>
<td>1.4 - 2.3</td>
<td>20. - 40.</td>
<td>Highly aligned carbon nanotubes</td>
</tr>
<tr>
<td>Flat panel displays</td>
<td>1.0 - 5.0</td>
<td>5. - 100</td>
<td>Highly ordered arrays on substrate</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>1.85 - 5.0</td>
<td>10.-50</td>
<td>Produced by Ar and H$_2$ arc method</td>
</tr>
<tr>
<td>AFM tips</td>
<td>1.0 - 2.0</td>
<td>18. - 35.</td>
<td>Grown directly by CVD onto Si tips (can be attached later)</td>
</tr>
</tbody>
</table>
Production Methods

- Arc discharge
- Laser ablation
- Chemical Vapor Deposition (CVD)
Arc–Discharge Process

- High-purity graphite rods under a helium atmosphere.
- T > 3000°C
- 20 to 40 V at a current in the range of 50 to 100 A
- Gap between the rods approximately 1 mm or less
- Lots of impurities: graphite, amorphous carbon, fullerenes
Laser Ablation Process

- Temperature 1200°C
- Pressure 500 Torr
- Cu collector for carbon clusters
- MWNT synthesized in pure graphite
- SWNT synthesized when Co, Ni, Fe, Y are used
- Laminar flow
- Fewer side products than Arc discharge
Chemical Vapor Deposition

CVD

Gas phase process
No substrate

FROM
CARBON MONOXIDE

(HiPCO®)
(CoMoCat®)
Growth Mechanism

**Extrusion or Root Growth**
- Metal
- Support

**Tip Growth**
- Metal
- Support

Chemical Reaction:
- $C_nH_m \rightarrow C + H_2$
CVD in Gas Phase Process

- Catalysts: Fe, Ni, Co, or alloys of the three metals
- Hydrocarbons: CH$_4$, C$_2$H$_2$, etc.
- Temperature: First furnace 1050°C
  Second furnace: 750°C
- Produce large amounts of MTWNs
CVD of Carbon Monoxide

- Thermal decomposition of iron pentacarbonyl in a flow of CO
- Temperature ~1050°C
- Pressure ~10 atm

\[ 2\text{CO(g)} \xrightarrow{\text{Fe(CO)}_5} \text{C(s)} + \text{CO}_2(g) \]
CVD of Carbon Monoxide

CoMoCat® PROCESS

- Disproportionation of CO over a Co/Mo, silica supported catalyst
- Temperatures 700-950°C
- Pressure (1–10 atm)

\[ 2\text{CO}(g) \xrightarrow{\text{Co : Mo}} \text{C}(s) + \text{CO}_2(g) \]
## Comparison of Nanotube Production Technology

<table>
<thead>
<tr>
<th>Properties</th>
<th>Arc Discharge</th>
<th>Laser Ablation</th>
<th>Gas Phase Process</th>
<th>Vapor Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diameter of SWNT Nanotubes</strong></td>
<td>1.2-1.4 nm</td>
<td>1.2-1.4 nm</td>
<td>0.8-1.4 nm</td>
<td>0.8-1.4 nm</td>
</tr>
<tr>
<td><strong>Length of Nanotubes</strong></td>
<td>1-10 microns</td>
<td>1-10 microns</td>
<td>Micron or longer</td>
<td>20 cm</td>
</tr>
<tr>
<td><strong>Yields</strong></td>
<td>~50%</td>
<td>~70%</td>
<td>50%</td>
<td>~97-99%</td>
</tr>
<tr>
<td><strong>Quality of nanotubes</strong></td>
<td>Produces largely defect free nanotubes.</td>
<td>Produces defect free nanotubes. Considered highest quality nanotubes.</td>
<td>Produces MWNT and SWNT; hard to separate.</td>
<td>Produces tubes with some defects. Number of defects declining.</td>
</tr>
<tr>
<td><strong>Production Quantities</strong></td>
<td>Could exceed 10g/day.</td>
<td>Less than 1g/day.</td>
<td>Semi Conductor In full operation, 500-2,000 kg per day.</td>
<td>Semi Conductor Theoretically can produce kg or more per day.</td>
</tr>
</tbody>
</table>

Source: BCC, Inc.
Market Forecast

- Derived from information and news sources

- Two sectors: Research and Commercial

- Research demand assumed to increase in proportion to government spending

- Commercial demand evaluated for 6 applications:
  - Batteries
  - Flat Panel Displays
  - AFM Probe Tips
  - Chemical Sensors
  - Hydrogen Storage
  - Fibers and Composites
Research Demand

- Government spending was estimated from the National Nanotechnology Initiative
- Largest spenders: U.S., Japan, W. Europe

Research demand was assumed to increase at the same rate as government spending

Research demand is essentially independent of price
Commercial Demand

- Flat Panel Display market

- Based on Applied Nanotech Inc. estimates on timeline and market share

- Average display size and nanotube quantity determined from technical papers

- Demand varies with market price and time

- Evaluated for 5 other applications
- Total demand in both research and commercial sectors
- Demand curves shift to the right with time
- Demand becomes less inelastic with time and at lower price
## Companies

<table>
<thead>
<tr>
<th>Company</th>
<th>Production (g/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbolex</td>
<td>35</td>
</tr>
<tr>
<td>Carbon Solutions Inc.</td>
<td>50</td>
</tr>
<tr>
<td>CNI</td>
<td>500</td>
</tr>
<tr>
<td>IIJIN</td>
<td>200</td>
</tr>
<tr>
<td>MER</td>
<td>10</td>
</tr>
<tr>
<td>Nanocarblab</td>
<td>3</td>
</tr>
<tr>
<td>Nanocyl</td>
<td>20</td>
</tr>
<tr>
<td>Nanolab</td>
<td>50</td>
</tr>
<tr>
<td>NanoLedge</td>
<td>120</td>
</tr>
<tr>
<td>NanoAmor</td>
<td>50</td>
</tr>
<tr>
<td>Shenzhen Nanotech</td>
<td>200</td>
</tr>
<tr>
<td>SouthWest</td>
<td>500</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td>145</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1738</td>
</tr>
</tbody>
</table>
Companies

The projected number of companies in the market was estimated based on the past trend.

Average production rate determined from market research.
Supply Forecast

- Based on projected number of companies
- Average production rate to increase at a maximum of 10% per year
- Supply curves were assumed to be linear
Market Equilibrium

- Intersection of supply and demand curves
- Price and quantity determined for each year

Market Equilibrium for 2005
Equilibrium

- Equilibrium quantity will increase at a nearly linear rate

- Equilibrium price will decrease over the next ten years
Production Method

- HiPCO and CoMoCat were analyzed to determine better option
- Process designs
- Initial cost estimates
  - Equipment
  - Raw materials
  - Operating costs
HiPCO Reactor

- Scaled-up from pilot as bundle of tubes
- Stainless steel tubes with heating elements
- Channels bored in tube wall
- Tube cost: $225

CO & Fe(CO)\textsubscript{5} inlet into reaction chamber

Heating element

CO Showerhead flow

Showerhead flow

Heating element
Purification Process

- Heat in furnace
- Sonicate in concentrated HCl
- Filter and dry in vacuum oven
- Anneal at 800°C
HiPCO Equipment Costs

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>25,050</td>
</tr>
<tr>
<td>Compressor</td>
<td>60,000</td>
</tr>
<tr>
<td>Molecular sieve</td>
<td>10,000</td>
</tr>
<tr>
<td>Nanotube filter</td>
<td>1,300</td>
</tr>
<tr>
<td>Vacuum oven</td>
<td>2,700</td>
</tr>
<tr>
<td>Furnace</td>
<td>2,000</td>
</tr>
<tr>
<td>Ultrasonic processor</td>
<td>7,940</td>
</tr>
<tr>
<td>Vacuum pump</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>109,490</strong></td>
</tr>
</tbody>
</table>

- Shown for a capacity of 360 kg per year
CoMoCat Flow Diagram

- Scale model designed so that ratio of all of the important forces is the same in the model as in the full-scale bed.
- Similar geometry
- Use Froude number

Height 1 m
Diameter 0.4 m

CO recycle stream

Absorbent bed
Ca(OH)₂
Removes CO₂

Waste from

Product out
Purification Flow Diagram

Products
CNT, SiO₂, CoMo

CNT's + CoMo + SiO₂ + O₂

O₂ addition
Mo, C, CNT's, O₂
Delivering Forms

Forms of delivering the nanotubes:

- a) freeze-dried web
- b) stable suspension
CoMoCat Equipment Costs

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>35,800</td>
</tr>
<tr>
<td>Compressor</td>
<td>50,300</td>
</tr>
<tr>
<td>Molecular sieve</td>
<td>10,000</td>
</tr>
<tr>
<td>Filters</td>
<td>1,300</td>
</tr>
<tr>
<td>Gas heater</td>
<td>11,000</td>
</tr>
<tr>
<td>Catalyst heater</td>
<td>15,000</td>
</tr>
<tr>
<td>Gel Drying bed</td>
<td>10,000</td>
</tr>
<tr>
<td>Sonicating Beds</td>
<td>11,500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>144,900</strong></td>
</tr>
</tbody>
</table>

- Shown for a capacity of 360 kg per year
- Pricing info: Matches & T.P. McNulty Associates
  M.S. Peters and K.D. Timmerhaus, Plant Design & Economics for Chemical Engineers
Production method comparisons

- Quality
- Technology
- Potential Market
- Fixed Capital Investment
- Operating Cost
Comparison of Quality

- **Bundle size**
  - CoMoCat (10-20 CNT’s)
  - HiPCO (50-100 CNT’s)

- **Impurities**
  - CoMoCat: less by wt%
  - HiPCO: fewer types
Comparison of Quality

- Distribution of semiconducting nanotubes (Chiral).
- The diameter of the nanotubes increases to the right.
Technology Comparisons

HiPCO
- Plug flow reactor
- Laminar flow
- Simple catalyst
- Yield
  - 50wt% SWNT
  - 50wt% Fe impurities
- Lower Selectivity
- Bigger bundles (50-100 CNTs)

CoMoCat
- Semi Batch reactor
- Turbulent flow
- Complicated catalyst
- Yield
  - 10wt% SWNT
  - 90wt% impurities
- Higher Selectivity
- Smaller bundles (10 – 20 CNTs)
Potential market for both processes are essentially the same
Processes were evaluated on a cost basis
# Operating Cost Analysis

<table>
<thead>
<tr>
<th>HiPCO</th>
<th>CoMoCat</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,589,499</td>
<td>2,230,000</td>
</tr>
<tr>
<td><strong>Annual utility cost</strong></td>
<td>($/ year)</td>
</tr>
<tr>
<td>596,000</td>
<td>2,020,000</td>
</tr>
<tr>
<td><strong>Annual raw material cost</strong></td>
<td>($/year)</td>
</tr>
<tr>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td><strong>Labor cost</strong></td>
<td>($/year)</td>
</tr>
<tr>
<td>4,185,500</td>
<td>5,250,000</td>
</tr>
<tr>
<td><strong>Annual Operating Costs</strong></td>
<td></td>
</tr>
</tbody>
</table>

• Shown for a capacity of 360 kg per year
## Fixed Cost Analysis

<table>
<thead>
<tr>
<th>Technology</th>
<th>HiPCO</th>
<th>CoMoCat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased equipment</td>
<td>$159,490.00</td>
<td>$169,490.00</td>
</tr>
<tr>
<td>delivered equipment</td>
<td>$23,923.50</td>
<td>$25,423.50</td>
</tr>
<tr>
<td>purchased equipment installation</td>
<td>$63,796.00</td>
<td>$67,796.00</td>
</tr>
<tr>
<td>instrumentation$Controls(installed)</td>
<td>$95,694.00</td>
<td>$101,694.00</td>
</tr>
<tr>
<td>Piping(isntalled)</td>
<td>$49,441.90</td>
<td>$49,441.90</td>
</tr>
<tr>
<td>Electrical systems(installed)</td>
<td>$39,872.50</td>
<td>$39,872.50</td>
</tr>
<tr>
<td>Buildings(land and constructions)</td>
<td>$639,593.50</td>
<td>$639,593.50</td>
</tr>
<tr>
<td>Yard improvements</td>
<td>$39,872.50</td>
<td>$39,872.50</td>
</tr>
<tr>
<td>Service facilities</td>
<td>$87,719.50</td>
<td>$87,719.50</td>
</tr>
<tr>
<td><strong>Total direct cost</strong></td>
<td>$1,199,403.40</td>
<td>$1,220,903.40</td>
</tr>
<tr>
<td>Engineering and supervision</td>
<td>$100,000.00</td>
<td>$100,000.00</td>
</tr>
<tr>
<td>Construction expenses</td>
<td>$250,000.00</td>
<td>$250,000.00</td>
</tr>
<tr>
<td>Legal expenses</td>
<td>$9,170.68</td>
<td>$9,170.68</td>
</tr>
<tr>
<td>Contractor's fee</td>
<td>$150,000.00</td>
<td>$150,000.00</td>
</tr>
<tr>
<td>Contingency</td>
<td>$80,701.94</td>
<td>$80,701.94</td>
</tr>
<tr>
<td>Advertising</td>
<td>$10,000.00</td>
<td>$10,000.00</td>
</tr>
<tr>
<td>Marketing</td>
<td>$5,000.00</td>
<td>$5,000.00</td>
</tr>
<tr>
<td><strong>Total indirect costs</strong></td>
<td>$604,872.62</td>
<td>$604,872.62</td>
</tr>
<tr>
<td><strong>FCI</strong></td>
<td>$1,804,276.02</td>
<td>$1,825,776.02</td>
</tr>
</tbody>
</table>

- Shown for a capacity of 360 kg per year
Mathematical Model

Input:
- FCI vs. Capacity
- Operating Costs
- Raw materials
- Locations
- Taxes
- Labor wages
- Demand

Output:
- Net present value
- Plant location
- Product market
<table>
<thead>
<tr>
<th>Capacity (kg/yr)</th>
<th>360</th>
<th>720</th>
<th>1080</th>
<th>1440</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased equipment</td>
<td>$159,490</td>
<td>$182,741</td>
<td>$205,992</td>
<td>$259,243</td>
</tr>
<tr>
<td>delivered equipment</td>
<td>$23,923</td>
<td>$27,411</td>
<td>$30,898</td>
<td>$38,886</td>
</tr>
<tr>
<td>purchased equipment installation</td>
<td>$63,796</td>
<td>$73,096</td>
<td>$82,396</td>
<td>$103,697</td>
</tr>
<tr>
<td>instrumentation.Controls(installed)</td>
<td>$95,694</td>
<td>$109,644</td>
<td>$123,595</td>
<td>$155,545</td>
</tr>
<tr>
<td>Piping(installed)</td>
<td>$49,441</td>
<td>$56,649</td>
<td>$63,857</td>
<td>$80,365</td>
</tr>
<tr>
<td>Electrical systems(installed)</td>
<td>$39,872</td>
<td>$45,685</td>
<td>$51,498</td>
<td>$64,810</td>
</tr>
<tr>
<td>Buildings(land and constructions)</td>
<td>$639,593</td>
<td>$639,593</td>
<td>$639,593</td>
<td>$639,593</td>
</tr>
<tr>
<td>Yard improvements</td>
<td>$39,872</td>
<td>$45,685</td>
<td>$51,498</td>
<td>$64,810</td>
</tr>
<tr>
<td>Service facilities</td>
<td>$87,719</td>
<td>$100,507</td>
<td>$113,295</td>
<td>$142,583</td>
</tr>
<tr>
<td><strong>Total direct cost</strong></td>
<td>$1,199,763</td>
<td>$1,281,734</td>
<td>$1,363,705</td>
<td>$1,550,976</td>
</tr>
<tr>
<td>Engineering and supervision</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Construction expenses</td>
<td>$250,000</td>
<td>$250,000</td>
<td>$250,000</td>
<td>$250,000</td>
</tr>
<tr>
<td>Legal expenses</td>
<td>$9,170</td>
<td>$10,507</td>
<td>$11,844</td>
<td>$14,906</td>
</tr>
<tr>
<td>Contractor's fee</td>
<td>$150,000</td>
<td>$150,000</td>
<td>$150,000</td>
<td>$150,000</td>
</tr>
<tr>
<td>Contingency</td>
<td>$80,701</td>
<td>$92,466</td>
<td>$104,231</td>
<td>$131,176</td>
</tr>
<tr>
<td>Advertising</td>
<td>$10,000</td>
<td>$10,000</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Marketing</td>
<td>$5,000</td>
<td>$5,000</td>
<td>$5,000</td>
<td>$5,000</td>
</tr>
<tr>
<td><strong>Total indirect costs</strong></td>
<td>$604,872</td>
<td>$602,974</td>
<td>$616,076</td>
<td>$646,083</td>
</tr>
<tr>
<td><strong>FCI</strong></td>
<td>$1,804,636</td>
<td>$1,884,708</td>
<td>$1,979,781</td>
<td>$2,197,059</td>
</tr>
</tbody>
</table>
Model Input

$y = 353.43x + 2E+06$

FCI vs capacity

FCI ($) vs capacity (kg/yr)
Model Input

operating cost vs capacity

\[ y = 194.2x + 2 \times 10^6 \]
Silicon Valley
Strengths
-$100M in state funding pledged over 4 years
-Tech-focused infrastructure, with myriad Of top players from high-tech industry
Weaknesses
-Still recovering from dot-com excesses
-High cost of living

South California
Strengths
- $100 M in state funding pledged over 4 years
-VC firms view funding of So. Cal start-ups favorably
-Cal. NanoSystems Institute fostering academic-industry collaboration
Weaknesses
- Competitive entrepreneurial environment can make funding difficult
- High cost of living

Illinois
Strengths
-2 of 6 NSF Nano research centers at Northwestern and UIUC (including RPI’s center, due to NSEC grant partnership)
-Strong nano research base
-Significant additional talent and infrastructure nearly at Purdue, Notre Dame, and Wisconsin
Weaknesses
Investment capital believed to be conservative than elsewhere

Massachusetts
Strengths
-1 of 6 NSF nano research centers at Harvard
-Track record of establishing new industries
-Abundant entrepreneurship
Weaknesses
-State has little money to fund initiatives
-High cost of living

Oklahoma
Strengths
-University of Oklahoma research
-SouthWest NanoTechnology Inc.
-CoMoCAT technology
Weaknesses
-Taxes

NY/NJ
Strengths
-3 of 6 NSF Nano research centers at Columbia, RPI and Cornell
-Great access to NYC-based venture capital
-NJ very supportive of industry-academic partnerships. Lucent recently donated its facility to serve as a NJ Nanotech Park
-Over $150M in state and IBM support for Center for Excellence in Nano (NY University at Albany)
Weaknesses
-No coordinated effort yet
-High cost of living

Texas
Strengths
-1 of 6 NSF Nano research centers at Rice
-Experience in attracting tech companies
-Texas Nanotechnology initiative fostering collaboration between industry, academia, government
Weaknesses
-Austin- Huston – Dallas cluster is geographically dispersed
-No concrete state funding or initiative yet
### Taxes and Labor

- **Total staff**: 22
- **Total wage paid per year**: $1,000,000

<table>
<thead>
<tr>
<th>States</th>
<th>State Income Tax</th>
<th>State Sales Tax</th>
<th>Property Tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>1% - 9.3%</td>
<td>6%</td>
<td>30%</td>
</tr>
<tr>
<td>Texas</td>
<td>0%</td>
<td>6.25%</td>
<td>25%</td>
</tr>
<tr>
<td>NY/NJ</td>
<td>1.4% - 6.37%</td>
<td>6%</td>
<td>34%</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>5.30%</td>
<td>5%</td>
<td>30%</td>
</tr>
<tr>
<td>Illinois</td>
<td>3%</td>
<td>6.25%</td>
<td>33.33%</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>0.5% - 7%</td>
<td>4.50%</td>
<td>15%</td>
</tr>
</tbody>
</table>
Model Input

- Forecasted demand for nanotubes

![Equilibrium Quantity Graph](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Quantity (kg/yea)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>700</td>
</tr>
<tr>
<td>2007</td>
<td>1300</td>
</tr>
<tr>
<td>2010</td>
<td>1900</td>
</tr>
<tr>
<td>2013</td>
<td>2500</td>
</tr>
</tbody>
</table>
Model Input

- Forecasted price

![Equilibrium Price Graph]

- Price ($/gram)
- Year

<table>
<thead>
<tr>
<th>Year</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>500</td>
</tr>
<tr>
<td>2006</td>
<td>400</td>
</tr>
<tr>
<td>2008</td>
<td>300</td>
</tr>
<tr>
<td>2010</td>
<td>200</td>
</tr>
<tr>
<td>2012</td>
<td>100</td>
</tr>
<tr>
<td>2014</td>
<td>0</td>
</tr>
</tbody>
</table>
Equations

$$FCI_i = A*bi_i + B*bc_i + C*Capacity_i$$

$$CF_{i,tp} = Revenue_{i,tp} - (Revenue_{i,tp} - d*FCI_i)*taxprop_i$$

$$TotalCosts_{i,tp} = RawMatCost_{i,tp} + OperatingCosts_{i,tp} + Capimprove_{tp}$$

Binary Variables

- bi = 1 if constructed
- bc = 1 if expanded

Amount taken directly from revenues to pay for capital investment
Equations

\[ TCI_i = FCI_i / 0.85 \]

Objective Function to be MAXIMIZED

\[
NPW = \sum_i \left( \sum_{tp} \frac{CF_{i,tp}}{(1+i)^{tp}} + \frac{(V_s + I_w)}{(1+i)^{tp}} \cdot FCI_i - TCI_i \right)
\]
Constraints

\[ \text{NumPlants} = \sum_i b_i \]

\[ \text{Capacity}_i \times b_i \geq \sum_j x_{i,j,tp} \]

\[ \text{Demand}_{j,tp} \times (PM) \geq \sum_i x_{i,j,tp} \]

\[ \text{MaxCap}_i \geq \text{Capacity}_i \]

\[ \sum_j x_{i,j,tp=1} = 0 \]
## Sensitivity Analysis

<table>
<thead>
<tr>
<th>Raw materials</th>
<th>Current price</th>
<th>+ 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPW (million$)</td>
<td>18</td>
<td>0.745</td>
</tr>
</tbody>
</table>
Model Output

- Net present value over 10 years: $18 million
- TCI = 2.5 million
- Plant Location: Oklahoma
- Plant Capacity: 241 kg/year
- ROI = 46%
- For $2.5 million total capital investment
Revenue and Costs

- Revenue: $0
- Cost of Goods Sold (COGS): $2,000,000
- Operating Costs: $4,000,000
- R&D: $6,000,000

Year (Year 1 = 2006)

1. FCX
2. Raw Material Cost
3. R&D
4. Operating Cost
5. Revenue

Dollars ($)

- Year 1: -$6,000,000
- Year 2: -$4,000,000
- Year 3: -$2,000,000
- Year 4: $0
- Year 5: $2,000,000
- Year 6: $4,000,000
- Year 7: $6,000,000
- Year 8: $8,000,000
- Year 9: $10,000,000
- Year 10: $12,000,000
Annual Cash Flow
Risk analysis

RISK CURVE

- Frequency
- Cumulative %

NPW

Frequency

0 20 40 60 80 100 120 140 160

-400000 1000000 6000000 11000000 16000000 21000000 26000000 31000000

120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
Business Plan

- Plan to capture 10% of the market
  - Competitive production rate of 1kg/day
  - Advertising and promotion
  - Low product cost allows to undersell competition

- Market product to research sectors until commercial applications develop

- Largest commercial sectors are fibers and composites and flat panel displays
Funding Requirement

- Seeking a backer to provide financial investment of $2.5 million
- Investor will receive 15% ownership of the company
Conclusions

- Construct facility with HiPCO process
  - Capacity: 241 kg/year
  - Location: California
- Total capital investment: $2.5 million
- Expected net present worth: $18 million
- Return on investment: 46 %
Future Considerations

- Expand plant to include functionalization
- Apply profits toward research facility
- Seek contracts with large companies
Questions?
Fluidized bed Reactor scale up

- Scale model designed so that ratio of all of the important forces is the same in the model as in the full-scale bed.
- Similar geometry
- Use Froude number

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{\rho_s U_o d_p}{\mu} )</td>
<td>Particle inertia/ gas viscous force</td>
</tr>
<tr>
<td>( \frac{\rho_f U_o L}{\mu} )</td>
<td>Gas inertia/ Gas viscous force</td>
</tr>
<tr>
<td>( \frac{U_o^2}{gL} )</td>
<td>Inertia /gravity force</td>
</tr>
<tr>
<td>( \frac{\rho_s}{\rho_f} )</td>
<td>Solid inertia/ Gas inertia force</td>
</tr>
<tr>
<td>( \frac{G_s}{\rho_s U_o} )</td>
<td>Solid recycle volumetric flow /Gas volumetric flow</td>
</tr>
<tr>
<td>L/D</td>
<td>Bed height/ bed diameter</td>
</tr>
</tbody>
</table>
Froude number

\[
(D_m/D_c) = \left(\frac{(V_f)_m}{(V_f)_c}\right)^{2/3}
\]

\[
\left(\frac{(V_f)_m}{(V_f)_c}\right)^{1/3} = \frac{(G_s/\rho)_m}{(G_s/\rho_s)_c}
\]

Wen-Ching Yang, *Handbook of Fluidization and Fluid-Particle Systems*, 2003